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ABSTRACT

During the present rifting episode at the Krafla fault swarm in North Iceland three basaltic eruptions have taken place. The lavas erupted represent less than 0.6% of the total volume of magma that has been moved through the Krafla magma reservoirs during the last three years. The main feature of the magma movement is a continuous upward flow of magma, about 5 m^3/sec, into holding reservoirs below the Krafla caldera at about 3 km depth. Part of this magma is then periodically injected into the fault swarm running through the Krafla caldera.

The lavas have a variable chemical composition caused by the mixing of two different magma compositions. Estimates of temperature, cooling rate, relative densities and mineral-liquid calculations indicate that the two main compositions cannot be accounted for by crystal separation in the magma reservoirs. The chemical difference is therefore already present when the magma reservoirs at 3 km are reached.

INTRODUCTION

This report is on the chemical composition of three basaltic lavas erupted in the Krafla region, North Iceland on December 20th 1975, April 27th 1977 and September 8th 1977. Although these lavas are very small in volume they are samples from a major magmatic movement, which is associated with a large scale rifting at the plate boundary running through North Iceland (1). The rifting is presently taking place on the 100 km long Krafla fault swarm which is one of four subparallel fault swarms running through North Iceland (2). The present rifting episode began on December 20th 1975 and takes place in short separate rifting events with earthquakes, fault movements, lateral injection of magma into the rift system and changes in fumarolic activity. The short rifting events are separated by intervals of a few months while magma accumulates in the magma reservoirs below the Krafla caldera situated centrally in the Krafla fault swarm (Fig. 1). The depth of these magma chambers is estimated at about 3 km from seismic evidence and ground deformation (1, 3, 4). The rate of inflow into the magma chambers is estimated from the rate of ground movement at 5 m^3/sec and has remained relatively uniform throughout. During the rifting events which may last from about one day to two months 5-15 km segments of the fault swarm are activated and rifting of up to 2 meters takes place.

Simultaneously with each rifting event magma from the central magma reservoirs is injected into the segment of the fault swarm being rifted. The net result will eventually be a dyke or a dyke system caused by the rifting and formed by horizontally moving magma.

The first rifting event started on December 20th 1975 and since then and including that event the amount of magma moved through the magma reservoirs below the Krafla caldera is about 3.9 x 10^8 m^3 (5). Only three of the rifting events that have taken place sofar have been

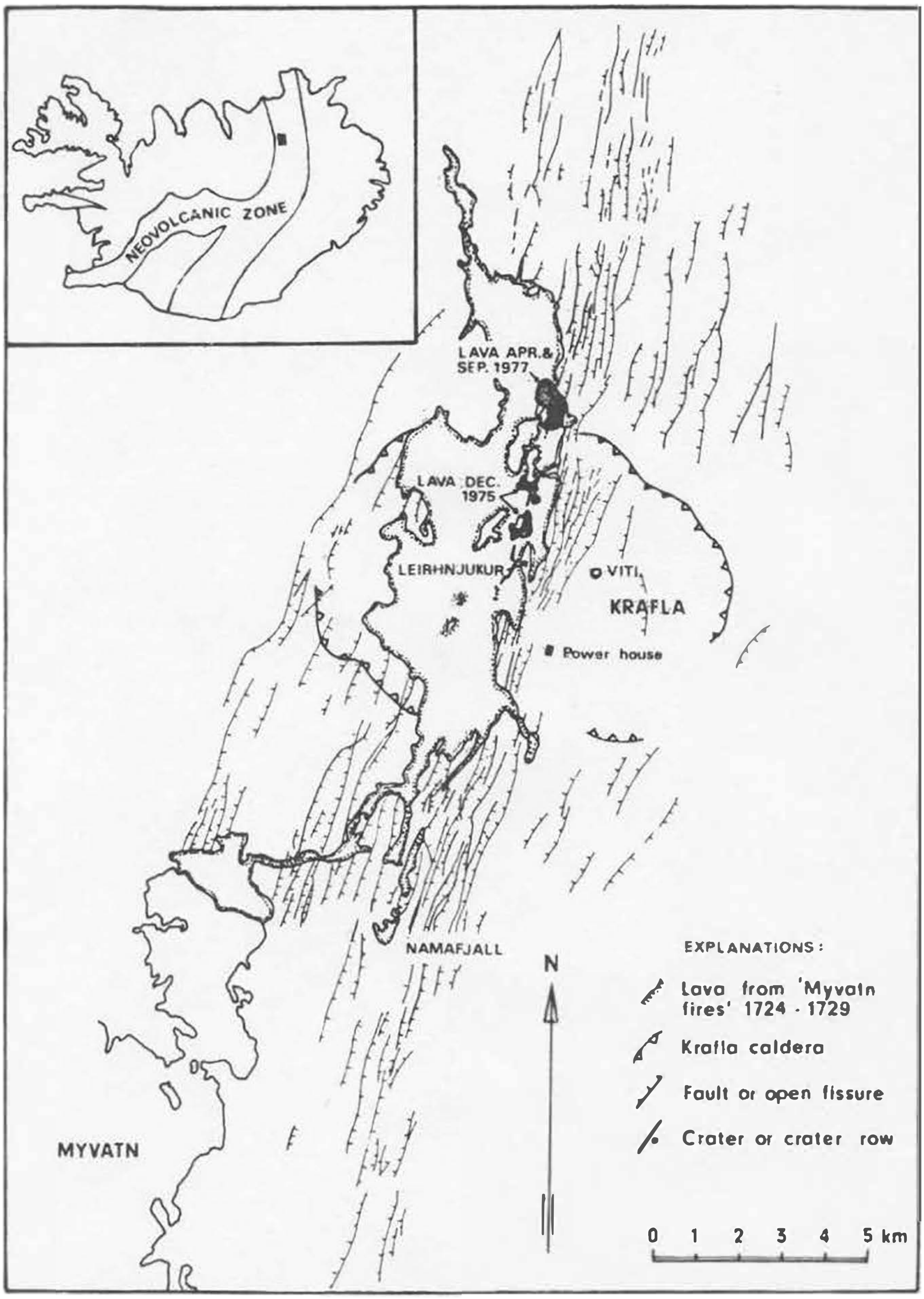

Fig. 1. Map showing the Krafla caldera and the new lavas. A map by Kristján Sæmundsson (1).

accompanied by lava eruptions. The total volume of the lavas is 2.4 x 10^6 m^3 or 0.6% of the total magma moved through the magma reservoirs below the Krafla caldera. The Krafla caldera has a well defined faulted outline but is filled with later products. The maximum vertical movement due to the influx of magma is close to the center of the caldera. Sofar no movement on the caldera faults has been observed, only on the fault swarm running through the caldera.

All three eruptions occurred within the Krafla caldera or on the caldera rim (Fig. 1), but not out in the fault swarm where the rifting took place. The lavas need therefore not be sampling the main bulk of the magma moved into the fault swarm each time. The only exception from this is an eruption through one of the boreholes in Námafjall about 10 km to the south of the center of the caldera (6).

Samples collected from all the new lavas have been chemically analyzed. The lavas were very little crystallized on eruption with crystals generally less than 0.2 mm in length. The only exceptions are very rare plagioclase glomerocrysts. The glassy scoria and flow tops were sampled for microprobe analysis of glass and minerals and due to the low crystallinity of the magma the glass analyses are very close to the actual magma composition. The samples should represent the state of the magma on eruption and be free from secondary effects due to slow cooling and flow. The present study shows that lavas erupted have variable chemical composition, even within a single eruption. From the analysis of minerals and surrounding glass the temperature of the lavas on eruption can be estimated as well as the oxygen fugacity. The composition of the minerals can also be used to test the feasibility of fractional crystallization in the shallow magma reservoirs.

Rifting episodes, similar to the present one, are known to have taken place in North Iceland every 100-150 years. The two last rifting episodes were closely associated with magmatism. The last rifting episode was in the Askja fissure swarm east of Krafla 1874-75. In that event a large acid eruption took place in the Askja caldera and almost simultaneously a basaltic eruption occurred in Sveinagjá 60 km to the north. In the "Mývatn fires" 1724-29 a voluminous, 5 x 10^8 m^3, basaltic eruption was accompanied by large scale rifting in the Krafla fault swarm (1). A few samples of the lava produced then are included in the present study with some samples of older lavas. The chemical composition of these lavas shows less variation than found in the present events.

MAIN FEATURES OF INDIVIDUAL ERUPTIONS

The present rifting episode in the Krafla area was heralded by increased seismic activity during the summer of 1975 (1). Precision distance measurements performed between 1968 and 1975 show fairly large movements during that period (7). It is likely that significant magmatic movement was taking place but details are uncertain. Since the beginning of rifting on December 20th 1975, crustal movements have been closely monitored allowing the volumes of magma movement to be estimated (1, 3, 5). Eight deflation/rifting events have taken place with three accompanied by lava eruptions. The three eruptions occurred on the same fissure as was active in the "Mývatn fires" 1724-29. Some of the significant features of the new eruptions and the chemistry of the lavas is discussed in the following section.

The volume estimates are for deflation events from December 1975 to July 10th 1978 inclusive.

Eruption of December 20th 1975

This eruption has been described in some detail elsewhere (1, 8, 9). Three small lavas were erupted on a 2 km long fissure (Fig. 2) near the center of the Krafla caldera just north of the hill Leirhnjúkur. The main rifting, however, started in Axarfjördur 45 km to the north of the caldera center about 10 hours later. The total volume of magma moved away from the magma reservoirs is estimated at 1.5 x 10^8 m^3 (5), but the volume of the lavas is 4 x 10^5 m^3.

