S-wave Shadows in the Krafla Caldera in NE-Iceland, Evidence for a Magma Chamber in the Crust

P. EINARSSON *Science Institute, University of Iceland, Reykjavik*

ABSTRACT

During the present tectonic activity in the volcanic rift zone in NE-Iceland it has become apparent that the attenuation of seismic waves is highly variable in the central region of the Krafla volcano. Earthquakes associated with the inflation of the volcano have been used to delineate two regions of high attenuation of S-waves within the caldera. These areas are located near the center of inflation, have horizontal dimensions of 1-2 km and are interpreted as the expression of a magma chamber. The top of the chamber is constrained by hypocentral locations and ray paths to be at about 3 km depth. Small pockets of magma may exist at shallower levels. The bottom of the chamber is not well constrained, but appears to be above 7 km depth. Generally S-waves propagate without any anomalous attenuation through layer 3 ($v_p = 6.5$ km sec^{-1}) across the volcanic rift zone in NE-Iceland. The rift zone therefore does not appear to be underlain by an extensive magma chamber at crustal levels. The Krafla magma chamber is a localized feature of the Krafla central volcano.

INTRODUCTION

The Krafla central volcano in NE-Iceland has been going through a series of inflation-deflation cycles since 1975 (BJÖRNSSON *et al.*, 1977). Magma is apparently accumulating at a fairly constant rate at the depth of approximately 3 km beneath the volcano causing a slow inflation. The inflation is interrupted by short periods of rapid deflation when magma is injected horizontally into the rift zone that transsects the volcano from south to north.

The structure of the volcanic rift zone in NE-Iceland is dominated by NNE-trending fault swarms that are arranged *en échelon* within the N-S trending zone (Fig. 1). Several of these swarms pass through central volcano complexes where acidic rocks and geothermal activity are common and volcanic activity is high (SAEMUNDSSON, 1974). A few of these central volcanoes such as the Krafla volcano have developed calderas. The Krafla caldera was formed in the last interglacial period and has since been filled with volcanic products.

The present activity of the Krafla volcano and the associated fault swarm has been accompanied by considerable seismic activity, both earthquakes and continuous volcanic tremor. Soon after the increase in seismic activity in 1975 it became apparent that the attenuation of seismic waves, especially S-waves, was very variable in the Krafla area. Periods of high seismic activity in the caldera and a recently installed network of short period seismographs have offered a rare opportunity to study the S-wave attenuation in the central region of inflation. This paper describes the first results of such a study in the Krafla region.

S-Wave attenuation has been studied before in other volcanic regions. GORSHKOV (1958) used the disappearance of S-waves to infer the presence of a magma chamber at the depth of 60-80 km under the Klyuchevskaya volcano in Kamchatka. Similar results have been obtained by

FEDOTOV and FARBEROV (1966) in Kamchatka, KUBOTA and BERG (1967) and MATUMOTO (1971) in the Katmai volcanic range in Alaska and ASPINALL *et al.* (1976) in St. Lucia in the West Indies. Recently evidence has accumulated that indicates the presence of crustal magma bodies in the Socorro area of the Rio Grande Rift in New Mexico (SANFORD *et al.*, 1977*a, b*). This conclusion is partly based on the screening of SV-waves from local earthquakes.

Abnormal attenuation of S-waves is also reported from the mid-ocean ridge system. MOLNAR and OLIVER (1969) found that Sn-waves propagate inefficiently across the mid-ocean ridge system and the concave side of most island arcs. SOLOMON (1973) found that long period shear waves from an earthquake in the Charlie-Gibbs Fracture Zone that passed under the southern end of the Reykjanes Ridge were strongly attenuated. REID *et al.* (1977) found a zone of high S-wave attenuation that coincides with the crest of the East Pacific Rise near 21°N.

