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HYDROTHERMAL ALTERATION OF BASALTIC ROCKS IN ICELANDIC
GEOTHERMAL AREAS

Hrefna Kristmannsdóttir, National Energy Authority,
Reykjavík, Iceland.

ABSTRACT

The results obtained by mineralogical investigations of basaltic rocks from deep drilling in several Icelandic geothermal areas are summarized.

Progressive alteration of basaltic rocks in high-temperature geothermal areas leads to the formation of three main alteration zones as expressed by the characteristic minerals: Smectite-zeolite zone, mixed-layer clay minerals prehnite zone and chlorite-epidote zone. The beginning of a fourth zone might be marked by the appearance of amphibole at the highest temperatures. The highest temperature measured in the areas is 298°C and the deepest drillholes are 1800 m.

The temperature range in the low-temperature geothermal areas (<150°C in uppermost 1 km) is well within that of the uppermost alteration zone of the high-temperature geothermal areas. In most low-temperature areas there are three or four distinct zeolite zones; in order of increasing temperature: The chabazite, (mesolite), stilbite and laumontite zones.

Examples are given of both high- and low-temperature areas where the alteration is assumed to be nearly in equilibrium at the prevailing temperatures, and where retrograde alteration of various degree is found.

INTRODUCTION

The rock-cuttings obtained by deep drilling in the geothermal areas are always studied to make the stratigraphic section of the rocks drilled into and to study the degree and kind of alteration.

A detailed mineralogical investigation of the altered underground rocks has been performed in some of the low-temperature areas (Sigvaldason 1963, Tómasson and Kristmannsdóttir 1974) and in several of the high-temperature areas (Tómasson and Kristmannsdóttir 1972, Gíslason 1973, Kristmannsdóttir and Tómasson 1974, Kristmannsdóttir and Tómasson 1975, Kristmannsdóttir unpubl. results from Krafla). The aim of this paper is to summarize the results of these studies. The structure of the geothermal areas and their relation to the geology of Iceland has been reviewed recently (Pálmason 1974). Recent papers (e.g. Arnórsson 1974) have dealt with the chemistry of geothermal waters in Iceland.

The altered rocks in all geothermal areas sofar investigated are almost exclusively basaltic hyaloclastites and lavas, sometimes intruded by basaltic dykes. Areas with some acid rocks are also known, but mineralogical investigation of the underground rocks has not been done sofar. Significant for the hydrothermal alteration is its patchy nature, i.e. certain zones are heavily altered whereas nearby horizons are very slightly altered. This is partly due to the different permeability of the rocks and is more a difference in quantity than type of the alteration. In a slightly altered basalt the same alteration mineral groups are found as in a heavily altered hyaloclastite at similar depths and rock temperatures. The basaltic glass is also highly predisposed to alteration and recrystallization. Even at the highest temperatures obtained (300°C), the basalts can appear rather unaffected. Olivine is the most easily altered of the minerals in the basalts and the plagioclase is the most resistant. The temperature is assumed to be the most important

factor controlling progressive alteration as it proceeds in a very similar way in areas with meteoric thermal water and in areas with seawater thermal brine. Another interesting fact in this connection is that the chemical composition of the rocks shows little significant variation by depth (fig. 1a and b and table 1) despite of markant changes in the mineralogy.

HIGH-TEMPERATURE GEOTHERMAL AREAS

All the high-temperature geothermal areas occur within the active volcanic zones in Iceland and many of them are seen to be connected to major volcanic centers (e.g. Pálmason and Samundsson 1974). The highest rock temperatures reached in the uppermost 2000 m drilled into are nearly 300°C.

By studies of several high-temperature areas the general scheme of alteration shown in figure 2 has been obtained. Figure 3 shows a section through a drillhole in Krafla, where the highest temperature measured sofar in an icelandic drillhole is found, nearly 300°C (298 ± 4) at 1100 m depth.

The indicated temperatures are obtained by a comparison of estimated rock temperatures and alteration minerals occurring in the areas, and are therefore not to be taken strictly as the equilibrium temperatures for the formation or disappearance of the relevant minerals. For most of the minerals an exact composition is not known and calculations of stability relations are impossible. The alteration occurring is, as mentioned in the introduction, supposed to be mainly temperature dependant. Chemical analyses of basalts from different depth levels do not indicate any systematic changes with depth of the main elements (fig. 1a, b and table 1).

