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# VOLCANIC ERUPTION THROUGH A GEOTHERMAL BOREHOLE AT NÁMAFJALL, ICELAND

by

Gudrún Larsen and Karl Grönvold
Nordic Volcanological Institute
University of Iceland

Sigurdur Thorarinsson
Science Institute
University of Iceland

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## ABSTRACT

During the present rifting episode in the Krafla fault swarm in North Iceland large scale subterraneous movement of basaltic magma is taking place. In three of the deflation and rifting events small and short lived lava eruptions have taken place. In one of them a minor amount of magma, about 3 tons, escaped to the surface through a 1134 meter deep hydrothermal borehole forming a small scoria sheet. The whole eruption lasted about 20 minutes or less.

## INTRODUCTION

On December 20th 1975 a major rifting episode began in the Krafla fault swarm in North Iceland (1, 2, 3). Since then and up to the present day the Krafla fault swarm and the associated Krafla central volcano have shown continuous tectonic and magmatic activity (4). On September 8th 1977 during a major underground magma movement a small amount of magma reached the depth range of boreholes in the Námafjall geothermal field. This caused a minor volcanic eruption through a borehole producing about 3 tons of fresh basaltic scoria in two pulses lasting about one minute each. In this account the main features of the borehole eruption are described both from eyewitness accounts and from observations made on the products. The borehole eruption is a small yet very significant manifestation of the activity presently taking place. Some of this activity is already described in other accounts (1, 2, 3, 4). It is necessary to give first a brief account of the events leading up to the borehole eruption and the rifting and the lava eruption that took place simultaneously.

During this present rifting episode about 70 km of the Krafla fault swarm in North Iceland (Fig. 1) have been activated and horizontal movements of over 2 meters have been observed. The rifting activity is closely associated with magmatism as the new rifts are intruded with magma fed horizontally along the rift from magma reservoirs below the Krafla caldera midways on the fault swarm. The depth of the reservoirs is estimated at about 3 km, using seismic (1) and ground deformation (4) evidence.

The rifting activity itself is a discontinuous process. Relatively short rifting events that activate 5-15 km long segments of the fault swarm are accompanied by simultaneous transfer of magma into the segment of the fault swarm being rifted in that event. The transfer