INSTRUMENTATION

The locations of the seismograph stations used for this study are shown in Fig. 1. Six of these stations are permanent and are a part of a larger network that covers most of the volcanic and seismic zones of Iceland. The stations SD and SN were temporary stations, operated in snow huts in March and April 1977. All the instruments were made at the Science Institute of the University of Iceland and are of similar design. The instrument consists of a vertical geophone with 2-3 Hz natural frequency, an amplifier with variable gain and filter settings, and a drum recorder. A continuous radio time signal is recorded with the seismic signal, thus time corrections are eliminated.

The pass-band of the instrument is between 3 and 30 Hz, limited by the natural frequency of the geophone at the low frequency end and the pen motor of the recorder at the high frequency end. The peak of the displacement response is between 10 and 15 Hz. Peak magnification depends on noise conditions, but 10^6 is frequently used. These instruments are ideally suited to record small local earthquakes in the presence of large microseismic disturbances.

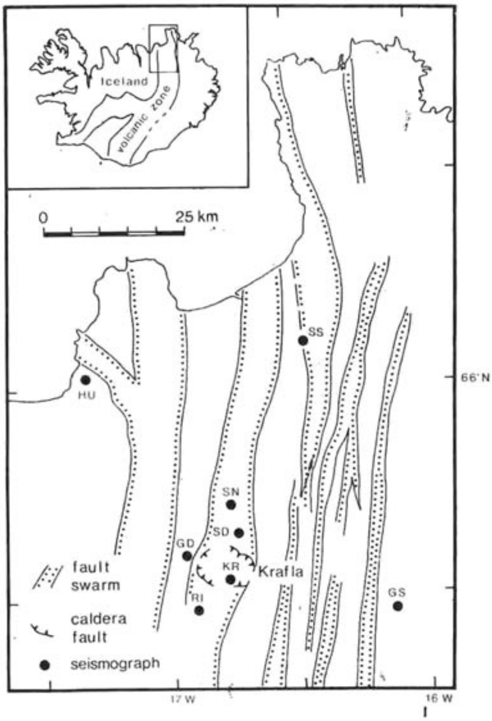

FIG. 1 - Index map showing the structure of the volcanic zone of NE-Iceland and the location of the seismograph stations used in this study. The fault swarms and the Krafla caldera fault are drawn after BJÖRNSSON *et al.* (1977).

THE DATA AND DATA ANALYSIS

During the period February-September 1976 the caldera region at Krafla was in a state of inflation. The elevation of the central part of the caldera increased by

5-7 mm per day (BJÖRNSSON *et al.*, 1977). Earthquake activity in the caldera increased in June and continued increasing until the end of September, when it stopped abruptly during a small deflation event. Three subsequent inflation periods were also accompanied by increased earthquake activity within the caldera, in October 1976, January 1977 and March-April 1977. These earthquakes were clearly related to the inflation process, and none of them reached magnitude 4. Earthquakes used in this study were mostly from August-September 1976 and the first half of March 1977.

A version of the computer program HYPOELLIPSE (LAHR and WARD, 1976) was used for the location of the earthquake hypocenters. The input to the program consists of the velocity structure of the crust, station corrections with respect to this structure and the arrival times of P-waves at the stations. S-wave arrival times are used whenever they are available. The program computes the origin time, the hypocentral coordinates and their standard errors.

The velocity structure of the Krafla area was derived from an extensive refraction survey done in NE-Iceland by the National Energy Authority in 1971-73. An average crustal structure was found from a composite travel time diagram using all the available travel times. Station corrections with respect to this structure were found by setting of an explosion in the crater lake Víti that is located within the epicentral zone in the central part of the Krafla caldera.

The accuracy of the hypocentral locations depends on a number of factors, such as the accuracy of arrival time readings, the number of arrival times used and the geometrical arrangement of stations with respect to the hypocenter. The hypocenters of earthquakes used in this study are located with standard error less than 1 km in all directions, and the RMS-value of the difference between calculated and observed travel times is 0.1 sec. or less. Errors in the vertical direction are usually larger than the horizontal errors.