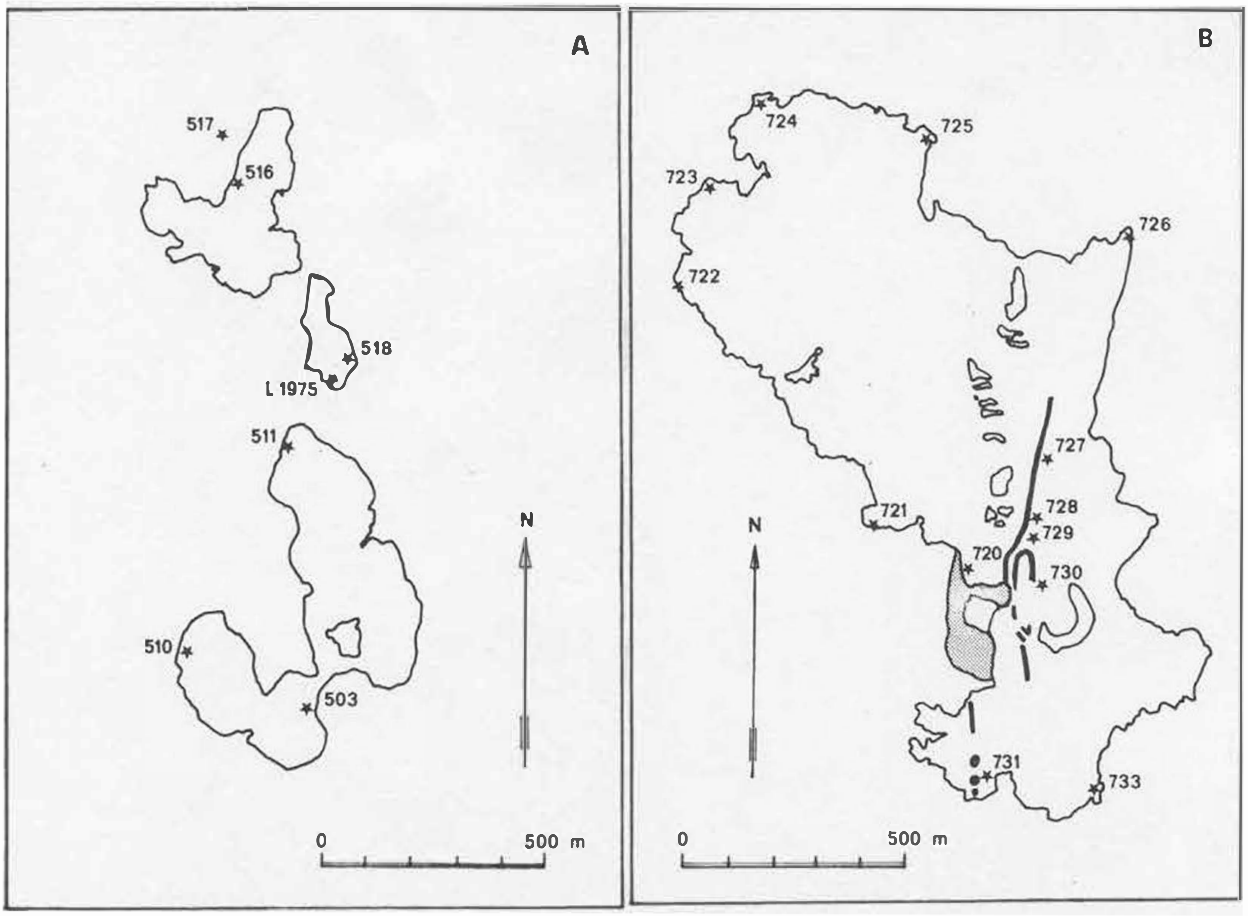

Fig. 2. Maps of the new lavas and sample localities. For location see figure 1.

A. Lava from 20th December 1975.

B. Lava from 27th April 1977 (shaded) and 8th September 1977 with sample locations.

The lava is glassy with a minor amount of plagioclase, olivine and augite microphenocrysts (< 0.2 mm along the longest axis). Rare plagioclase glomerocrysts are present.

Glass samples from the scoriacous flow tops were analyzed by the microprobe. No significant variation was found between the three samples and the average is listed in Table 1. In addition seven whole rock samples were analyzed by XRF and are listed in Appendix 1. The whole rock samples show no variation. They are very similar to the glass samples and show that the amount of crystals in the samples is not enough to affect the chemical composition within the analytical precision.

TABLE 1

Average chemical compositions of the Krafla lavas erupted 1975-1977

	SiO_2	TiO_2	Al_2O_3	FeO^t	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
Dec. 1975	50.2	2.14	13.1	14.8	0.24	5.39	10.4	2.50	0.33	0.22
April 1977	47.9	1.66	14.5	12.1	0.20	7.05	12.2	2.30	0.26	0.14
Sept. 1977 lava	48.9	1.53	14.5	11.6	0.19	7.41	12.2	2.13	0.23	0.14
Sept. 1977 borehole	50.0	2.24	12.7	14.9	0.24	5.16	10.3	2.34	0.37	0.23

Eruption of April 27th 1977

No eruptions were associated with the deflation/rifting events of September 1976, October 31st 1976, January 20th 1977, when the magma moved to the north along the fault swarm. On April 27th rifting took place to the south of the Krafla caldera for the first time (9). The main rifting was at Bjarnarflag, about 10 km to the south of the caldera center while an eruption took place near the northern caldera rim (Fig. 1).

The deflation started with seismic tremor at 1317 hours. It is not known exactly when the eruption took place but at 1730 hours "ash fall" was noticed near lake Mývatn. This "ash" was mainly altered rock fragments produced by the phreatic activity that accompanied and followed the eruption.

The eruption took place on a 200 m long fissure close to the northern end of the fissure active in the "Mývatn fires" 1724-29 (Fig. 2). The volume of the erupted lava is about 10^4 m^3 while the total amount of the magma moved from the magma reservoirs into the fissure swarm is estimated at 4.6×10^7 m^3. One glassy sample of this lava was analyzed on the microprobe. The composition of the glass is markedly different from that of the December 1975 eruption (Table 1). The lava has a minor amount of olivine and plagioclase microphenocrysts. No pyroxene was found. Rare large plagioclase is present.

Eruption of September 8th 1977

This event started with seismic tremor at 1547 hours. Simultaneously a continuously recording tiltmeter in the Krafla power house (10) showed that deflation had begun. At about 1800 hours the eruption started on a 800 m long fissure near the northern rim of the Krafla caldera (Fig. 1). The south end of this fissure coincides with the April fissure. Around 1930 hours most of the lava was already erupted and at around 2230 activity on the fissure ceased completely. The volume of the lava is estimated at 2×10^6 m^3 (Fig. 2).

Shortly after 2230 hours movement started on faults at Námafjall 10 km to the south of the caldera. At about 2345 hours magma was erupted from a 1134 meter deep borehole at Námafjall. About 26 m^3 of scoria were produced equivalent to 1.2 m^3 calculated as solid rock (6). The volume of magma injected into the rift system is estimated at 1.8×10^7 m^3.

Glassy samples collected from flow tops and crater scoria were analyzed on the microprobe. These analyses show that the lava has variable chemical composition. Of the thirteen samples analyzed nine are similar and the average composition of these is listed in Table 1, but analyses of individual samples are given in Appendix 2. Analyses of the scoria from the borehole show chemical composition quite different from the main lava (Table 1). The lava samples have a minor amount of olivine and plagioclase microphenocrysts (<0.2 mm) but no pyroxene. The borehole scoria is extremely poor in crystals but has a few microphenocrysts of olivine, plagioclase and augite. Plagioclase glomerocrysts were only found in the least magnesian lava sample (KRA 732) collected at the southernmost crater last active.

Each sample listed in Appendix 2 represents scoria or glassy crust collected from a small area (less than 1 m^2). Duplicate sections of samples KRA 725 and KRA 733, which both have lower MgO values than the main lava, were analyzed. KRA 733 gave the same value as before, but for KRA 724 the duplicate values are similar to the main magma composition. The heterogeneities found within the lava are therefore likely to be on the ten cm scale as no significant variation has been found within individual thin section (2.5 cm in diameter). There is no obvious time sequence in which the chemically variable samples were erupted.

The chemical compositions of the samples from the September 8th 1977 eruption are plotted on a MgO diagram in Fig. 3 with the compositions of the lavas from the two previous eruptions.

The analyses in Table 1 and Fig. 3 show that each of the four magmas (if the borehole eruption of September 8th 1977 is treated as a separate eruption) has a distinct chemical composition. The two lava eruptions from the northern part of the caldera, from April and the average from September 1977, are similar in composition. However, the lava samples not included in the average show a trend extending between the average and the borehole magma.

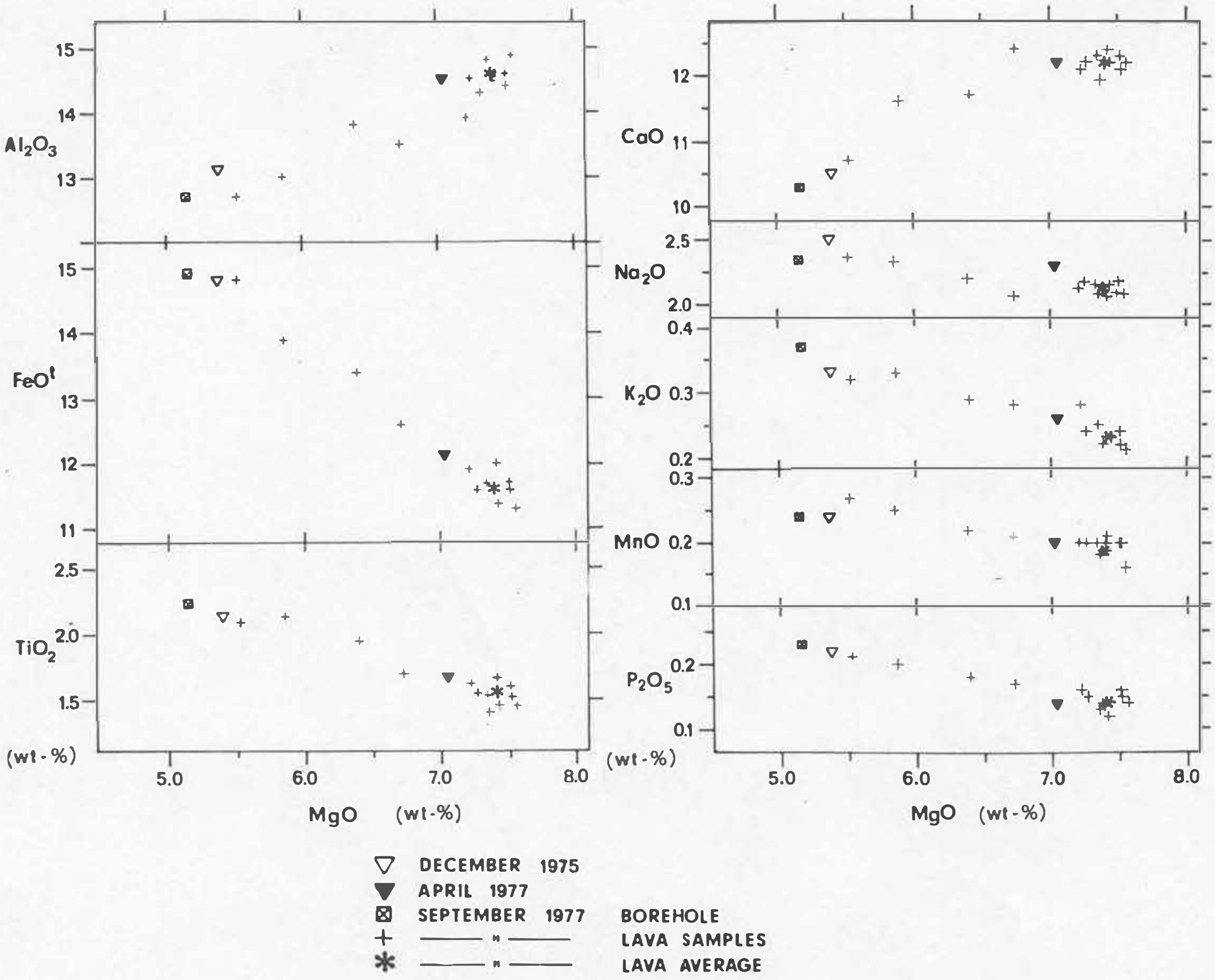

Fig. 3. Variation diagrams for eruptions at Krafla 1975-1977. Analyses of glass phase.
The average for the 8th September lava is for the MgO richer samples only.