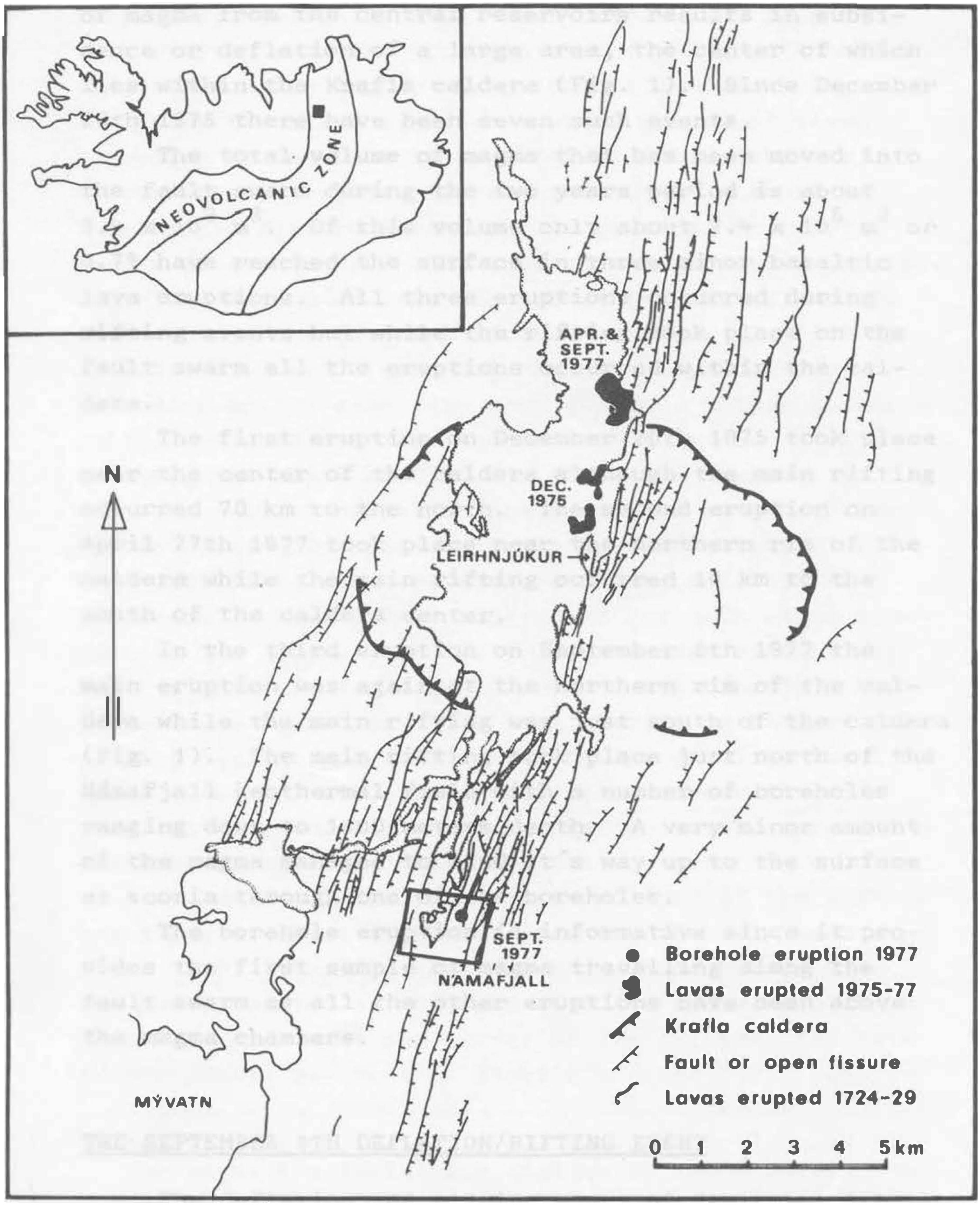


Fig. 1. The main geological features of the Krafla area and location of the eruptions 1975-1977. The Námafjall area is shown in greater detail in Fig. 2.

of magma from the central reservoirs results in subsidence or deflation of a large area, the center of which lies within the Krafla caldera (Fig. 1). Since December 20th 1975 there have been seven such events.

The total volume of magma that has been moved into the fault swarm during the two years period is about $3.4 \times 10^8$ $m^3$. Of this volume only about $2.4 \times 10^6$ $m^3$ or 0.7% have reached the surface in three minor basaltic lava eruptions. All three eruptions occurred during rifting events but while the rifting took place on the fault swarm all the eruptions occurred within the caldera.

The first eruption on December 20th 1975 took place near the center of the caldera although the main rifting occurred 70 km to the north. The second eruption on April 27th 1977 took place near the northern rim of the caldera while the main rifting occurred 10 km to the south of the caldera center.

In the third eruption on September 8th 1977 the main eruption was again at the northern rim of the caldera while the main rifting was just south of the caldera (Fig. 1). The main rifting took place just north of the Námafjall geothermal field with a number of boreholes ranging down to 1800 meters depth. A very minor amount of the magma managed to find it´s way up to the surface as scoria through one of the boreholes.

The borehole eruption is informative since it provides the first sample of magma travelling along the fault swarm as all the other eruptions have been above the magma chambers.

## THE SEPTEMBER 8TH DEFLATION/RIFTING EVENT

The deflation and rifting event of September 8th 1977 started with a volcanic tremor on the seismographs at 1547 hours and at about the same time the center of the caldera started deflating. Just before 1800 lava eruption started near the northern rim of the Krafla caldera (Fig. 1). According to the pilots of an overflying aeroplane the first sign was a white column of steam darkening at the base after a few minutes. Shortly thereafter lava spattering started out of a short portion of the fissure which rapidly extended to a total length of 800 meters. The lava output increased quickly, reaching maximum in less than about 30 minutes, and by 1930 most of the lava was already erupted. By 2230 the activity died out. Assuming that the magma started ascending at the same time when volcanic tremor appeared on the seismometers the rate of ascent is about 0.5 m/sec assuming the depth of 3 km for the magma chamber.