More than 95 % of all earthquakes within the caldera have calculated depths shallower than 4 km, and depths are fairly evenly distributed in the range 0-4 km. Allowing for the error in location, one can conclude that most earthquakes are located in the depth range 0-3 km. The earthquakes below 4 km are mostly deeper than 7 km, *i.e.* almost no earthquakes are located in the depth range 4-7 km.

THE S-WAVE SHADOWS

Earthquakes in the caldera region of the Krafla volcano have very variable appearance on the seismograms at local seismic stations. The most conspicuous feature is the absence or the small amplitude of S-waves on a large proportion of the recorded earthquakes. At a few of the stations, especially the stations RI, GS and SN, the earthquakes can be separated into groups depending on whether the S-wave is recorded or not. The stations SD, GD and KR are too close to the earthquake sources for a clear separation of P- and S-waves, and on the way to the stations HU and SS the seismic waves appear to suffer additional distortion from structures outside of the caldera region of Krafla. Seismograms of typical earthquakes recorded at RI and SN are shown in Fig. 2. The separation of the earthquakes into groups is done by visual inspection of the paper records. A wave train was classified as attenuated only if there was no increase in amplitude visible after the maximum P-wave amplitude.

There can be several reasons for the absence of S-waves on a seismogram. The earthquake source may be purely explosive or implosive and be spherically symmetrical, and would thus not produce any S-waves. Even if the source is of the double couple type, the seismograph station may be located on a nodal surface for the SV-wave. Finally the S-wave could be attenuated by a fluid or semi-fluid body located in the wave path between the source and the station.