The ground movement during the September 8th 1977 deflation was monitored in detail by a newly installed continuously recording tiltmeter (10). This tilt variation which reflects the deflation rate is shown in Fig. 4. The deflation starts between 1540 and 1550 hours simultaneously with a seismic tremor. At about 1800 hours the eruption starts near the northern rim of the caldera. The depth of the magma reservoirs is estimated at about 3 km and if the magma leaves the reservoirs when deflation and seismic tremor starts, the rate of ascent is 0.4 m/sec. This deflation was interrupted shortly after the eruption started for about 30 minutes. Then the main deflation started and continued in a regular way (Fig. 4). Assuming that the second and main deflation represents the start of the intrusion into the fault swarm to the south and the borehole eruption took place at about 2345 hours, the rate of movement is about 0.5 m/sec. Similar rates of movement were derived for the April 27th event (9).

The fact that the deflation can be divided into two stages and the lavas have variable chemical composition may be significant. It is argued later, that the different magmas are unlikely to be related by processes taking place in the magma reservoirs at 3 km depth. The break

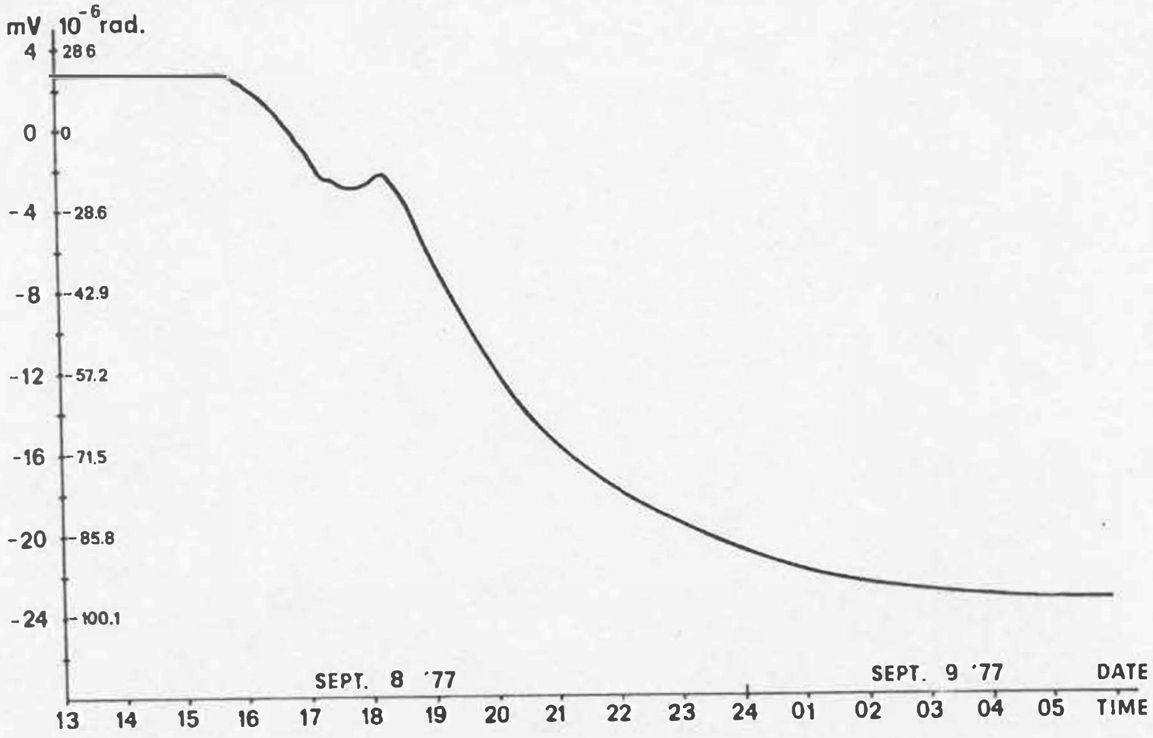

Fig. 4. Tilt variation of the N-S component in the power house at Krafla 8th and 9th September 1977 (10).

in the deflation might therefore mean that separate magma reservoirs were being drained to produce the eruption and to intrude the fault swarm to the south.

During the deflation event of January 6th to 22nd 1978 magma moved again to the north, but no eruption took place.

PETROLOGY OF THE LAVAS

The discussion of the petrology is based on glassy samples collected from quickly cooled flow tops and glassy scoria from craters. These samples are likely to represent the state of the liquid just prior to the eruption. Three types of crystals are found in the samples:

a) Large plagioclase crystals usually found as glomerocrysts ranging up to 5 millimeters in length.

b) Small phenocrysts or microphenocrysts ranging up to 0.2 mm in length. These are olivines and plagioclases in the MgO richer magma and augite as well in the MgO poor magma.

c) Quench crystals. In some of the glass fragments there are abundant crystal needles. These are too small for microprobe analysis and most likely formed during or subsequent to the eruption.

There is no transition between the first two groups, but there is a size range for the smaller crystals.

The glomerocrysts and the phenocrysts have been analyzed with the microprobe as well as the surrounding glass. The main analytical results are given in the present section with some evaluation of possible equilibrium relations. Other properties that may be derived from the mineral-glass pairs are discussed in the next chapter.

Olivine is found in all the products and forms fairly regular granular or hopper olivines (11).

The average composition of olivines in the four main magma compositions is given in Table 2, but the individual analyses are given in the Appendices 3, 4, 6 and 7.

TABLE 2

Average composition of olivines in the lavas listed in Table 1

		FeO	MnO	MgO	CaO	NiO	Total	Fo
Des. 1975	37.0	26.0		36.1			99.8	71.2
April 1977	38.8	17.8	0.26	41.2	0.31	0.20	98.7	80.5
Sept. 1977 lava	39.5	16.6	0.23	42.8	0.32	0.22	99.7	82.1
Sept. 1977 borehole	37.7	25.7	0.35	35.7	0.29	0.13	99.9	71.2

For actual analysis see Appendices 3, 4, 6, 7.
- = not determined.

Roeder & Emslie (12) demonstrated experimentally that for a limited compositional interval the K_D value for the distribution of MgO and FeO between olivine and liquid is virtually constant. The concentration of the FeO in the glass was not measured directly but using the above mentioned experimental results the FeO content can be estimated and K_D calculated. The K_D values range between 0.30 and 0.31 (see Table 6) in good agreement with the experimental results (12), which gave the average of 0.30. The olivines in the main compositional types are therefore considered to be in equilibrium.

The forsterite content of individual samples is plotted on a combined histogram in Fig. 5.

The range of Fo values within individual lava types is limited. There is, however, a small but significant varia-

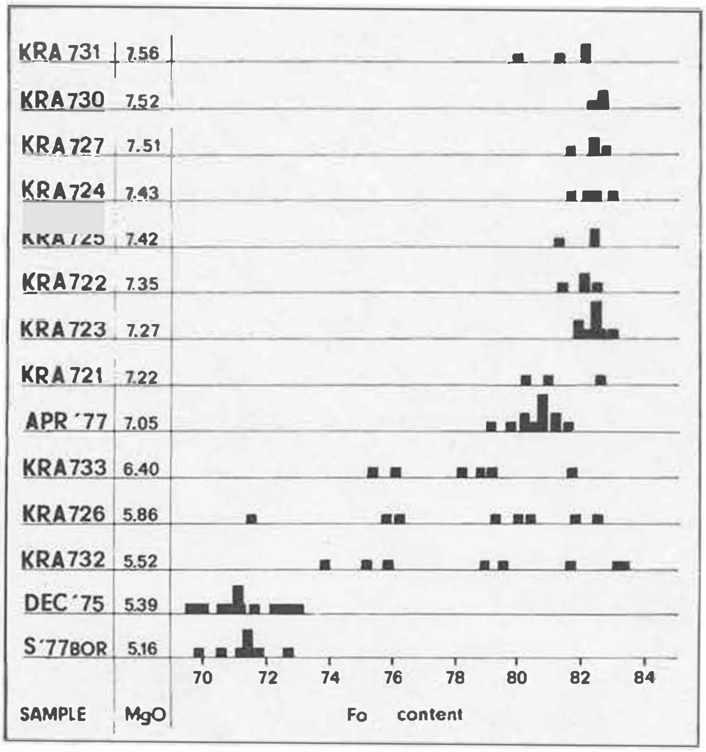

Fig. 5. Variation in the Fo content of olivine in samples from the Krafla eruptions 1975-1977. Samples with the prefix KRA are from the September 8th 1977 eruption. The MgO value refers to the glass associated with the olivine.

tion between the April and September 1977 lavas reflecting the small difference in MgO content of the glass. Exceptions from this relative olivine homogeniety are samples KRA 726, 732 and 733 from the September 8th eruption, which have variable olivine composition and these three samples also represent the compositions that differ from the most common (average) composition of that lava (Appendix 2). There is no apparent difference in the grain size of crystallinity of the samples. And as olivines can be expected to react fairly quickly with the surrounding liquid, it is unlikely that the olivines in the three samples have grown out of the liquid in which they are presently found. The scatter of the Fo values (Fig. 5) is restricted between the values of the main compositions and suggests that the lava samples with the intermediate composition represent mixing of two magma types. The olivines have partially changed their composition but not reached equilibrium.

Plagioclase is found in all the lavas in three generations glomerocrysts, microphenocrysts and microlites. The glomerocrysts have variable composition (Appendix 8) and appear to be out of equilibrium. The microphenocrysts are generally very thin and therefore difficult to analyse. Average compositions of plagioclase microphenocrysts from the main different lava compositions are presented in Table 3, but individual analyses for all plagioclases are listed in Appendices 8-12.