The initial deflation phase stopped at about 1720 and is apparently related to the lava eruption. The main deflation, however, started at about 1820. This deflation is most likely related to the main magma movement to the south. The center of the main rifting segment in this event was just north of the Námafjall high temperature area (Fig. 1). Some overlap is between this rifting segment and that rifted in the previous event on April 27th 1977 since reference lines across the rift zone that already had increased by two meters extended a further one meter on September 8th.

At Námafjall the first observed sign of the rifting event was movement of faults crossing the main road at about 2240. Assuming that the main magma movement to the south started at 1820 and with the distance of 9 km from Leirhnjúkur at the center of the caldera, the rate of horizontal movement is about 0.6 m/sec[x]. A similar

[x] The figures for vertical and horizontal movement of the magma are strikingly similar to the figures (0.6 m/sec) 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 (6, cf. p.30).

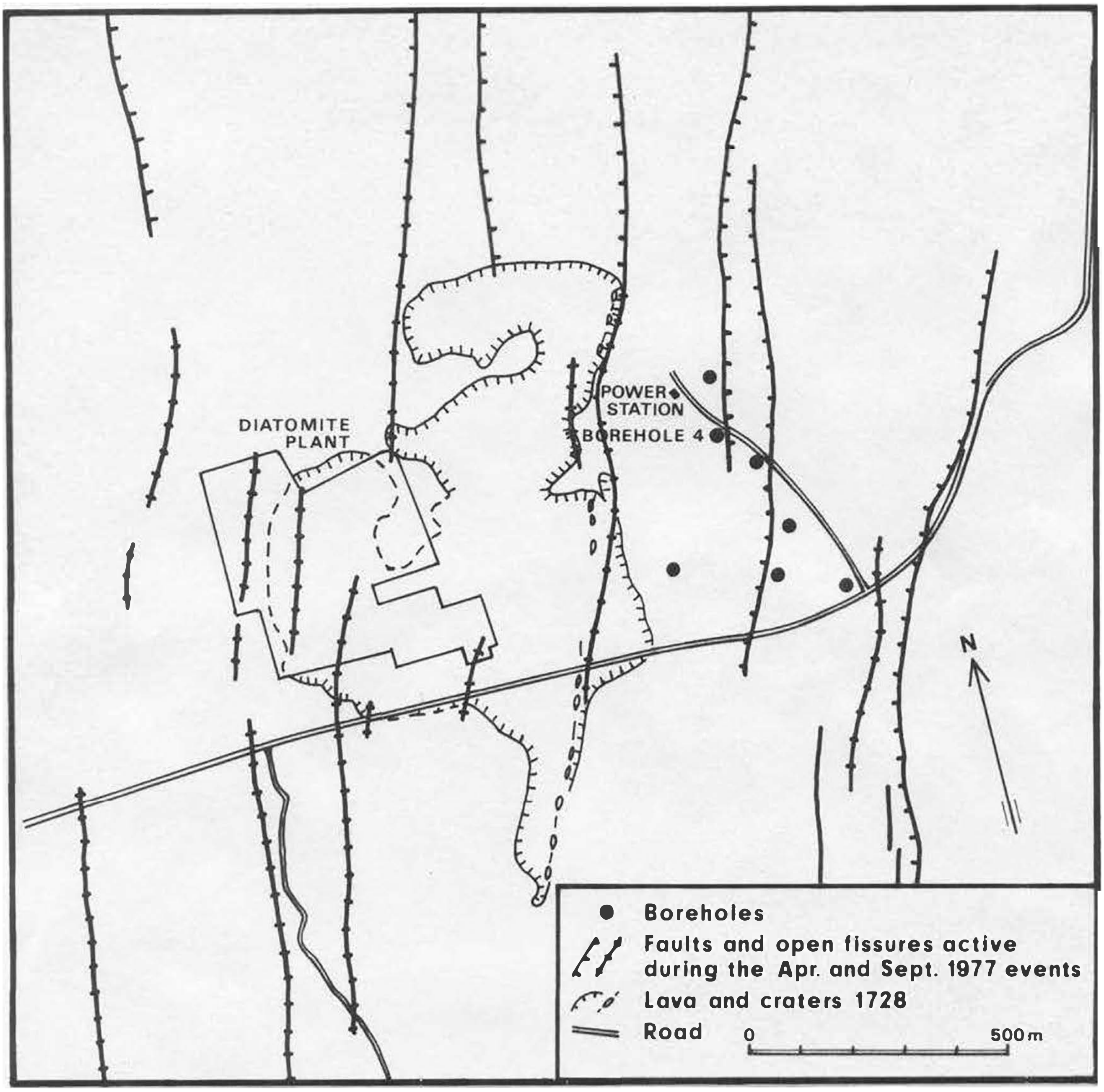


Fig. 2. Sketch map of the Námafjall area from an aerial photograph of September 9th 1977. The location of boreholes is shown and the location of the Diatomite factory. The faults shown on the map have all been active in the recent events. Five of the seven boreholes were in production on September 8th 1977. For location see Fig. 1.

velocity was derived for magma movement in the previous April deflation/rifting event (3).

The eruption through the borehole took place about one hour later, at 2345. The rate of deflation decreased rapidly and at about five in the morning of the 9th September deflation had stopped and the center of the caldera was inflating again.

The observations discussed above suggest that the deflation/rifting event of September 8th 1977 can be split into two separate phases. The first phase of the deflation was connected with the eruption at the northern rim of the caldera. The second and main deflation phase was due to magma movement along the fault swarm to the south, where the south going magma was sampled by the borehole eruption.

## THE BOREHOLE ERUPTION

The Námafjall high temperature area lies on the Krafla fault swarm 9 km to the south of the center of the Krafla caldera. It has been exploited for steam since 1963. The steam is used for drying diatomite mud pumped from the bottom of Lake Mývatn and also to drive a 3 MW electric power station.

The five boreholes operating at present are spaced with the distance of 80-200 meters (Fig. 2) and extend down to 650-1800 meters with casing extending down to 500-600 meters. The deepest hole has an additional slotted liner down to the bottom at 1800 meters. 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 1134 meters deep, has 7" casing down to 380 meters and 5" casing down to 625 meters. The diameter from 625 to the bottom is 6 1/4" and this part has no casing or liner. The main aquifers are reported at 638 and 1038 meters (Fig. 3) (8). The temperature of