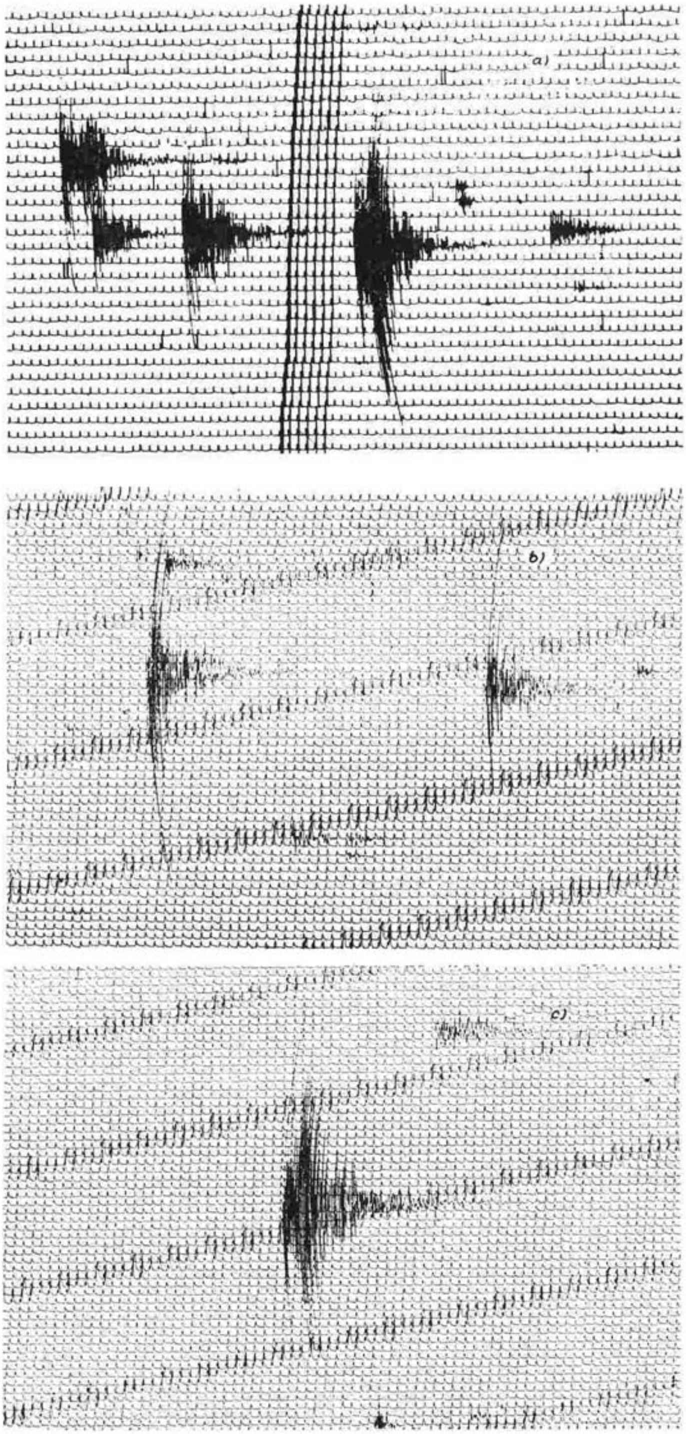

Fig. 2 - Seismogram sections from the stations RI (*a*) and SN (*b* and *c*). The small tick marks are second marks. Typical earthquakes with clear S-waves (*a* and *c*) and without S-waves (*a* and *b*) can be seen.

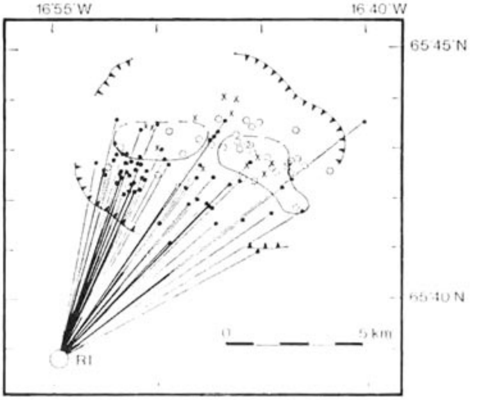

FIG. 3 - S-wave paths to the station RI. Epicenters of earthquakes that are recorded with a clear S-wave are marked with a black dot, open circles denote earthquakes with no recorded S-wave at RI. Earthquakes of intermediate character are marked with X. Areas of maximum attenuation of S-waves are delineated. The caldera fault is drawn after BJÖRSSON *et al.* (1977).

In the case of the Krafla earthquakes the first reason can be excluded on the basis of P-wave first motion data. Furthermore, many earthquakes are recorded with S-waves at one station but without S-waves at another station.

Focal mechanism effects are not considered to be a likely explanation for the absence of the S-waves. The large proportion of earthquakes without S-waves would require extremely high regularity in the focal mechanisms which is hardly to be expected in the central region of an inflating volcano. The focal mechanism may be responsible for the absence of the S-wave in a few cases, but not all.

Assuming that the absence of S-waves is caused by attenuation along the wave paths one can attempt to map the regions of maximum attenuation. Relatively accurate earthquake locations and a large number of ray paths are needed for a meaningful study of this sort. The seismic stations RI, GS and SN are used in this study since the separation between the different types of wave trains is most clearly seen at these stations. In Figs. 3, 4 and 5 the wave paths are marked along which clear S-waves have been transmitted. No abnormal attenuation seems to take place in regions crossed by such paths. In particular, attenuation appears to be normal in most of the SW-part of the caldera (Fig. 3) and in areas adjacent to the caldera. S-waves propagate across the rift zone to the station GS without much attenuation.