TABLE 3

Plagioclase microphenocrysts - average composition of lavas listed in Table 1

	SiO_2	Al_2O_3	FeO^t	CaO	Na_2O		Total	An
Dec. 1975	49.6	31.3	0.78	15.2	2.78	0.05	99.7	74.9
April 1977	50.3	30.6	0.76	14.8	3.09	0.06	99.6	72.4
Sept. 1977 lava	50.0	30.8	0.87	14.4	3.07	0.06	99.2	71.8
Sept. 1977 borehole	52.9	29.0	1.20	13.2	4.03	0.09	100.4	64.1

Whereas the olivines are most likely in equilibrium with their surrounding magma the plagioclase-liquid equilibrium is less certain. Drake (13) derived partition coefficients for plagioclase liquid pairs of variable compositions as a function of temperature only. We have tried to estimate the plagioclase-liquid equilibrium in two ways. One is by experiments on natural Icelandic basalt

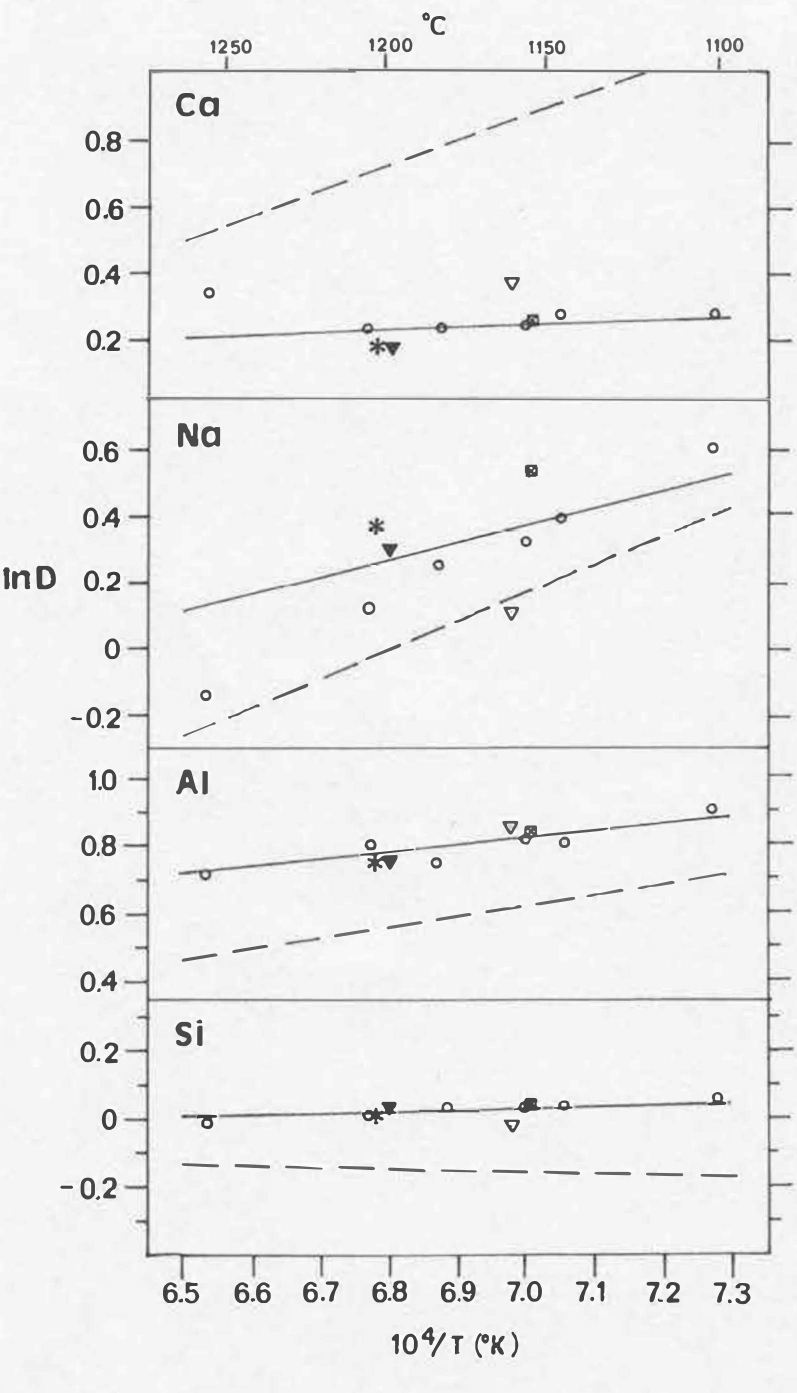

Fig. 6. Distribution coefficients D for plagioclase-glass. The broken line is from Drake(13). The other line is a best fit line for Icelandic microphenocrysts (14). Open circles are experiments performed in this study. Other symbols as in Fig. 3.

compositions. The other by analyzing natural glasses, which contain small amounts of plagioclase and olivine, and using the temperature derived from the olivine-glass pair as the equilibrium temperature. The results of these two methods and of Drake´s experiments are shown in Fig. 6. Also shown in the figure are the D-values (wt.% in plagioclase/wt.% in liquid) for the plagioclase compositions from Table 3 using the glass compositions from Table 1. From this it is apparent that Drake´s values are different from those obtained for the Icelandic basalts, most probably due to compositional effects. The results for the Icelandic basalts and the Krafla lavas show reasonable correlation except for Na. The data of Fig. 6, however, leads us to suggest that at least in the more magnesian lavas of April and September 1977 there is equilibrium between plagioclase and liquid.

The composition of the glomerocrysts differs markedly from that of the microphenocrysts (Appendix 8). If therefore the microphenocrysts are in equilibrium the glomerocrysts are out of equilibrium and the irregular zoning suggests that they are xenocrysts incorporated into the magma only shortly before the eruption.

The microphenocrysts from the December 20th 1975 eruption might possibly be fragments of glomerocrysts rather than microphenocrysts (Appendix 12).

Clinopyroxene is only found in the lava from December 20th 1975 and the borehole eruption of September 8th 1977. These are the magmas with low MgO content (MgO 5.2 and 5.4%). The augite grains are scarce and small and only three grains in the borehole scoria gave satisfactory analysis (Table 4).

Compared with results obtained sofar for Icelandic tholeiites both experimentally and using natural glass-pyroxene pairs and olivine-clincpyroxene pairs (14) the clinopyroxenes appear to be in equilibrium with the liquids in which they were erupted.

TABLE 4

The composition of clinopyroxene from the September 8th 1977 borehole eruption

SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Cr_2O_3	Total	Mg	Fe	Ca
49.5	1.42	4.30	11.1	0.00	15.2	17.1	0.24	0.32	99.5	45.1	18.5	36.4
48.5	0.99	3.66	12.4	0.38	16.9	14.9	0.19	0.11	98.1	48.9	20.1	31.0
51.4	0.86	3.32	11.0	0.30	16.1	16.6	0.22	0.42	100.2	47.1	18.0	34.9
Average												
49.8	1.09	3.76	11.5	0.34	16.1	16.2	0.22	0.28	99.3	47.1	18.9	34.0

SOME PROPERTIES OF THE MAGMA

From the chemical data available, especially on glass-mineral pairs, and the petrological observations, it is possible to estimate some of the properties of the magma erupted.

The temperature of the magma on eruption can be estimated from the mineral-glass analyses of the products. The most successful geothermometers is the olivine-liquid pair. Roeder & Emslie (12) demonstrated experimentally that olivine composition is dependent on the composition of the melt only. As the liquidus temperature is also dependent on the melt composition the olivine-glass pair can be used to estimate the temperature of equilibration. This temperature can be calculated either from the distribution of MgO or FeO between olivine and the liquid. As the microprobe does not distinguish between Fe^{2+} and Fe^{3+} the MgO distribution is applied. The equation used is

$$\log \left(\frac{X^{ol}_{MgO}}{X^{liq}_{MgO}} \right) \quad \frac{3740}{T} - 1.87$$

X = mole fraction and T = temp. °K

The magma compositions in Table 1 and the average olivine compositions in Table 2 gave the temperatures listed in Table 5. According to similar equations by Leeman & Scheidegger (15) the values for the two September 8th 1977 eruptions are 1202°C and 1159°C, respectively.

TABLE 5

Temperature estimates for the different magma types using the distribution of Mg between olivine and liquid (12) and equations of Mathez (18) for plagioclase at different water pressures

Sample	$MgO^{ol/liq}$	0 kb(H_2O)	0.5 kb(H_2O)	1.0 kb(H_2O)	5.0 kb(H_2O)
Dec. 1975	1159	1170	1203	1152	853
April 1977	1198	1196	1236	1184	901
Sept. 1977 lava	1202	1185	1221	1172	888
Sept. 1977 borehole	1153	1158	1187	1137	838

In view of the very slight crystallization of the samples the olivine temperature is close to the liquidus temperature. For Hawaiian basalts with olivine as the first liquidus phase the temperature FeO/(FeO+MgO) relation has been shown to be linear (16). The results in Table 5 were therefore compared with experimental results on Icelandic basalts and temperatures derived from olivine-glass pairs in a variety of Icelandic basalts. The results are shown in Fig. 7. The magmas higher in MgO show good correlation with the other Icelandic basalts, but the magmas lower in MgO show higher temperatures. But since both plagioclase and clinopyroxene are also liquidus phases in those samples other chemical parameters may be more important in controlling the liquidus temperature. The data on Icelandic basalt shows a significant difference from the Hawaiian data with higher liquidus temperature for same $FeO^t/(FeO^t+MgO)$ ratio.

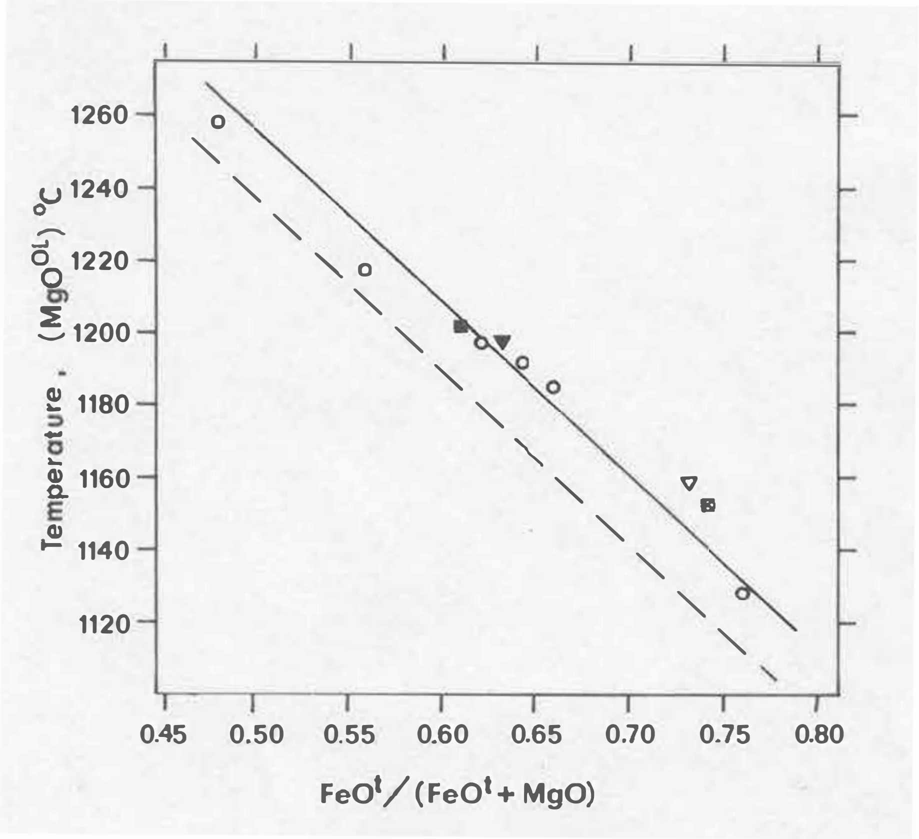

Fig. 7. Variation of $FeO^t/(FeO^t+MgO)$ with temperature. The triangles and squares are for the Krafla lavas (table 1), but the circles represent experimental results on some Icelandic basalts (14). The solid line represents the best fit for Icelandic basalts (using MgO^{ol}-temperature) and the broken line represents experimental results for Hawaiian basalts (16).

Temperature estimates can also be obtained from the plagioclase-glass pair and here the Kudo & Weill geothermometer (17) with modifications by Mathez (18) is used. This geothermometer is dependent on the water pressure (P_{H_2O}) of the magma. Temperature estimates were obtained for P_{H_2O} = 0, 0.5, 1.0, 5.0 kb (Table 5). For the April 1977 lava and the borehole scoria the derived temperature at 0 kb P_{H_2O} is in good agreement with the olivine temperature.