A strong enrichment of potassium is however found in the upper levels of the upflow zone in the Reykjanes thermal area (Björnsson et al. 1970). In a drillhole near the border of the area no or at least very slight enrichment of K₂O is found (Kristmannsdóttir 1971).

The Nesjavellir field is known to be on the borders of a larger geothermal area and neither in analyses of basalts from that area nor in the analysed basalts from Krafla this effect was found. The sharp changes in mineralogy of the rocks are not reflected by significant changes in the bulk chemistry. No systematic changes by the depth are found in the altered rocks compared to fresh basalts from the areas (e.g. 6 in table 1). Hydration, oxidation and in a few samples some enrichment of SiO_2 are the main chemical changes by the alteration process. The altered hyaloclastic rocks are more hydrated than the basalts, but have otherwise a composition similar to the basalts (table 2).

The degree of alteration is variable from one geothermal field to another and the temperatures at which certain alteration minerals appear also vary. By comparison of all the geothermal areas and by comparison with other data from the areas a few maximum and minimum temperatures for forming and disappearance of certain minerals have been obtained.

Smectite is the dominant clay mineral at temperatures below 200°C . Where smectites occur at temperature above 200°C they have started to be transformed to chlorite, and mixed-layer clay minerals of smectite and chlorite occur together with them.

Chlorite is the dominant sheet silicate at temperatures above 230°C . At 260°C all other clay minerals have normally disappeared. The zeolites disappear at temperatures below 250°C . Epidote is found continuously at temperatures above 260°C . Amphibole has only been found in one area at temperatures above 280°C . Temperatures exceeding 280°C have been measured in the other areas too, but the maximum temperatures reached are lower there.

The zeolites most commonly found in the high temperature areas are mordenite, heulandite, laumontite, analcime and wairakite. Also found are stilbite, philipsite, epistilbite and gmelinite. Distinct zoning in the appearance of the zeolite species is rarely found due to the sharply rising temperature gradients below 200°C and the

common changes in the upper levels of the areas. In drillholes where the rock temperature appear to rise gradually and undisturbed in the upper strata a common sequence in zeolite appearance is heulandite, mordenite, laumontite. Analcime and/or wairakite are found scattered throughout the zeolite zone and far below it and at much higher temperatures than the other zeolites. The clay minerals formed have been described in recent publications (Kristmannsdóttir and Tómasson 1974, Kristmannsdóttir 1975). The smectites are iron-rich saponites which are gradually transformed to chlorites. Mixed-layer minerals of different types and "swelling chlorites" are intermediate stages in this transformation. All the clay minerals are poorly and irregularly crystallized.

In the Krafla geothermal area the alteration is assumed to be nearly in equilibrium at the prevailing temperatures. Effects of contact metamorphism due to intrusions known to have occurred in the area are, however, considered responsible for some of the alteration phenomena observed (e.g. the parawollastonite). In the Nesjavellir area (Kristmannsdóttir and Tómasson 1974) the alteration is of a much lower degree than the prevailing temperatures would suggest, and fresh glass is found down to 450 m depth at rock temperatures of nearly 200°C. Recent migration of the thermal activity is clearly the cause of this. At greater depth (1600 m) in this area, smectite is found in a rather fresh dolerite intruding the basalt lavas. The rock temperatures there exceed 260°C and the smectite occurs below a zone dominated by chlorite. This is mainly due to the lower permeability in the intrusives. Thin basalt horizons between the dolerite intrusions are more heavily altered.

LOW-TEMPERATURE GEOTHERMAL AREAS

The low-temperature geothermal areas occur in Quaternary rocks on the borders flanking the active volcanic zones and also in Tertiary formations. The definition of a low-temperature area is that the maximum temperature does not exceed 150°C at 1000 m depth. The hydrothermal alteration in this temperature range is well within that of the smectite-zeolite zone of the high-temperature geothermal areas.

In fig. 4 are summarized results of mineralogical investigation of mainly the Reykir and Reykjavík geothermal areas (Tómasson and Kristmannsdóttir 1974), but comparison to other known areas shows closely similar results (unpublished data). In the areas studied tholeiitic basalt lavas and hyaloclastites are the dominant rocks.

As seen in the figure there have been distinguished four alteration zones according to the dominant zeolites. Chabazite is dominant in the coolest and least altered strata. Opal, calcite and sometimes levyne are also found in this zone. Mesolite/scolecite commonly form a separate zone beneath, but it sometimes intermingles with the third zone shown in the figure, the stilbite dominated zone. The fourth zone is always clearly developed and reaches to the highest temperatures obtained in the areas. Laumontite is dominant in this zone. Stilbite is found sporadically in the uppermost parts and analcime can be found throughout the zone. Quartz appears on the margins of the third zone and is continuously found in the fourth zone.