Epicenters of earthquakes that are recorded without S-waves at the respective station are marked with open circles in Figs. 3, 4 and 5. By combining the data from all three stations one can find the approximate boundaries of the attenuating regions. Two separate areas appear to be largely responsible for the disappearance of the S-waves. One area is located in the eastern and southeastern part of the caldera. This area is delineated mostly by waves recorded at RI and GS (Figs. 3 and 4). The other area is located in the western part of the caldera and is delineated by waves recorded at RI and SN (Figs. 3 and 5). This area is displaced slightly to the north with respect to the epicentral area. Most earthquakes in the western part of the caldera are thus recorded with a clear S-wave at RI, but at SN the S-wave is missing on a large majority of the earth-

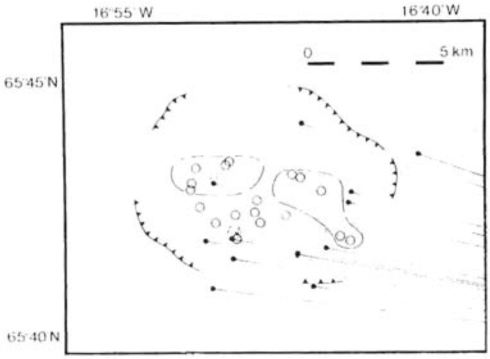

FIG. 4 - S-wave paths to the station GS. Symbols as in Fig. 3. Numbers show the depth of earthquakes that are deeper than 5 km.

quakes. The southern boundary of the attenuative area is better defined than the northern boundary. The conclusion that there are two areas is mostly based on the recording of S-wave at RI (Fig. 3). Several rays pass between the two areas. These rays are shallow and the attenuating body may be undivided at greater depth.

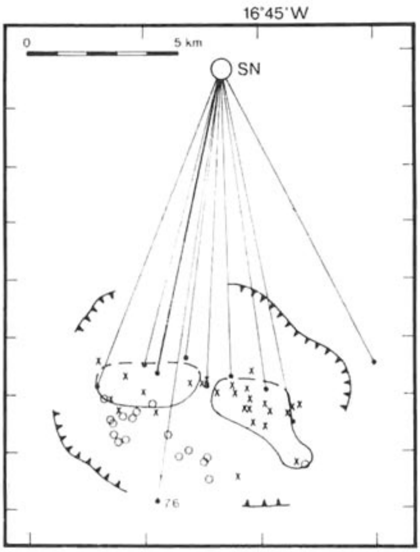

FIG. 5 - S-wave paths to the station SN. Symbols as in Fig. 3.

The orizontal extent of the attenuating zones is given in Figs. 3, 4 and 5. The diameters are of the order of 1-2 km. The vertical extent is more difficult to ascertain. In the vertical dimension the wave path is critically dependent on the depth of the hypocenter and the velocity structure, neither of which is well enough known for a detailed mapping of the attenuating bodies. One can, however, put some constraints on the upper and lower boundaries.

The hypocenters are mostly at depths of 3 km or less. The seismic rays recorded at RI, GS and SN are in most cases critically refracted rays. Because of the limited horizontal extent of the attenuating bodies and their proximity to the epicentral zones one can conclude that only a small proportion of the rays reaches depths greater than 3 km in the areas of attenuation. The depth to the upper boundary of the attenuating bodies is therefore not likely to be larger than 3 km. On the other hand, the depth to the boundary is not likely to be much less than 3 km. The earthquakes are clearly associated with the inflation process of the Krafla volcano and can be explained by brittle failure of the crust above an inflating magma body. This inflating body may be small and is not necessarily identical with the body that causes the attenuation. Brittle failure is not likely to occur within the attenuating body. The upper limit of the body is therefore likely to coincide with the depth where the frequency of earthquakes begins to decrease, which is about the depth of 3 km. Small, discontinuous bodies may, however, occur at smaller depths. The boundaries of the attenuating zones drawn in Figs. 3, 4 and 5 should be regarded as contours of the attenuating bodies at the depth of approximately 3 km.