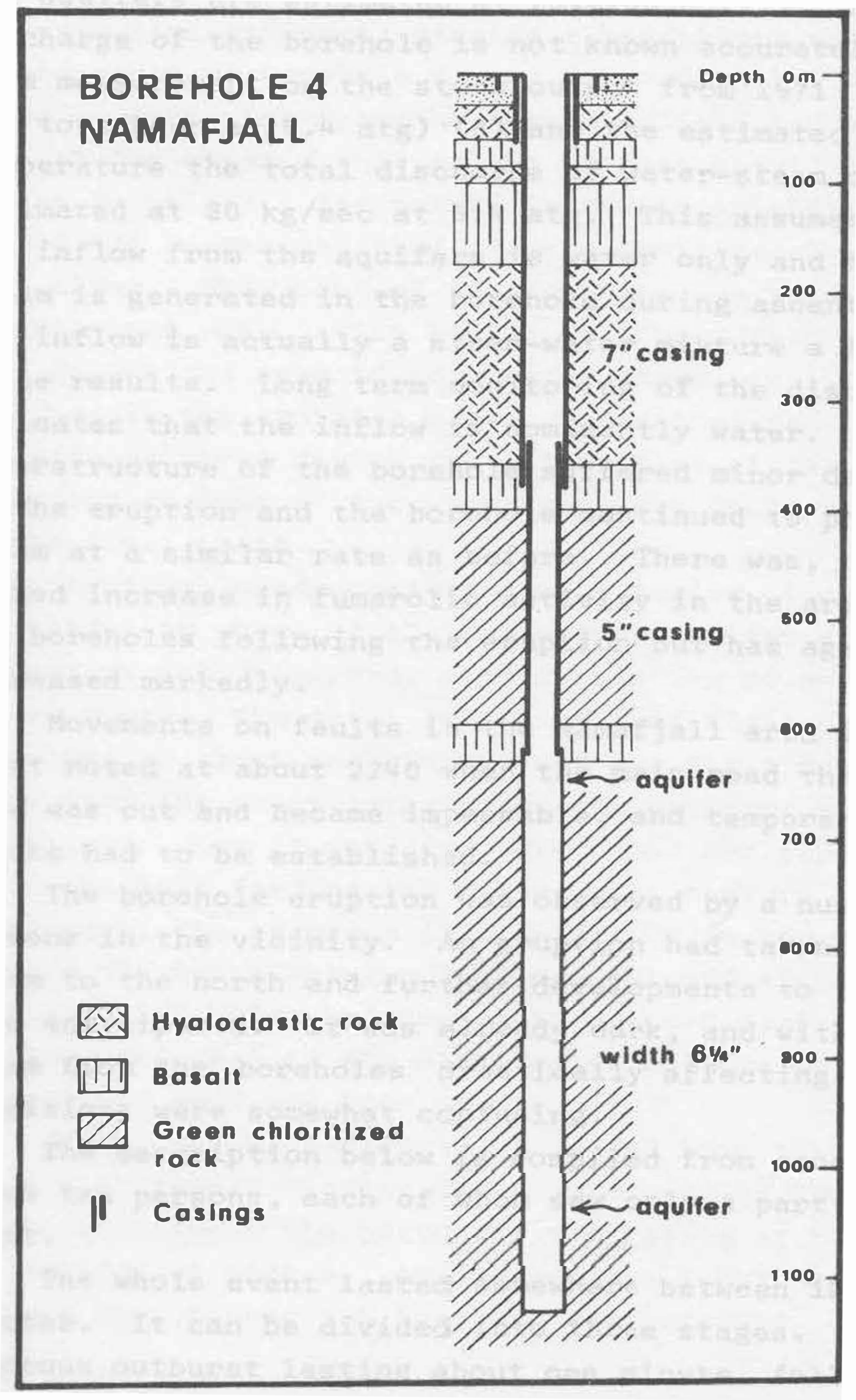


Fig. 3. Schematic section of borehole 4 in Námafjall. Adapted from a report of the Natural Energy Authority (8).

the aquifers are estimated at 251-256°C (7). The total discharge of the borehole is not known accurately but from measurement on the steam output from 1971 (22 tons/hour at 6.4 atg) (8) and the estimated aquifer temperature the total discharge of water-steam can be estimated at 30 kg/sec at 6.4 atg. This assumes that the inflow from the aquifers is water only and that steam is generated in the borehole during ascent. If the inflow is actually a steam-water mixture a lower value results. Long term monitoring of the discharge indicates that the inflow is dominantly water. 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. There was, however, marked increase in fumarolic activity in the area around the boreholes following the eruption but has again decreased markedly.

Movements on faults in the Námafjall area were first noted at about 2240 when the main road through the area was cut and became impassable, and temporary road blocks had to be established.

The borehole eruption was observed by a number of persons in the vicinity. An eruption had taken place 12 km to the north and further developments to the south were anticipated. It was already dark, and with the steam from the boreholes drastically affecting visibility, conditions were somewhat confusing.

The description below is compiled from accounts of about ten persons, each of whom saw only a part of the event.

The whole event lasted somewhere between 10-25 minutes. It can be divided into three stages. First a vigorous outburst lasting about one minute, followed by a relatively quiet period of 10-20 minutes. Then came a final phase lasting about one minute, similar to the first phase but less vigorous.

The first phase was best observed by a policeman (Fridrik Steingrímsson) manning a road block about 450 meters south of borehole 4. At approximately 2345 hours he heard an explosion from the borehole field and saw through the steam a thin column of fire about 15-25 meters in height. The column increased slightly in width upward and sparks and cinders were continuously shot from the column. This part of the eruption was accompanied by a continuous roar. This lasted no longer than one minute.