^uRetrograde alteration from high to low temperature minerals is extremely sluggish. Where formerly high grade metamorphism has been active the results can overshadow the alteration due to recent low temperature hydrothermal alteration. The resultant mineralogy can in such areas be very complicated and signs of regular mineral zones can be difficult to see.

Chlorite and smectite are sometimes found together through most of a 2000 m deep drillhole (e.g. some of the Reykir drillholes) and can either be accompanied by mixed-layer minerals or not. Careful examination of the chlorite (Kristmannsdóttir unpubl.) have in many cases shown the initiation of a retro^ugrade alteration. In other areas a zoning similar to that of the high-temperature areas is found.

In such areas the smectite zone is often rather thin and irregular. In other areas the clay mineral zones appear fairly regularly with chlorite as the dominant sheet silicate from approximately 125°C. Also here signs of retrograde alteration are commonly shown by the chlorite. The zeolite zones are often superimposed on the clay mineral zones and are thought to have been adjusted to the prevailing conditions. Epidote is found at very varying depths and rock temperatures and is always thought to be relict.

DISCUSSION

From the available data of mineralogical investigation of rocks from geothermal areas preliminary alteration schemes have been proposed. These schemes are based on the assumption that temperature, depth, permeability and age of the geothermal systems are the main controlling factors of the alteration and the schemes are valid only for basaltic rocks. As seen from the data presented the alteration found in rocks from low-temperature areas is of a very complicated origin. Regular zoning in terms of dominant alteration minerals is found for the zeolites and approximate temperature ranges can be fixed. For the other alteration minerals the picture is more diffuse. In some cases the appearance of minerals belonging to high-temperature alteration zones of the high-temperature areas can be explained as relics from former high-temperature effects as e.g. contact metamorphism from central volcanoes (Reykir, Reykjavík). In other cases this explanation lacks any strong support. A detailed comparison of the type and the composition of those minerals to the same mineral types from the high-temperature areas is needed to solve this problem. Much more data has been obtained from the high-temperature areas and the mineral zones and rock temperatures within them are considered to be better established. Results from geothermal areas elsewhere (Muffler, L.J.P., and White, D.E., 1969, Seki 1969, Miyashiro, A., 1973) shows the same main trends. Due to the commonly quite different composition of the original rocks some of the alteration mineral types formed in the Icelandic areas are rather unique.

TABLE 1

Chemical analyses of basalts in drill cuttings from different depths in drillhole 5 on Nesjavellir. 1 is from 368 m, 2 from 596 m, 3 from 758 m, 4 from 1378 m and 5 from 1784 m. For comparison is also shown (6) an analyse of a recent lava from the area (K. Grönvold pers. comm.). The samples were selected from slightly plagioclase-phyric fine grained tholeiite lavas (with the exception of sample 5, which is thought to be a dyke) from various depths.

TABLE 2

Chemical analyses of basalts and hyaloclastites in drill cuttings from drillholes in the Reykjanes high-temperature area.

- 1) is of a basalt lava from 1300 m depth in drillhole 8.
- 2) is of a basaltic hyaloclastite from 306 m depth in drillhole 8.
- 3) is of basaltic fragments in a hyaloclastic breccia from 466 m depth in drillhole 3.
- 4) is of a glassy matrix in the same breccia as 3.

FIGURE CAPTIONS

- 1) Changes in the chemical composition with depth of hydrothermally altered basalts from two of the high-temperature areas.
 - 1a) Analyses of basalts from Krafla.
 - 1b) Analyses of basalts from Nesjavellir.
- 2) A simplified scheme showing the alteration zones appearing in the high-temperature areas and the distribution of main alteration minerals within the zones. The rock temperature at the zone borders are also indicated.
- 3) The figure shows the distribution of alteration minerals in a 1204 m deep drillhole in the Krafla high-temperature geothermal area. Also shown is a simplified geologic section and estimated rock temperatures.
- 4) The figure shows the zeolite zones found in the Reykjavík and Reykir low-temperature areas and the occurrence of other alteration minerals. The rock temperatures bordering the zones are approximate.