The lower boundary of the attenuating bodies is not well constrained. Most of the available seismic rays cross the caldera at shallow levels and only few probe the deeper regions. The deeper rays have to come from relatively deep earthquaes, and only three earthquakes could be found that were usable for this study. All of them occurred at the depth of about 7 km (Figs. 4 and 5). The rays pass through the caldera region without suffering much attenuation, which indicates that the lower boundary of the attenuating bodies is shallower than 7 km.

LIMITATIONS OF THE METHOD

The method of analysis as described in the previous section can only be applied successfully under favorable conditions. The first condition is the availability of a large number of seismic rays crossing the region to be studied. One therefore needs either a large number of seismographs or numerous favorably located earthquakes. The latter condition was partly fulfilled in the case of Krafla.

Several factors limit the resolution of the method. Location errors, the effects of focal mechanism, « false » S-waves, diffraction and lateral refraction blur the picture of the bodies to be delineated.

The location errors in the case of Krafla were of the order of 1 km in the horizontal directions. Fortunately the dimensions of the attenuating areas were somewhat larger. Minor inconsistencies in Figs. 3, 4 and 5 can be accounted for by errors in epicenter locations. Obviously no consistent results can be obtained in areas where the errors are larger than the dimensions of the bodies to be delineated.

In some cases the focal mechanism and the source-station relationship may be such that the station is located on a nodal surface for the SV-wave. The seismogram may therefore give the impression that the ray has passed through attenuating material. This effect is only rarely observed in other seismically active areas in Iceland and is not believed to be important in Krafla, although it may cause inconsistency in a few cases.

Waves other than the S-wave may arrive late in the wave train and be difficult to distinguish from a true S-wave. These may be reflected P-waves, converted waves or surface waves. An attenuated wave train may thus be classified as an unattenuated one and cause an apparent inconsistency.

The presence of an attenuating body implies lateral heterogeneity in the structure, which means that the seismic rays may be refracted horizontally. This effect may cause some uncertainty in the location of the earthquakes and thus in the position of the boundary of the attenuating body, but errors exceeding 1 km are not expected.

Seismic waves will be diffracted around a body that has velocity different from its surroundings. In particular, S-waves will be diffracted around the attenuating bodies delineated in this study. The bodies do not cast sharp, infinitely long shadows. Some S-wave energy is diffracted into the geometrical shadow region with the result that the bodies appear to be smaller than they really are.

The diffraction of seismic waves has been studied theoretically by many authors. In general the sharpness of the shadow is dependent on the wavelength relative to the dimensions of the diffracting body. The shadow is sharper and deeper for waves of higher frequency. But there are also effects that depend on the shape of the body.

Teng and Richards (1969) studied the diffraction around a cylindrical cavity. In this case the effect on P-, SV-, and SH-waves is not equal. For a horizontal cylinder the half-amplitude point is shifted outward from the geometrical shadow boundary for P- and SV-waves but inward for SH-waves. The effect on the S-waves would be reversed for a vertical cylinder. There may thus be a broad region where the body has a polarizing effect on the S-waves. This effect was used by Kubota and Berg (1967) to conclude that magma chambers in the Katmai Volcanic Range were of spheroidal shape with a horizontal major axis.

The effects of diffraction limit the applicability of the S-wave screening method in volcanic areas. Clearly the frequency of the available seismic waves sets a limit to the size of the magma chambers that can be detected. For optimum results high frequency, three-component seismographs should be used. In the Krafla area the energy of the S-waves is mainly within the frequency band 5-10 Hz, i.e. the wavelengths are of the order of 300-600 m. This gives some idea of the resolution.

DISCUSSION

The attenuation effects in the Krafla area are large, or else a study of this sort would not give positive results. One can attempt to give a maximum estimate of the quality factor Qs in the attenuating bodies. The attenuated wave trains had no sign of an S-wave, which means that for some of them the S-wave must have been attenuated by a factor of at least 10. The wavelengths are 0.3-0.6 km and the horizontal extent of the bodies is about 1-2 km or 2-7 wavelengths. Attenuation by a factor of 10 in 7 wavelengths gives a Qs of 10. This is a maximum value, the true value is probably much lower.