During the next 10-20 minutes 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. The total length of this final phase is estimated at about one minute. It was first during this phase that the exact location of the eruption was established when it was discovered that the pipe directly above the hole feeding the steam-water mixture had been ruptured by the eruption (Pl. 1-2). It is not known whether the steam-water output was cut off at any time during the eruption but during the second part 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 somewhere between the bottom of the casing at 625 m and the aquifer at 1038 m. At the surface substantial movement on faults near the borehole was observed.

## PRODUCTS OF THE ERUPTION

The eruption produced a very small sheet of tephra (scoria and cinders), which can be traced some 180 meters

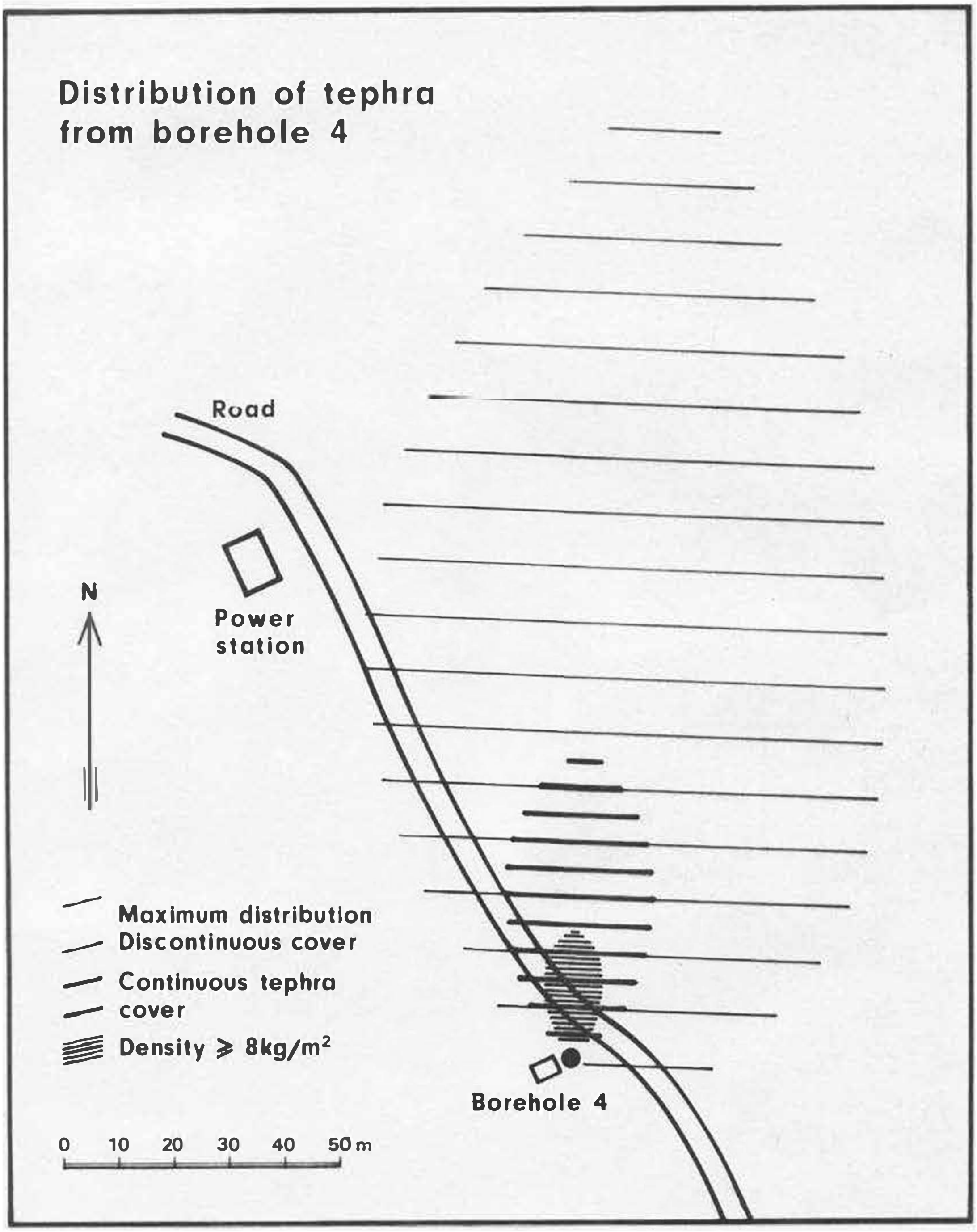


Fig. 4. The distribution of the tephra from the eruption of borehole 4, September 8th 1977. (For location see Figs. 1 and 2).

away from the borehole. The distribution is shown on Fig. 4 (adapted from a map drawn by Hjörtur Tryggvason).