<u>FeO and fO_2</u> The microprobe analysis for iron does not distinguish between Fe^{3+} and Fe^{2+}. The actual FeO content of the liquid is important as well as the fO_2, which correlates with the Fe^{3+}/Fe^{2+} ratio (19). Direct

measurements of the Fe_2O_3/FeO ratio in the scoria give inconsistent results. However, Roeder & Emslie (12) measured the FeO distribution between olivine and liquid and from their experiments obtained the equation

$$\log \left(\frac{X^{ol}_{FeO}}{X^{liq}_{FeO}} \right) = \frac{3911}{T} - 2.50$$

Using this equation for the liquid composition in Table 1 and the olivine averages in Table 2, the FeO values in Table 6 are obtained.

Knowing the FeO value of the liquid the distribution coefficient K_D between olivine and liquid

$$K_D = \frac{X^{ol}_{FeO} \; X^{liq}_{MgO}}{X^{ol}_{MgO} \; X^{liq}_{FeO}}$$

can be calculated and the results (Table 6) all fall between 0.30 and 0.31, which is in good agreement with the results of Roeder & Emslie and indicates equilibrium conditions.

TABLE 6

FeO, fO_2 and K_D calculated by equations of Roeder & Emslie (12) using olivine-glass compositions

	FeO	Fe_2O_3/FeO		
Dec. 1975	12.6	0.19		0.309
April 1977	9.97	0.24	$10^{-8.56}$	0.305
Sept. 1977 lava	9.47	0.26	$10^{-8.33}$	0.307
Sept. 1977 borehole	12.0	0.27		0.307

A further equation from Roeder & Emslie correlates the Fe^{3+}/Fe^{2+} ratio with the fO_2 at 1200 ± 5°C

$$\log \left(\frac{X_{FeO}}{X_{FeO_{1.5}}} \right) \quad 0.20 \log fO_2 - 1.04$$

Using this equation the values $fO_2 = 10^{-8.56}$ and $10^{-8.33}$ are obtained for the April and September eruptions respectively (Table 6). This is close to the QMF-buffer, which has $fO_2 = 10^{-8.47}$ at 1200°C.

Mineral-liquid calculations can be used to test the feasibility of deriving the MgO poorer magma from the MgO richer magma by crystal fractionation. The minerals observed in the lavas appear to be near the liquidus and in equilibrium. The composition of the minerals extracted should be the same as in the MgO poorer magma or somewhere intermediate between those observed in the two main magma compositions.

The first test was to try to mix the borehole magma with the minerals observed in that magma to produce the September 1977 main lava. The results (Table 7) indicate

TABLE 7

Mixing calculations for mixing September drillhole magma and plagioclase, olivine and augite to produce the September 1977 lava composition

	SiO_2	TiO_2	Al_2O_3	FeO^t	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
(1)	50.0	2.24	12.7	14.9	0.24	5.16	10.3	2.34	0.37	0.23
(2)	37.8			25.9	0.35	35.6	0.29			
(3)	52.9		29.0	1.20			13.2	4.03	0.09	
(4)	49.8	1.09	3.8	11.5	0.34	16.1	16.2	0.22		
(5)	48.8	1.53	14.5	11.6	0.19	7.41	12.2	2.13	0.23	0.14
(6)	49.3	1.33	14.1	11.2	0.20	7.33	11.5	2.19	0.21	0.12
(7)	0.6	0.20	0.4	0.4	0.01	0.08	0.7	0.02	0.02	0.02

(1) September 8th 1977 drillhole magma
(2) " " " " olivine
(3) " " " " plagioclase
(4) " " " " augite
(5) " " " lava composition
(6) Calculated composition (50% liq (1) + 25% pl + 20% augite + 5% ol)
(7) Difference between calculated and actual composition

that the mineral extract would need to be about 50% (25% pl, 20% cpx and 5% ol). The difference, however, between the calculated magma composition and the real composition is large for Al_2O_3, FeO^t and CaO and makes this model rather unlikely. A composition of the minerals intermediate between the two compositions observed brings no improvement. An attempt was also made to relate the two liquids using only olivine and plagioclase from the September 1977 lava as only these phases were observed in that lava. This gave no better results.

The results from these mineral-liquid calculations do not support a model where the two magma compositions are related to each other by extraction of the minerals observed in the liquids.

<u>Density differences between crystals and magma</u> can also be used to test the feasibility of differential movement of crystals and liquid. The upward velocity of the magma can be estimated and the possibility of flowage differentiation during the ascent from the magma reservoirs can be evaluated. Stoke´s law relates settling velocity of a spherical solid in a liquid with the radius of the solid and the density difference between the solid and liquid. Thus the radius of a crystal settling in a rising magma at the rate of ascent can be determined by Stoke´s law.

$$v \quad \frac{2gr^2(P_1-P_2)}{9\eta}$$

v = settling velocity
r = radius of solid sphere
P_1 density of solid
P_2 = density of liquid
η viscosity
g = 980 cm/sec

The time from the initial observed volcanic tremor until the appearance of the magma at the surface was about 8×10^3 sec and the estimated depth of the magma reservoirs is 3×10^3 m giving 0.4 m/sec for the upward velocity. The density of the magma is estimated from the chemical composition using the method of Bottinga & Weill (20) at

2.62% g/cm^3 assuming 1% water content (2.71 g/cm^3 for dry magma). For plagioclase the density used is 2.72 g/cm^3 and 4.15 g/cm^3 for olivine. The viscosity is estimated using the method of Shaw (21) at 200 poise.

The result of these calculations is that plagioclase crystals with diameter up to 27 cm would move with the liquid to the surface and olivine crystals with a diameter up to 7 cm. This makes the presence of any large crystals in the process of fractionation in the magma reservoirs below Krafla unlikely.

Cooling rate is of interest when trying to answer the question whether the microphenocrysts are formed during ascent or whether they are formed in the magma reservoirs below Krafla. Experiments have been performed on the rate of crystals growth in lunar samples, and have changed some of the generally accepted ideas of cooling rate relationships of phenocryst and groundmass (22). Donaldson (11) divides olivine crystals into different groups depending on their regularity. According to his classification the olivine microphenocrysts in the Krafla lavas are granular or hopper textured. He attempted to reproduce the different textures by varying the cooling rate. Most of his experiments were on MgO rich liquids similar to Moon basalts, but comparison with the ocean floor basalt type included in his study suggests cooling rate of about 50°C/hour as a maximum. The lack of zoning of the crystals from the MgO richer lavas also suggests that cooling was relatively slow.

The grain size of plagioclase is known to be dependent on cooling rates. Grove & Walker (23) presented experimental results from cooling experiments on a quartz normative lunar basalt correlating cooling rate with crystal width. Using these results the plagioclase microphenocryst grains suggest a maximum cooling rate of 47-15°C/hour for grains 10-20 μm in diameter, which is in reasonable agreement with the olivine results.

A maximum cooling rate of less than 50°C/hour suggests that the microphenocrysts observed in the lava are those present in the magma reservoirs below Krafla, but not crystallized during ascent.

OLDER LAVAS

"Mývatn fires" 1724-29

The last rifting episode in the Krafla area which took place in 1724-29, is often referred to as "the Mývatn fires". Accounts of these events were published in Copenhagen in 1726 (24) and later (25). These accounts indicate that the sequence of events was similar to what has been observed in the Krafla area during the present episode. The initial explosive eruption on May 17th 1724 was followed by large scale fault movements, earthquake activity and land elevation. The initial rifting appears to have been mainly in the southern part of the fault swarm, whereas in the present episode the first activity was to the north. Separated events of rifting and earthquake activity followed, accompanied by changes in hydrothermal activity. Four events are recorded until September 1725. The records are not clear for 1726 and the first half of 1727. It is likely that movement in the northern part of the fault swarm was not severly felt in the farming district near Mývatn. It is not certain from the records, whether the first eruption on May 17th 1724 was the only eruption during the first year, or whether other small eruptions followed. The main lava eruption started on August 21st 1727 and continued until September 1729. The eruptive fissure has a total length of 11 km. Mainly the northern half was active, but small eruptions took place at Námafjall as well. The areal extent of the lava is 33 km^2 and the volume is estimated at 0.5 km^3 (see Fig. 1).

Analyses of six samples from this eruption are listed in Table 8 with one older XRF analysis by Níels Óskarsson.

TABLE 8

Chemical analyses of the lava from 1724-29, the "Mývatn fires". Microprobe analyses on glasses produced by melting the sample above the liquidus

	SiO_2	TiO_2	Al_2O_3	FeO^t	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
KRA 101	50.0	2.12	13.5	14.3	0.26	6.02	10.4	2.29	0.36	0.23
KRA 102	49.5	2.08	13.2	14.3	0.25	5.71	10.2	2.33	0.38	0.23
KRA 105	50.2	2.05	13.5	13.7	0.24	6.07	10.4	2.31	0.37	0.22
KRA 106	49.9	2.03	13.5	13.5	0.23	5.65	10.1	2.28	0.37	0.24
KRA 107	49.5	1.97	13.4	14.3	0.25	5.70	10.5	2.25	0.32	0.20
KRA 109	49.7	2.04	13.1	14.5	0.24	5.63	10.2	2.34	0.34	0.22
NAL 74	50.8	1.82	13.6	13.8	0.21	6.20	11.1	2.02	0.30	0.15

KRA 101	Near the northernmost craters.
KRA 102	" " " "
KRA 105	From near the craters active in Dec. 1975.
KRA 106	From Leirhnjúkur.
KRA 107	Bjarnarflag - the southernmost craters.
KRA 109	South of Hlídarfjall.
NAL 74	Eldá, XRF analysis by Níels Óskarsson.

All these analyses are whole rock analyses since the samples were crushed and melted in the furnace above the liquidus and the glass then analyzed on the microprobe. The samples were collected from various parts of the fissure to see if marked variation along the length could be detected. The results are plotted on a MgO diagram in Fig. 8.

The composition falls within the range observed for lavas of the present events. The variation is relatively restricted but apparently significant. No detailed petrological study has yet been made, but the same phases appear to be present i.e. plagioclase in two generations, olivine and clinopyroxene. Variations in mineral content are apparently not reflected in the chemistry. Further work is in progress on glassy samples from the crater scoria.