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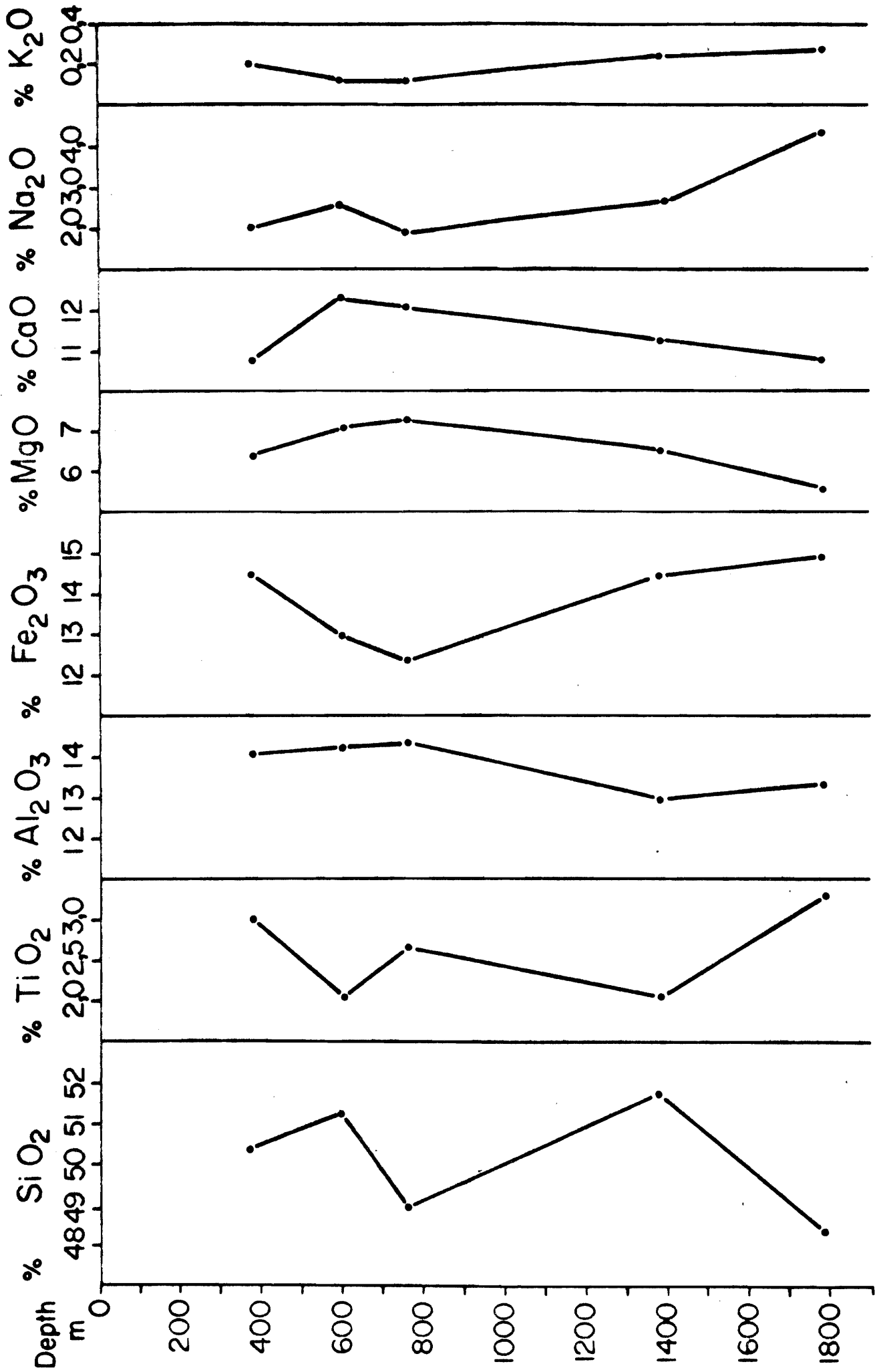
TABLE 1