Since the scoria and cinders are very loosely packed and non-uniformly distributed, thickness estimates are uncertain, especially away from the borehole. An area about 50 meter long and 25 meter maximal width is covered by a continuous sheet of tephra.

The volume of the total output is estimated at 26 $m^3$.

The density of the deposit was estimated at 0.12 $g/cm^3$ by weighing the scoria from a volume of 40 x 50 x 7 cm. According to this the total weight of the deposit is 3100 kg. The density of the dry magma is 2.73 $g/cm^3$ calculated by using the method of Bottinga & Weill (9). The volume of the magma is therefore 1.2 $m^3$. As the magma was probably already degassing when it reached the borehole, this is likely to be an underestimate of the actual volume injected.

The tephra is greyish-black in colour and coarse grained. Median (Ø 50) grain size is -4.2 Ø (18.4 mm) (Fig. 5). This could be an underestimate as the largest clasts break very easily during collection and sieving. Grains smaller than 1 mm are scarce.

The clasts 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 (Pl. 4-5). 2) Grains entirely made of torn glass froth of various shapes and sizes (Pl. 6). 3) Crusted clasts of various sizes and shapes, each with a neat frothy sphere protruding from one end (Pl. 7).

There are gradations between the different types of clasts making it possible to establish how they were formed. Upon injection into the borehole, the magma 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 appear

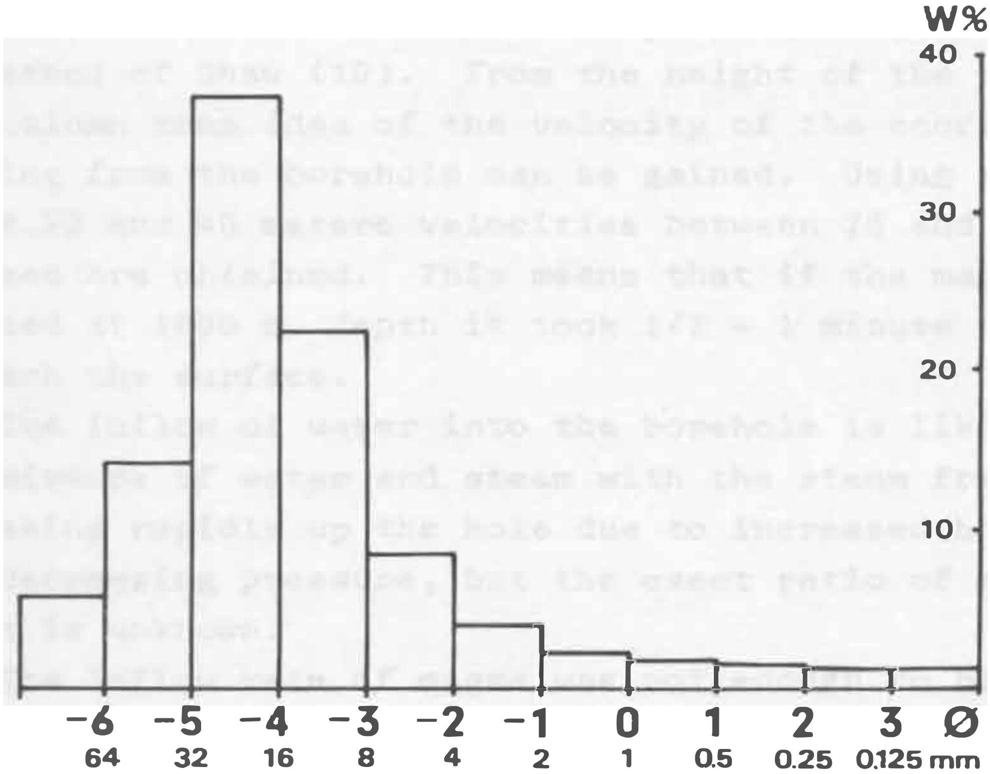


Fig. 5. Grain size histogram of the tephra from the borehole eruption. Clasts of type 1 are mostly found in grain sizes larger than -3 Ø while most clasts of type 2 are smaller than -4 Ø. The sample is collected about 20 m from the "vent".