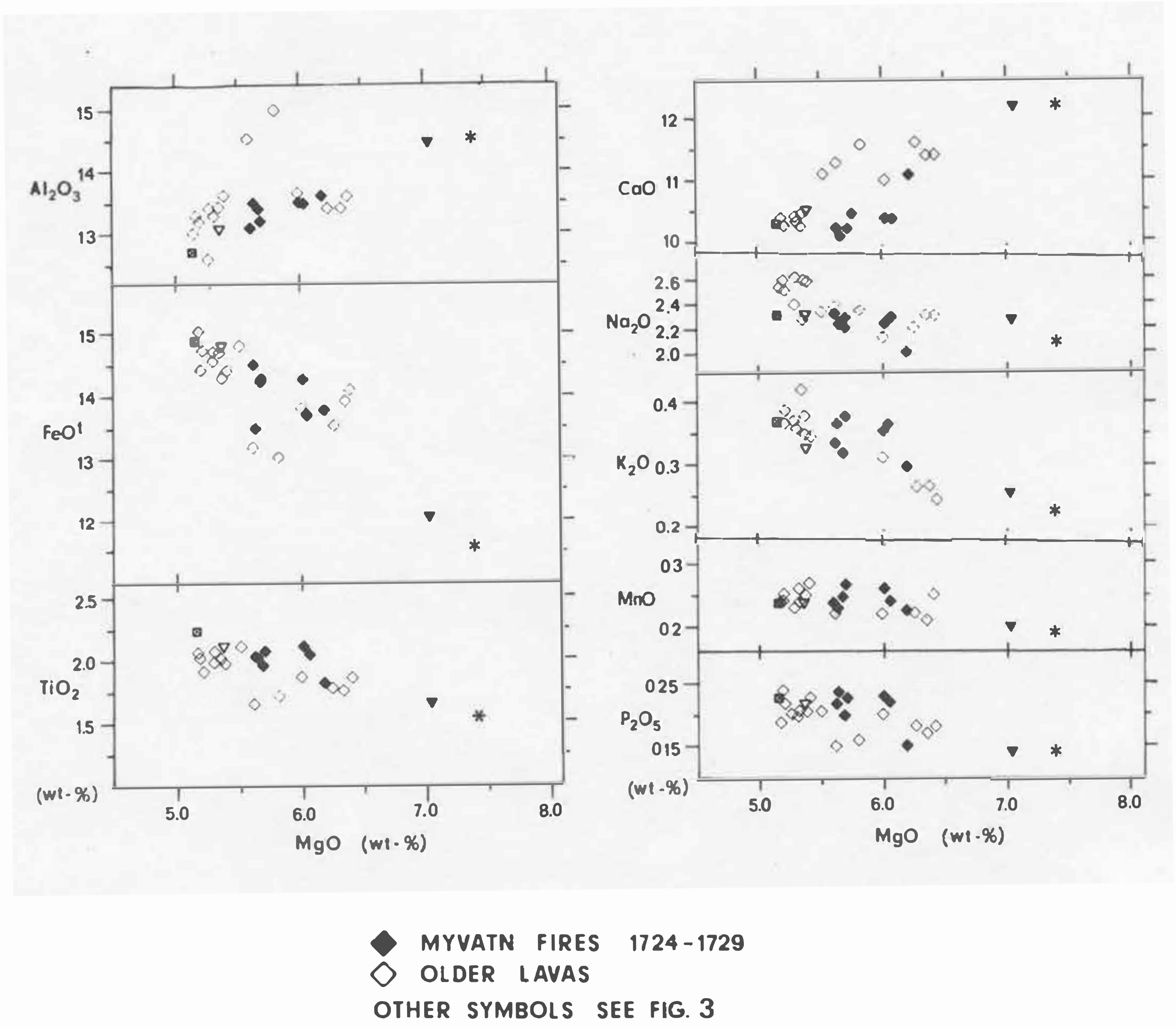

Fig. 8. Variation diagrams for post-glacial lavas in the Namafjall-Krafla area. Whole rock analyses.

Postglacial activity in the Krafla Námafjall area

During postglacial times about 20 basaltic fissure eruptions have taken place on the Krafla fault swarm (26). These eruptions are not symmetrically arranged about the Krafla caldera. The fissures extend only 5 km to the north of the caldera margin, but to the south at Námafjall (Fig. 1) there is a concentration of crater rows representing possibly 15 individual eruptions. Since there is a hiatus in the activity between Krafla and Námafjall, it has not been possible to correlate individual eruptions in the two areas together. But it is to be expected that some of the eruptions at least form a part of the same rifting event.

The eruptions can be arranged in a chronological order using the Hekla layers H_3 and H_5 as marker horizons. Thorarinsson´s (27) suggestion that the eruptive activity is in two phases, has been confirmed by more recent mapping (26).

a) the Ludent phase, older than H_5 (6000 years) with 13 eruptions in Krafla and 8 in Námafjall.

b) The Hverfjall phase, younger than H_3 (2900 years) with 7 eruptions in Krafla and 7 in Námafjall.

No eruptions have been found from the interval between 6000 years and until 2900 years ago.

Thirteen samples from these lavas were analyzed by the same method as the samples from the Mývatn fires, i.e. whole rock samples melted to glass and analyzed on the microprobe. The analyses are listed in Table 9 and plotted in Fig. 8 together with the analyses from the Mývatn fires.

The variation is greater than for the Mývatn fires 1724-29 alone and a number of the samples are very similar to the December 1975 lava and the borehole eruption. The MgO values do not extend much beyond that observed for the Mývatn fires and no values are found approaching the 1977 lava eruption (i.e. MgO 7.0-7.4). From these data no systematic variation can be seen, either with time or between the two main centers Krafla and Námafjall.

Table 9 Chemical analyses of post-glacial lavas from the Námafjall - Krafla area.
Whole rock analyses of fused glasses.

	SiO_2	TiO_2	Al_2O_3	FeO^t	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
N 129	50.2	2.01	13.4	14.3	0.25	5.38	10.1	2.61	0.35	0.21
N 131	50.2	1.96	13.6	14.4	0.27	5.41	10.1	2.60	0.35	0.23
N 146	50.9	2.00	13.3	14.4	0.24	5.20	9.93	2.60	0.37	0.24
N 189	50.8	2.06	12.6	14.5	0.23	5.30	10.0	2.43	0.37	0.20
N 209	49.9	1.76	13.4	13.9	0.21	6.36	11.0	2.32	0.26	0.17
N 121	50.6	1.91	13.2	14.7	0.25	5.22	9.94	2.54	0.39	0.22
N 122	50.2	1.76	13.4	13.5	0.22	6.26	11.2	2.22	0.26	0.18
KRA 104	50.1	2.07	13.3	14.7	0.24	5.35	9.91	2.31	0.42	0.21
N 29	50.6	2.03	13.0	15.0	0.24	5.19	10.0	2.55	0.38	0.19
N 31	50.0	1.64	14.5	13.2	0.22	5.62	10.9	2.40	0.25	0.15
N 30	49.6	1.85	13.6	14.1	0.25	6.42	11.0	2.33	0.24	0.18
KRA 108	50.0	1.85	13.6	13.8	0.22	6.01	10.6	2.16	0.31	0.20
N 142	50.4	1.99	13.4	14.7	0.26	5.31	9.97	2.63	0.36	0.20

N 129, N 131, N 146, N 189 are from Krafla older than H5 (6000 years)
N 209, N 121, N 122, KRA 104 are from Krafla younger than H3 (2900 years)
N 29, N 31 are from Námafjall older than H5
N 30, KRA 108 are from Námafjall younger than H3
N 142 is from Krafla uncertain age

A systematic petrologic study has not been done on the lava samples. But the main features are similar to those discussed for the more recent samples, i.e. olivine and clinopyroxene and two generations of plagioclase.

No further attempt is made here to correlate the present magma compositions at Krafla with other lavas in the region except to point out that:

(a) The region to the north and northwest of Krafla is dominated by MgO rich lavas.

(b) In interglacial times MgO rich lavas have been erupted in the Krafla area.

So chemical compositions similar to the 1977 lavas are common in this region.

SUMMARY

Basaltic magma is being moved upwards in the crust below the Krafla caldera at the rate of 5 m^3/sec. The depth of the reservoirs, where the magma is being stored, is about 3 km, but the depth of the source area is not known. Sofar about 3.9 x 10^8 m^3 of the magma have been intruded into the Krafla fault swarm to the north and south, but 2.4 x 10^6 m^3 have been erupted in three eruptions.

The chemical composition of the magma that has appeared at the surface is variable. The variation is greater than observed in previous postglacial fissure eruptions in the fault swarm. Rapidly quenched samples from the crater scoria and the lava surface show that on eruption the magma was very little crystallized. The MgO richer magma (MgO 7.0-7.4%) has only olivine and plagioclase microphenocrysts, while the MgO poorer magma (MgO 5.2-5.4%) has augite in addition. The very low crystallinity of the magma in both cases indicates that the temperature at the time of eruption was close to the liquidus. From the glass-olivine composition this temperature is estimated at about 1200°C and 1156°C for the MgO richer and MgO poorer magmas respectively.

The data presented and the derived properties of the magma can be used to evaluate the possibility of crystal fractionation in the Krafla reservoirs.

(a) If the magma was fractionating greater crystallinity would be expected. The steady inflow into the magma reservoirs makes a very clean separation unlikely and calculations using Stoke´s law indicate that larger crystals than actually found would not be differentiated during ascent.

(b) Mineral-liquid calculations using the actual compositions found give relatively large discrepancies. They also indicate that 50% of the liquid would need

to be plagioclase but only 5% olivine. But with the low density contrast between magma and plagioclase this appears unlikely.

(c) The first eruption (December 20th 1975) is of the most evolved type. On September 9th 1977 the least evolved magma was erupted first, but the most evolved at the end.

(d) The apparently fine scale of the heterogeniety of the samples and the variation in olivine composition in the intermediate samples suggests mixing of two or more liquids rather than a single erupting magma chamber.

The present interpretation is therefore that magma of low crystallinity is flowing into magma reservoirs below Krafla and that the chemical composition is already variable. Magmas of different composition are being stored in separate reservoirs. This could come about in two ways. The upflowing magma could have variable composition with time and then successively filling partly or totally isolated reservoirs. Another possible explanation is two or more magma conduits tapping different source areas and then feeding seperate reservoirs. In rifting events like on September 8th 1977, at least two separate reservoirs are being drained producing a partly mixed magma, where the liquid has time to mix but the microphenocrysts not to equilibrate. The presence of more than one magma reservoir is also suggested by analyses of seismic S-wave attenuation (4).

Krafla shows in many respects similar behaviour as Kilauea in Hawaii with gradual inflation of magma reservoirs at about 3 km depth and then relatively rapid deflation, often accompanied by eruptions in the rift zones. In a detailed study of the Kilauea lavas Wright & Fiske (28) found convincing evidence for magma mixing. They also found no simple way of relating the least evolved summit magmas by simple fractionation processes in the established reservoirs.