The attenuating bodies are located in the central part of the Krafla caldera. In other areas of the world where abnormal attenuation of S-waves has been found, there also seems to be a close association with volcanism, and it is usually assumed that the attenuation is caused by magma. This interpretation also seems to be the most plausible one in the case of Krafla. Here the center of inflation and deflation during the present tectonic and magmatic activity is also near the center of the caldera (BJÖRNSSON *et al.*, 1977; TRYGGVASON, 1978) which further strengthens the interpretation.

The seismic evidence can give little information about the internal structure of the magma chamber at Krafla and only a rough idea about its shape. The « chamber » could be a massive lump of molten magma, but it might also consist of a number of small, more or less interconnected chambers, pockets, sills or dykes. It is probable that the inflation presently taking place in the Krafla caldera is caused by a steady inflow of magma into this magma chamber or some subdivision of it. Deflation events are caused by horizontal injection of magma away from the central region of the Krafla volcano.

The formation of a magma chamber large enough to be detected by seismic waves is a process that requires much time, probably a considerable part of the life time of the volcano. Repeated injection of magma into the roots of a volcano results in elevated temperatures. Depending on the rate of injection and the rate of cooling the magma may stay in a molten state at some critical depth. Some remelting may take place in the surrounding material. The present injection mechanism in the Krafla volcano is particularly effective. Magma is brought from below to a depth of about 3 km where it stays for a while and delivers heat to the surrounding material. Then the magma is injected horizontally away from the central part of the volcano and is replaced by fresh magma from below. Thus heat is delivered to the central part of the volcano with only limited increase in volume.

The magma chamber of Krafla is located in the upper part of and slightly above crustal layer 3 ($v_p = 6.5$ km s^{-1}) which is at the depth of about 3.5 km in this region (PÁLMASON, 1963). The depth to the bottom of layer 3 is not accurately known in this region, but is probably in the range 10-15 km. S-waves are usually transmitted efficiently through layer 3. In particular we note that S-waves from Krafla earthquakes are well recorded at the station GS which is located east of the volcanic rift zone. This means that S-waves are transmitted across the rift zone at crustal levels without any abnormal attenuation. The attenuating bodies at Krafla appear to be a local phenomenon associated with the central volcano and are not a general feature of the rift zone.

Only a part of the available data have been analyzed in this study and inflation of the Krafla caldera continues at the time of writing. There is therefore no doubt that the picture presented in this paper will be improved and refined in the future.

CONCLUSIONS

The main conclusions of this study can be summarized as follows:

1. Two areas within the Krafla caldera have been delineated where S-waves of local earthquakes are strongly attenuated.
2. The attenuation is interpreted as being caused by magma in some kind of a magma chamber.
3. The extent of the magma chamber can be estimated by seismic ray tracing and the location pattern of earth-

quakes within the caldera. The upper limit of the magma body is at the depth of about 3 km and the lower limit is probably shallower than 7 km. The body is divided near its top.
4. The volcanic rift zone in Northern Iceland is not underlain by a continuous magma chamber at crustal levels. The Krafla magma chamber is a localized feature of the Krafla central volcano.

ACKNOWLEDGEMENTS

This work was partly supported by the National Energy Authority in Reykjavik and by a special grant from the Icelandic Ministry of Education. Many persons assisted in the data collection and analysis, but special thanks are due to Halldór Ólafsson, Nordic Volcanological Institute, and Sverrir Tryggvason who helped operate the stations SD and SN under difficult circumstances. Many of the ideas presented in this paper were discussed extensively in an informal research group on the Krafla events. Sveinbjörn Björnsson, Gudmundur Sigvaldason and Eysteinn Tryggvason offered valuable suggestions for the improvement of the manuscript.