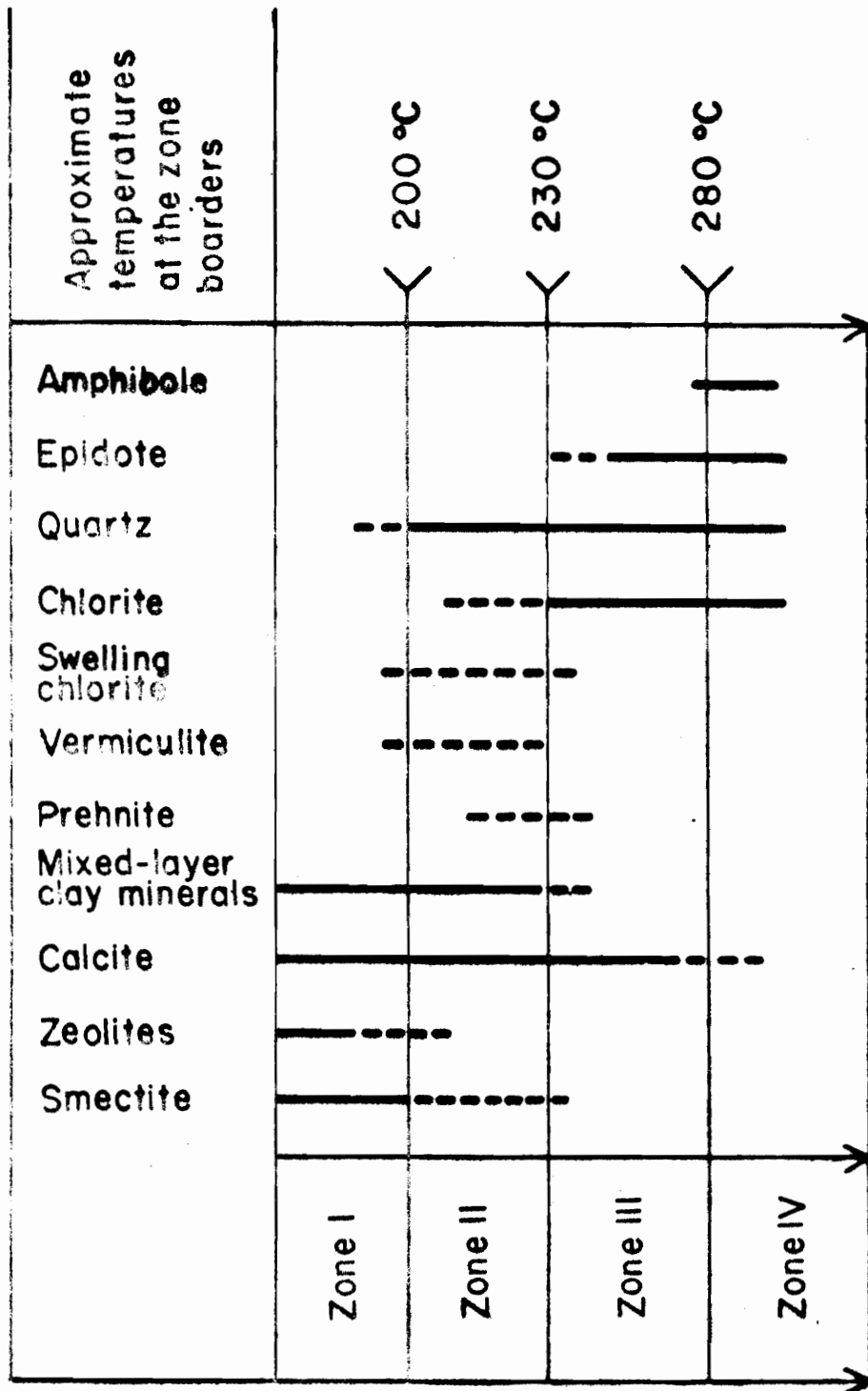
	1	2	3	4	5	6
SiO ₂	50,33	51,21	48,94	51,73	48,36	49,6
TiO ₂	3,00	2,02	2,72	2,01	3,27	1,4
Al ₂ O ₃	14,05	14,20	14,29	12,92	13,26	14,2
Fe ₂ O ₃	14,43	12,96	12,34	14,42	14,83	13,0
MgO	6,40	7,08	7,27	6,50	5,52	6,90
CaO	10,73	12,30	12,06	11,23	10,79	12,90
Na ₂ O	2,05	2,59	1,94	2,71	4,31	2,2
K ₂ O	0,20	0,12	0,12	0,24	0,26	0,23
	101,24	102,48	99,38	101,76	100,60	100,43