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APPENDIX 1

Leirhnjúkur eruption December 20th 1975
Chemical analysis of whole rocks by XRF (N. Óskarsson)

	SiO_2	TiO_2	Al_2O_3	FeO^t	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
NAM 503	50.25	2.13	13.42	14.87	0.243	5.43	10.30	2.38	0.334	0.23
NAM 510	50.27	2.10	13.42	14.79	0.244	5.55	10.30	2.33	0.333	0.22
NAM 511	50.21	2.11	13.48	14.75	0.241	5.43	10.25	2.38	0.325	0.21
NAM 516	50.15	2.12	13.52	14.67	0.242	5.52	10.42	2.38	0.320	0.22
NAM 517	50.20	2.10	13.60	14.81	0.243	5.48	10.26	2.37	0.318	0.21
NAM 518	50.17	2.13	13.52	14.80	0.244	5.42	10.30	2.38	0.320	0.21
L 1975	50.24	2.13	13.46	14.76	0.241	5.48	10.43	2.34	0.331	0.22
Average	50.2	2.11	13.5	14.8	0.24	5.47	10.3	2.36	0.33	0.22
Micropr. anal. of glasses	50.2	2.14	13.1	14.8	0.24	5.39	10.4	2.50	0.29	0.22

APPENDIX 2

Lava eruption September 1977 north of the Krafla caldera
Microprobe analysis of glasses

	SiO_2	TiO_2	Al_2O_3	FeO^t	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
KRA 732	49.4	2.10	12.7	14.8	0.27	5.52	10.7	2.36	0.31	0.21
KRA 726	49.9	2.15	13.0	13.9	0.25	5.86	11.6	2.33	0.33	0.20
KRA 733	50.0	1.96	13.8	13.4	0.22	6.40	11.7	2.20	0.29	0.20
KRA 728	49.6	1.70	13.5	12.6	0.21	6.73	12.4	2.04	0.28	0.17
KRA 720	48.5	1.40	14.8	11.3	0.18	7.38	11.9	2.08	0.22	0.14
KRA 721	48.8	1.62	13.9	11.9	0.20	7.22	12.1	2.12	0.28	0.16
KRA 722	48.8	1.54	14.3	11.7	0.20	7.35	12.3	2.16	0.25	0.13
KRA 723	49.2	1.55	14.5	11.6	0.20	7.27	12.2	2.18	0.22	0.15
KRA 724	48.7	1.46	14.6	11.4	0.21	7.43	12.2	2.16	0.23	0.14
KRA 725	49.1	1.66	14.5	12.1	0.20	7.42	12.4	2.07	0.23	0.11
KRA 727	49.0	1.60	14.6	11.7	0.20	7.51	12.3	2.10	0.22	0.16
KRA 730	48.3	1.52	14.4	11.6	0.20	7.52	12.1	2.18	0.24	0.15
KRA 731	49.7	1.46	14.9	11.3	0.16	7.56	12.2	2.08	0.21	0.14
Average of 9 lower analyses										
	48.9	1.53	14.5	11.6	0.19	7.41	12.2	2.13	0.23	0.14

APPENDIX 3

Eruption April 27, 1977
Olivine compositions

	SiO_2	FeO	MnO	MgO	CaO	NiO	Total	Fo
April 1977	38.7	17.3	0.32	40.7	0.31	0.23	97.7	80.7
	38.3	18.7	0.29	39.5	0.34	0.11	97.4	79.1
	38.7	17.9	0.27	39.6	0.31	0.24	97.2	79.7
	39.1	17.2	0.27	42.5	0.32	0.20	99.8	81.5
	38.5	18.4	0.25	41.7	0.36	0.21	99.5	80.2
	39.9	17.6	0.31	42.4	0.35	0.19	100.3	81.1
	38.8	17.3	0.21	41.9	0.28	0.21	98.8	81.2
	38.6	18.2	0.24	41.5	0.30	0.22	99.0	80.3
	38.7	17.6	0.24	41.4	0.28	0.21	98.5	80.8
	38.4	17.6	0.24	40.6	0.29	0.19	97.5	80.5
	39.1	17.9	0.23	41.8	0.33	0.19	99.8	80.6
	39.1	17.6	0.29	41.3	0.30	0.14	98.9	80.7
Average	38.8	17.8	0.26	41.2	0.31	0.20	98.7	80.5

APPENDIX 4 Eruption September 8th 1977. Olivine compositions of main lava samples with MgO 7.22 - 7.56%.

	SiO_2	FeO	MnO	MgO	CaO	NiO	Total	Fo
KRA 721	39.6	16.1	0.20	42.4	0.30	0.28	98.8	82.5
	39.3	17.5	0.24	41.5	0.42	0.18	99.1	80.9
	39.3	18.3	0.25	41.6	0.28	0.26	100.0	80.2
Average	39.4	17.3	0.23	41.8	0.33	0.24	99.3	81.2
KRA 722	39.6	16.0	0.22	42.1	0.33	0.30	98.5	82.4
	39.8	16.3	0.24	41.6	0.32	0.21	98.5	82.0
	39.9	17.0	0.17	41.5	0.32	0.17	99.0	81.3
	39.6	16.2	0.24	41.5	0.32	0.23	98.1	82.1
Average	39.7	16.4	0.22	41.7	0.32	0.23	98.6	81.9
KRA 723	39.3	16.4	0.24	43.1	0.34	0.22	99.7	82.4
	39.4	16.8	0.26	42.9	0.33	0.20	99.8	82.0
	39.3	16.5	0.23	43.1	0.32	0.31	99.8	82.3
	39.1	16.0	0.22	43.3	0.32	0.18	99.1	82.8
	38.6	16.9	0.25	44.2	0.37	0.26	100.6	82.4
	39.5	16.7	0.27	43.8	0.35	0.23	100.9	82.4
	39.3	15.9	0.25	43.4	0.29	0.20	99.3	82.9
	39.7	16.1	0.27	42.8	0.32	0.20	99.4	82.6
	39.1	16.5	0.20	43.2	0.32	0.18	99.5	82.3
	39.3	16.8	0.24	42.6	0.32	0.24	99.5	81.9
	39.4	16.3	0.23	43.0	0.40	0.21	99.5	82.5
Average	39.3	16.5	0.24	43.2	0.33	0.22	99.8	82.4
KRA 724	40.0	16.4	0.25	44.4	0.31	0.24	101.6	82.9
	39.6	17.0	0.22	44.1	0.37	0.19	101.5	82.2
	39.5	16.2	0.24	42.5	0.31	0.17	98.9	82.4
	39.6	17.0	0.18	42.7	0.30	0.18	99.9	81.7
Average	39.7	16.7	0.22	43.4	0.32	0.20	100.5	82.3

APPENDIX 4 (continued)

	SiO_2	FeO	MnO	MgO	CaO	NiO	Total	Fo
KRA 725	40.4	17.7	0.24	42.8	0.35	0.18	101.7	82.9
	40.0	16.6	0.24	43.2	0.33	0.23	100.6	82.3
	40.0	16.5	0.23	43.4	0.33	0.23	100.7	82.4
Average	40.1	16.9	0.24	43.1	0.34	0.21	100.9	82.0
KRA 727	39.3	17.1	0.19	42.5	0.38	0.25	99.7	81.6
	39.7	16.0	0.24	42.9	0.33	0.22	99.3	82.7
	39.4	16.4	0.23	42.8	0.31	0.18	99.4	82.3
	39.5	16.2	0.22	42.4	0.28	0.20	98.6	82.3
Average	39.5	16.4	0.22	42.7	0.33	0.21	99.4	82.2
KRA 730	39.0	16.3	0.21	42.5	0.26	0.21	98.4	82.3
	39.9	16.6	0.19	44.2	0.33	0.22	101.5	82.6
	39.1	16.6	0.24	44.1	0.29	0.23	100.5	82.6
Average	39.3	16.5	0.21	43.7	0.29	0.22	100.5	82.5
KRA 731	38.8	16.4	0.26	42.1	0.28	0.21	98.1	82.1
	39.7	16.6	0.22	43.6	0.35	0.21	100.6	79.9
	39.6	16.5	0.20	42.4	0.35	0.21	99.3	82.1
	39.0	17.5	0.25	42.3	0.29	0.14	99.4	81.2
Average	39.3	16.8	0.23	42.6	0.32	0.19	99.4	81.3
Average	39.5	16.6	0.23	42.8	0.32	0.22	99.7	82.1

APPENDIX 5 Eruption September 8th 1977. Olivine compositions of main lava samples of "mixed composition".

	SiO_2	FeO	MnO	MgO	CaO	NiO	Total	Fo
KRA 726	39.2	17.1	0.27	43.1	0.31	0.19	100.2	81.8
	38.7	22.1	0.32	38.8	0.34	0.14	100.4	75.8
	37.5	25.9	0.37	36.6	0.33	0.12	100.8	71.5
	39.4	18.4	0.24	42.3	0.27	0.15	100.8	80.4
	38.7	21.7	0.28	38.6	0.30	0.15	99.7	76.1
	39.4	19.4	0.28	41.5	0.30	0.18	101.0	79.3
	39.2	16.2	0.23	42.7	0.30	0.20	98.8	82.4
	39.0	18.1	0.28	40.6	0.31	0.21	98.5	80.0
Average	38.9	19.9	0.28	40.5	0.31	0.24	99.8	78.4
KRA 733	38.4	19.9	0.26	39.9	0.33	0.14	99.0	78.2
	39.5	17.0	0.20	42.4	0.31	0.21	99.7	81.7
	39.5	19.3	0.28	40.2	0.35	0.15	99.7	78.8
	38.9	22.0	0.27	37.7	0.35	0.09	100.3	75.3
	39.1	21.8	0.30	38.7	0.35	0.14	100.4	76.0
	39.5	18.9	0.22	40.2	0.35	0.15	99.4	79.1
Average	39.2	19.8	0.26	39.9	0.34	0.15	99.6	78.2
KRA 732	38.3	2.29	0.28	39.0	0.29	0.08	100.9	75.2
	38.1	23.2	0.32	36.9	0.27	0.06	98.9	73.9
	37.8	21.9	0.37	38.4	0.28	0.14	98.9	75.8
	39.6	15.5	0.20	43.7	0.32	0.24	99.5	83.4
	39.2	15.7	0.25	43.6	0.27	0.20	99.2	83.2
	38.5	16.8	0.21	42.2	0.29	0.16	98.2	81.7
	38.6	19.5	0.28	40.8	0.32	0.11	99.6	78.9
	37.5	27.1	0.40	34.3	0.40	0.11	99.8	69.2
	38.5	18.8	0.23	40.9	0.27	0.15	98.9	79.5
Average	38.5	20.2	0.28	40.0	0.30	0.14	99.4	

APPENDIX 6 Borehole eruption September 8th 1977. Olivine compositions.

	SiO_2	FeO	MnO	MgO	CaO	NiO	Total	Fo
Borehole 1071	37.4	27.1		35.1			99.6	69.8
	37.4	26.6		35.7			99.7	70.5
	38.0	25.8		36.2			100.0	71.4
	37.2	24.1		36.0			97.3	72.7
	38.4	25.4		36.2			99.1	71.8
	37.7	25.4		35.6			98.7	71.4
Average	37.8	25.7		35.8			99.3	71.3
Borehole KRA 734	37.8	25.0	0.35	34.7	0.28	0.14	98.4	71.2
	37.1	26.3	0.36	36.6	0.30	0.12	100.8	71.3
Average	37.4	25.6	0.35	35.6	0.29	0.13	99.4	71.2
Average	37.7	25.7	0.35	35.7	0.29	0.13	99.9	71.2

APPENDIX 7

Eruption December 20th 1975.
Olivine compositions.

	SiO_2	FeO	MnO	MgO	CaO	NiO	Total	Fo
KRA 503	37.1	26.2	0.36	36.1	0.37	0.11	100.2	71.1
KRA 504	38.1	27.0		35.2			100.3	71.1
	37.7	25.9		35.4			99.0	70.9
	38.8	27.3		35.0			100.3	69.6
	37.2	25.5		36.1			98.8	71.6
Average	37.7	26.4		35.4			99.5	70.5
KRA 507	38.1	24.9		37.0			100.1	72.6
	37.6	26.3		36.5			100.4	71.2
	37.1	26.7		35.9			99.7	70.6
	38.6	24.4		36.9			99.9	72.9
	37.5	25.6		37.4			100.6	72.3
Average	37.8	25.6		36.7			100.1	71.9
Average	37.7	26.0		36.1			99.8	71.2

APPENDIX 8 Eruption April 27th 1977.
Plagioclase compositions.