REFERENCES

ASPINALL, W. P., MICHAEL, M. O., TOMBLIN, J. 1976, *Evidence for Fluid Bodies beneath the Sulphur Springs Geothermal Region, St. Lucia, West Indies.* Geophys. Res. Lett., *3*, p. 87.

BJÖRNSSON, A., SAEMUNDSSON, K., EINARSSON, P., TRYGGVASON, E., GRÖNVOLD, K., 1977, *Current Rifting Episode in North Iceland.* Nature, *266*, p. 318-323.

FEDOTOV, S. A. and FARBEROV, A. I., 1966, *On the Absorption of Transverse Seismic Waves in the Earth's Crust and Upper Mantle in the Region of the Avachinskii Group of Volcanoes.* In: *Volcanism and Deep Structure of the Earth.* Trudy Vtorogo Vses. Vulcanol. Soveshchaniya, Vol. 3, Izd. Nauka, Moscow.

GORSHKOV, G. S., 1958, *On Some Theoretical Problems of Volcanology.* Bull. Volcanol., *19*, p. 108-113.

KUBOTA, S. and BERG. E., 1967, *Evidence for Magma in the Katmai Volcanic Range.* Bull. Volcanol., *31*, p. 175-214.

LAHR, J. C. and WARD, P. L., 1976, *Hypoellipse: A Computer Program for Determining Local Hypocentral Parameters, Magnitude and First Motion Pattern.* U.S. Geol. Surv. Open-File Report.

MATUMOTO, T., 1971, *Seismic Body Waves Observed in the Vicinity of Mount Katmai, Alaska, and Evidence for the Existence of Molten Chambers.* Geol. Soc. Amer. Bull., *82*, p. 2905-2920.

MOLNAR, P. and OLIVER, J., 1969, *Lateral Variations of Attenuation in the Upper Mantle and Discontinuities in the Lithosphere.* J. Geophys. Res., *74*, p. 2648-2682.

PÁLMASON, G., 1963, *Seismic Refraction Investigation of the Basalt Lavas in Northern and Eastern Iceland.* Jökull, *13*, p. 40-60.

REID, I., ORCUTT, J. A., PROTHERO W. A., 1977, *Seismic Evidence for a Narrow Zone of Partial Melting Underlying the East Pacific Rise at 21°N.* Geol. Soc. Amer. Bull., *88*, p. 678-682.

SAEMUNDSSON, K., 1974, *Evolution of the Axial Rifting Zone in Northern Iceland and the Tjörnes Fracture Zone.* Geol. Soc. Amer. Bull., *85*, p. 495.

SANFORD, A. R., MOTT, R. P., SHULESKI, P. J., RINEHART, E. J., CARAVELLA, F. J., WARD, R. M.. WALLACE, T. C., 1977*a*, *Geophysical Evidence for a Magma Body in the Crust in the Vicinity of Socorro, New Mexico.* Amer. Geophys. Union Monograph, *20*, p. 385-403.

————, RINEHART, E. J., SHULESKI, P. J., JOHNSTON, J. A., 1977*b*, *Evidence from Microearthquake Studies for Small Magma Bodies in the Upper Crust of the Rio Grande Rift near Socorro, New Mexico* (Abstract). Trans. Amer. Geophys. Union, *58*, p. 1188.

SOLOMON, S. C., 1973, *Shear-wave Attenuation and Melting beneath the Mid-Atlantic Ridge.* J. Geophys. Res., *78*, p. 6044.

TENG, T. and RICHARDS P. G., 1969, *Diffracted P, SV and SH Waves and Their Shadow Boundary Shifts.* J. Geophys. Res., *74*, p. 1537-1555.

TRYGGVASON, E., 1978, *Tilt Observations in the Krafla-Mývatn Area 1976-1977.* Nordic Volcanological Institute, Reykjavík, Report 78 02, 45 pp.

Manuscript received July 1978; reviewed Aug. 1978
Revised ms. received Nov. 1978