to have broken at various depths, most of them presumably at or near the top of the borehole, giving the red glowing colour to the column. Clasts with glassy crust on one side formed from the cooled exterior of the lumps, while the molten interior disintergrated into fragments of twisted glass froth. When found unbroken the size of the crusted clasts commonly is ca. 15 x 10 x 4 cm (Pl. 4). The most common thickness of the glassy crust is 2 mm but ranges from 0.5-5 mm.

Assuming that the bulk of the magma was injected into the hole during the two one minute periods the intrusion rate is about 25 kg/sec which is of the same order as the amount of steam-water production of the borehole. The viscosity of the magma is estimated at

250 poises calculated from the composition according to the method of Shaw (10). From the height of the eruption column some idea of the velocity of the scoria escaping from the borehole can be gained. Using the height 20 and 40 meters velocities between 20 and 30 m/sec are obtained. This means that if the magma was injected at 1000 m depth it took 1/2 - 1 minute for it to reach the surface.

The inflow of water into the borehole is likely to be a mixture of water and steam with the steam fraction increasing rapidly up the hole due to increased boiling with decreasing pressure, but the exact ratio of the phases is unknown.

The inflow rate of magma was not enough to block the borehole but the fact that large amount of the scoria was still molten when the surface was reached indicates that in the steam-water mixture with which the scoria was travelling all the water had changed into steam. Otherwise greater cooling effects would be expected.

## THE CHEMISTRY AND THE PETROLOGY OF THE MAGMA

The scoria produced is extremely vesicular and composed almost entirely of glass. There are very occasional microphenocrysts (less than 1%) 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 appear to be in equilibrium with the liquid at the time of cooling.

From the olivine glass composition the temperature of the magma at the time of chilling can be estimated (11) giving 1153°C. From the plagioclase-glass composition the temperature is estimated at 1158°C using the modefied Kudo-Weill plagioclase thermometer (12). The sum of the analysis of the major elements is 98.8% and it can be expected that the difference is mainly due to water, so that although the magma is already degassing and

TABLE 1

Microprobe analysis of the products from the eruption of borehole 4 at Námafjall, September 8th 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 |

extremely vesicular there is still 1% water left in the magma.

From the chemical composition of the magma the density can be estimated using the method of Bottinga & Weill (9) and for dry magma the density is 2.73 g/cm$^3$ but with 1% water dissolved 2.65 g/cm$^3$. The viscosity can be estimated using the method of Shaw (10) which gives 250 poises assuming 1% water content.

Three glass samples from the borehole scoria were analysed and appear to be homogenous within the analytical precision. The chemistry of the borehole scoria is, however, markedly different from that of the lava erupted few hours previously 12 km to the north. It has been argued (13), that at least two different magma chambers were involved. The initial eruption within the caldera came from one chamber while the magma pulse to the south amounting to about $1.8 \times 10^7$ m$^3$ came from another magma chamber and was sampled by the borehole eruption.

The fact that magma with very similar chemistry was erupted near the center of the Krafla caldera in December 1975 at the initial rifting event supports that the eruption products from the borehole were actually transfered from the central magma chambers.

In the previous rifting event on April 27th the center of the rifting was at Námafjall where the boreholes are and although the amount of magma moved into the fault swarm was $4.5 \times 10^7$ $m^3$ the effect on the boreholes was relatively small (3). During the rifting event on September 9th 1977 when the eruption took place, the changes in the thermal activity around the boreholes was much more noticeable. It therefore appears that in this second event the magma reached shallower levels with a thin vein from the main magma body reaching the levels of the boreholes.

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