	SiO_2	Al_2O_3	FeO^t	CaO	Na_2O	K_2O	Total	An
Microphenocrysts								
	51.2	31.0	0.82	15.0	2.89	0.06	101.0	73.9
	51.1	30.8	0.56	15.3	3.06	0.05	100.9	73.3
	50.0	30.4	0.81	15.3	3.12	0.07	99.7	72.8
	50.6	30.3	0.85	14.1	3.10	0.05	99.0	71.3
	50.3	30.4	0.74	14.9	3.16	0.05	99.6	72.0
	49.6	30.3	0.89	14.6	3.18	0.07	98.6	71.5
	49.3	31.2	0.65	14.7	3.10	0.07	99.1	72.1
Average	50.3	30.6	0.76	14.8	3.09	0.06	99.6	72.4
Glomerocrysts								
Core	49.0	31.5	0.73	15.5	2.72	0.03	99.5	75.9
	47.3	32.8	0.79	16.7	1.93	0.05	99.6	82.8
	49.1	31.4	0.74	15.7	2.71	0.02	99.6	76.2
	46.5	32.6	0.76	16.6	2.24	0.05	98.7	80.2
	48.2	32.3	0.88	16.4	2.41	0.02	100.2	78.9
	40.0	31.5	0.74	15.3	2.95	0.04	99.5	73.9
Rim	49.1	31.8	0.63	15.7	2.54	0.05	99.8	77.3
	47.3	31.8	0.80	15.4	2.71	0.06	98.0	75.9

APPENDIX 9

Eruption September 8th 1977. Main lava.
Plagioclase composition.

	SiO_2	Al_2O_3	FeO^t	CaO	Na_2O	K_2O	Total	An
Microphenocrysts								
KRA 725	50.2	31.5	0.62	14.4	2.89	0.12	99.7	72.8
	50.2	30.0	1.17	14.1	3.11	0.07	98.7	71.2
	50.4	30.5	0.98	13.9	3.28	0.04	99.1	69.9
	50.2	30.5	0.87	14.5	3.01	0.04	99.0	72.4
	50.3	31.0	0.76	14.4	3.10	0.06	99.5	71.7
	49.8	30.8	0.86	14.9	3.13	0.09	99.5	72.1
	49.1	31.4	0.84	14.7	3.00	0.05	99.1	72.8
Average	50.0	30.8	0.87	14.4	3.07	0.06	99.2	71.8

APPENDIX 10 Eruption September 8th 1977. Plagioclase compositions of lava samples of "mixed composition"

	SiO_2	Al_2O_3	FeO^t	CaO	Na_2O	K_2O	Total	An
KRA 732 glomerocrysts								
Core	48.8	32.4	0.67	15.6	2.29	0.05	99.8	78.8
Rim	53.4	28.6	0.98	13.1	3.85	0.07	99.9	65.0
Core	49.2	31.6	0.74	16.1	2.43	0.03	100.0	78.4
	49.1	31.2	0.83	16.2	2.41	0.06	99.9	78.5
	51.6	29.9	0.72	14.4	3.20	0.05	99.9	71.0
	49.7	31.3	0.86	15.7	2.33	0.06	100.0	78.6
	52.2	29.0	0.82	14.5	3.12	0.07	99.6	71.6
Rim	50.8	29.6	0.85	15.4	2.75	0.04	99.4	75.3
	51.1	29.2	0.77	13.8	3.44	0.08	99.3	68.7
	52.3	29.7	0.84	14.2	3.30	0.03	100.4	70.3
Core	49.8	30.9	0.77	15.4	2.44	0.06	99.4	77.4
	48.8	31.5	0.70	15.9	22.5	0.02	99.6	79.5
	51.9	29.4	0.76	13.6	3.52	0.12	99.3	67.6
	50.1	29.7	0.76	14.8	2.86	0.06	98.2	73.8
Rim	50.8	30.1	0.77	14.5	2.83	0.07	99.1	73.6
Core	48.1	32.2	0.55	16.6	1.88	0.02	99.4	83.0
	48.2	32.1	0.54	16.6	1.87	0.06	99.3	82.7
	48.4	32.5	0.56	17.0	1.75	0.02	100.2	84.2
	47.6	33.2	0.55	17.2	1.44	0.02	100.1	86.8
Core	50.3	31.1	0.73	15.4	2.62	0.04	100.2	76.3
	49.9	31.8	0.70	15.9	2.38	0.04	100.8	78.6
	50.1	30.7	0.78	15.1	2.64	0.06	99.4	75.8
	50.4	31.3	0.80	15.1	2.68	0.06	100.4	75.5
Rim	49.8	31.9	0.80	15.5	2.42	0.07	100.5	77.7
	50.9	30.9	0.81	14.7	2.92	0.06	100.4	73.1
Core	49.4	32.1	0.76	15.4	2.42	0.04	100.0	77.6
	49.6	32.2	0.72	15.5	2.28	0.03	100.4	78.8
	51.6	31.0	0.71	14.1	3.26	0.04	100.7	70.4

APPENDIX 10 (continued)

	SiO_2	Al_2O_3	FeO^t	CaO	Na_2O	K_2O	Total	An
KRA 732 glomerocrysts (cont.)								
Core	49.1	31.7	0.68	15.7	2.22	0.03	99.5	79.5
	50.0	32.2	0.72	16.2	2.18	0.07	101.4	80.0
	50.5	31.7	0.76	15.4	2.44	0.05	100.6	77.3
Core	50.1	31.9	0.85	15.4	2.37	0.02	100.6	78.2
	51.2	30.8	0.86	14.7	2.88	0.07	100.4	73.5
KRA 732 microphenocrysts								
	54.4	29.1	0.95	12.9	3.89	0.10	101.3	64.2
	53.1	29.4	0.94	12.7	3.90	0.06	100.0	64.0
	53.7	29.9	0.85	13.2	3.77	0.05	101.5	65.8
	52.9	27.6	1.61	12.6	3.70	0.11	98.5	64.8
	52.3	29.7	0.91	13.1	3.67	0.11	99.8	65.9
	50.8	31.0	0.71	14.4	2.93	0.04	99.8	72.8
	52.9	29.8	0.99	13.3	3.56	0.06	100.6	67.1
	51.8	30.4	0.87	14.1	3.20	0.04	100.4	70.7
KRA 733 microphenocrysts								
	52.3	30.0	0.91	14.5	3.36	0.08	101.0	70.1
	52.1	29.5	1.05	13.9	3.47	0.07	100.2	68.6
	52.7	29.7	1.08	13.3	3.55	0.04	100.4	67.3
	51.4	30.8	1.01	14.6	3.09	0.03	100.9	72.1
	50.6	30.0	0.97	13.5	3.42	0.05	98.5	68.4
	51.0	30.3	0.87	13.8	3.39	0.05	99.4	69.0
	51.3	29.2	1.62	13.9	3.38	0.06	99.6	69.2
	51.0	30.2	1.05	14.1	3.51	0.06	99.9	68.6
	50.0	31.1	0.81	15.0	2.94	0.05	99.9	73.6
	51.8	29.8	1.15	13.9	3.53	0.06	100.1	68.2
	50.5	30.3	1.16	14.0	3.28	0.06	99.3	69.9
	51.8	29.5	0.87	13.6	3.64	0.06	99.5	67.2

APPENDIX 10 (continued)

	SiO_2	Al_2O_3	FeO^t	CaO	Na_2O	K_2O	Total	An
KRA 733 microphenocrysts (cont.)								
	52.2	29.8	1.52	13.8	3.46	0.03	100.8	68.6
	52.8	30.1	0.75	13.4	3.43	0.07	100.6	68.1
	52.1	30.6	1.07	14.2	3.09	0.06	101.1	71.4
	52.0	30.0	1.06	14.0	3.42	0.03	100.5	69.2
	49.8	30.4	0.76	13.6	3.37	0.09	98.1	68.8
	50.1	30.4	0.92	14.2	3.22	0.06	98.9	70.6
	50.7	30.1	1.16	13.6	3.62	0.05	99.2	67.2
	50.2	30.5	0.72	13.9	3.34	0.08	98.7	69.3
	50.6	30.4	0.93	13.6	3.51	0.08	99.1	67.9
	50.6	30.2	0.92	13.7	3.55	0.07	99.1	67.8
	50.8	30.4	0.83	14.0	3.41	0.06	99.5	69.1
	50.7	30.8	0.83	14.2	3.36	0.09	100.0	69.7

APPENDIX 11 Borehole eruption September 8th 1977.
Plagioclase compositions.

	SiO_2	Al_2O_3	FeO^t	CaO	Na_2O	K_2O	Total	An
1071 microphenocrysts								
	53.5	29.2	1.18	13.1	4.00	0.08	101.0	64.2
	53.9	28.3	1.19	12.6	4.26	0.12	100.5	61.6
	52.0	29.2	1.12	13.4	4.06	0.07	100.8	64.4
	53.0	29.2	1.20	13.4	3.78	0.08	100.7	65.8
	52.6	29.2	1.25	13.4	3.95	0.07	100.5	65.1
	52.5	29.0	1.26	13.1	4.12	0.12	100.1	63.2
Average	52.9	29.0	1.20	13.2	4.03	0.09	100.4	64.1

APPENDIX 12

Eruption December 20th 1975. Plagioclase compositions.

	SiO_2	Al_2O_3	FeO^t	CaO	Na_2O	K_2O	Total	An
Glomerocrysts								
NAM 504	47.5	33.2	0.72	16.7	1.96	0.05	100.6	82.2
	49.6	32.7	0.85	16.3	2.25	0.04	101.9	79.8
	48.2	31.9	0.86	16.4	2.24	0.07	99.7	79.9
NAM 518	47.3	33.0	0.87	15.5	2.35	0.06	99.3	78.2
	49.1	32.3	0.75	14.9	2.63	0.08	99.8	75.4
	49.6	31.8	0.86	15.4	2.62	0.08	100.5	76.1
	49.2	31.5	0.79	14.5	2.58	0.05	99.8	75.4
Microphenocrysts								
KRA 504	50.3	31.1	0.85	14.6	3.06	0.02	99.9	72.4
	49.5	31.4	0.73	14.9	2.98	0.08	99.6	73.1
	50.5	31.6	0.85	15.6	2.75	0.01	101.2	75.7
Average	50.1	31.4	0.81	15.0	2.93	0.04	100.3	73.7
KRA 507	49.2	31.6	0.80	15.7	2.50	0.07	99.9	77.3
	49.1	31.0	0.67	15.1	2.57	0.06	98.6	76.3
	49.0	30.6	0.79	15.0	2.78	0.06	98.3	74.6
Average	49.1	31.1	0.75	15.3	2.62	0.06	98.9	76.1
Average	49.6	31.3	0.78	15.2	2.78	0.05	99.7	74.9