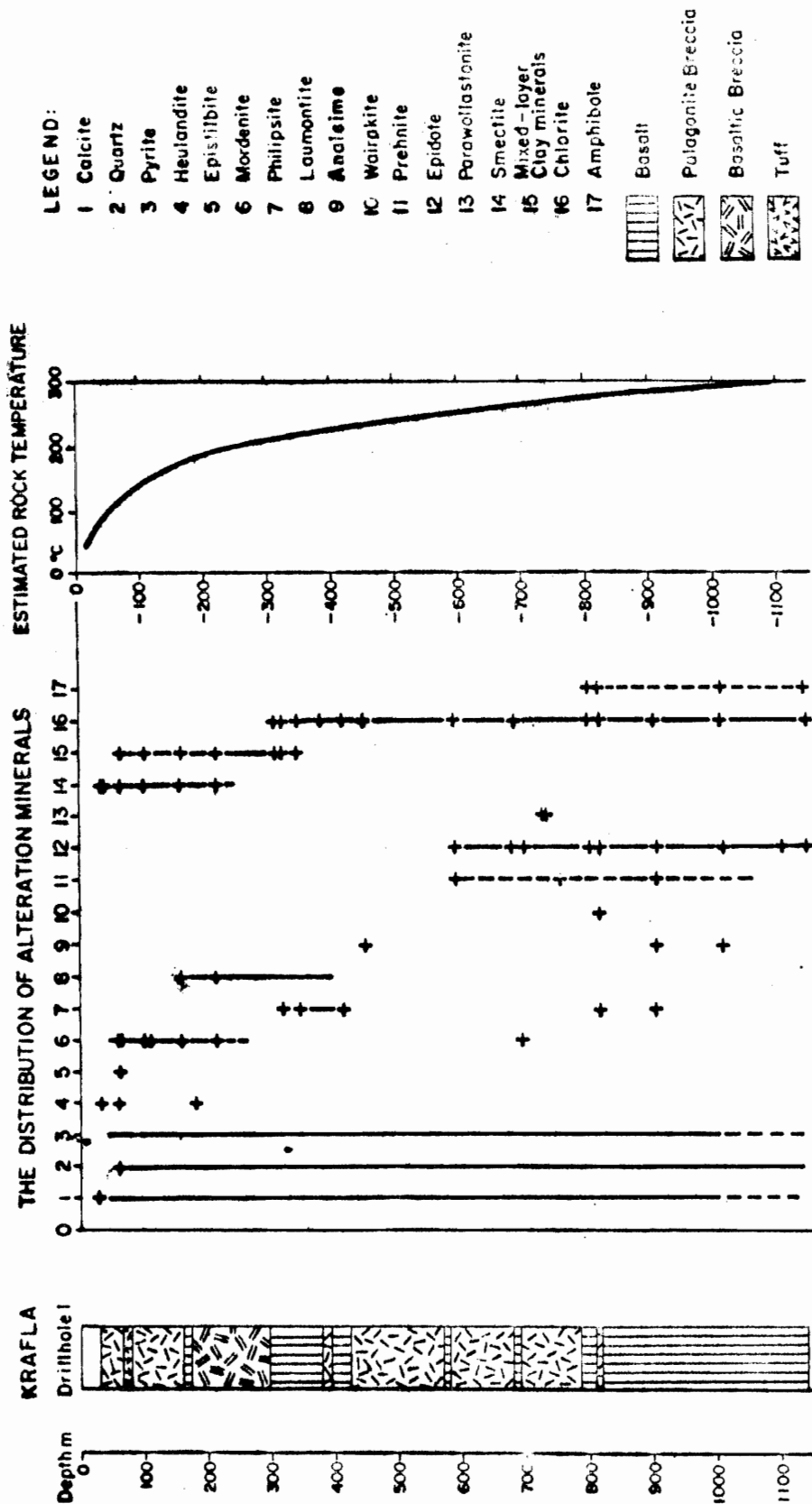
TABLE 2

	1	2	3	4
SiO ₂	48,91	46,78	46,79	43,71
TiO ₂	1,55	0,50	2,50	1,48
Al ₂ O ₃	11,83	13,01	11,18	10,59
Fe ₂ O ₃	11,85	8,03	13,99	11,69
MgO	8,06	7,80	8,35	7,44
CaO	12,85	9,85	9,76	8,36
Na ₂ O	2,05	2,88	2,86	2,22
K ₂ O	0,11	0,47	0,34	1,13
ignition loss	1,65	9,29	2,91	10,89
	98,86	99,23	98,68	97,51

Fig. 1







ORKUSTOFNUN
 KRAFLA
 Dreifing myndbreytingar stinda
 með dýpi
 16.9.75 MK/ER (nr. 16) Tr. 57 Fnr. 12802
 P. Jónsson, J. K. K.

Fig. 3



Fig. 4

