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Hydrothermal Alteration of Basaltic Rocks in Icelandic Geothermal Areas

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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 drill holes are 1800 m.

The temperature range in the *low-temperature* geothermal areas (<150°C in the 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 degrees is found.

INTRODUCTION

The rock cuttings obtained by deep drilling in the geothermal areas are always studied in order to develop the stratigraphic section of 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, 1962; Tómasson and Kristmannsdóttir, 1974) and in several of the high-temperature areas (Tómasson and Kristmannsdóttir, 1972; Gíslason, 1973; Kristmannsdóttir and Tómasson, 1975; Kristmannsdóttir, unpubl. results from Krafla). The aim of this paper is to summarize the results of these works. The structure of the geothermal areas and their relation to the geology of Iceland has been recently reviewed (Pálmason, 1974). Recent papers (for example, Arnórsson, 1974) have dealt with the chemistry of geothermal waters in Iceland.

The altered rocks in all geothermal areas so far investigated are almost exclusively basaltic hyaloclastites and basalt lavas, sometimes intruded by basaltic dikes. Areas with some acid rocks are also known, but mineralogical investigation of the underground rocks has so far not been done. Significant for the hydrothermal alteration is its patchy nature, for example, 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 rather than type of alteration. In a slightly altered basalt the same alteration mineral groups are found as in a heavily altered hyaloclastite at similar depth and rock temperature. 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. Of the minerals in the basalts, olivine is most easily altered and the plagioclase is the most resistant. The temperature is assumed to be the most important factor controlling progressive alteration as it proceeds very similarly in areas with meteoric thermal water and in areas with thermal brine. Another interesting fact in this connection is that the chemical composition of the rocks shows only slight changes by depth (Figs. 1 and 2, and Table 1) despite marked changes in mineralogy.

HIGH-TEMPERATURE GEOTHERMAL AREAS

The high-temperature geothermal areas all occur within the active volcanic zones in Iceland and many of them are seen to be connected to main volcanic centers (for example, Pálmason and Sæmundsson, 1974). The highest rock temperatures reached in the uppermost 2000 m of drilling are nearly 300°C.

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

The indicated temperatures are obtained by comparison of estimated rock temperatures and alteration minerals occurring in the areas and are 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. As mentioned in the introduction, the alteration occurring is supposed to be mainly temperature (and depth) dependent. Chemical analyses of basalts from different depth levels do not indicate any systematic changes by depth of the main elements (Figs. 1 and 2; Table 1).

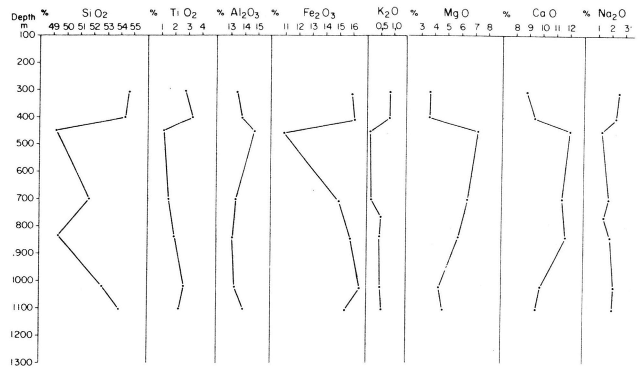

Figure 1. Changes in chemical composition with depth of hydrothermally altered basalts from the Krafla high-temperature area.

Table 1. Chemical analysis of basalts from different depths in Drill Hole No. 5 on Nesjavellir.

Constituents	368 m	596 m	758 m	1378 m	1784 m	Note
	Drill-hole depth					
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_2O_3	14.05	14.20	14.29	12.92	13.26	14.2
Fe_2O_3	14.48	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_2O	2.05	2.59	1.94	2.71	4.31	2.2
K_2O	0.20	0.12	0.12	0.24	0.26	0.23
	101.24	102.48	99.68	101.76	100.60	100.43

Note: The sixth column shows an analysis of a recent lava from the area.

However, a strong enrichment of potassium is found in the upper levels of the upflow zone in the Reykjanes area (Björnsson, et al, 1970). In a drill hole near the border of the area no, or at least very slight, enrichment of K_2O is found (Kristmannsdóttir, 1971). The Nesjavellir area is known to be on the borders of a bigger area and neither there nor in the analyzed basalts from Krafla was this effect found. The sharp changes in mineralogy of the rocks are thus not reflected by marked changes in chemistry. Compared to fresh basalts from the areas (for example, column 6 in Table 1) the major changes found in the altered rocks are hydration and oxidation and in a few samples some enrichment of SiO_2. The altered hyaloclastic rocks are more hydrated than the basalts, but otherwise have a composition similar to the basalts (Table 2).

In the different areas the degree of alteration varies a great deal and the temperatures at which certain alteration minerals appear also varies. Through comparison with data from all the areas, a few maximun and minimum temperatures for the formation and disappearance of certain minerals have been obtained.

Chlorite is very seldom the dominant sheet silicate in the high-temperature areas at temperatures below 230°C. In the few observed cases signs of retrograde alteration have been found in the minerals. Where smectites occur at temperatures above 200°C they have started to be transformed into chlorite, and mixed-layer minerals occur together with them. 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, phillipsite, epistilbite, and gmelinite. Any distinct zoning by the appearance of the zeolite species is rarely found due to the sharply rising temperature gradients below 200°C and the common changes

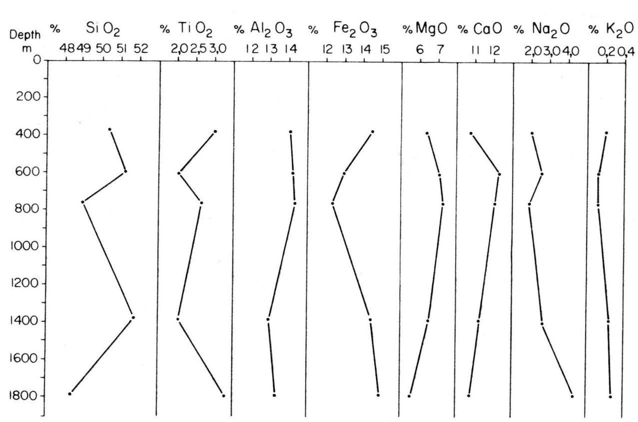

Figure 2. Changes in chemical composition with depth of hydrothermally altered basalts from the Nesjavellir high-temperature area.

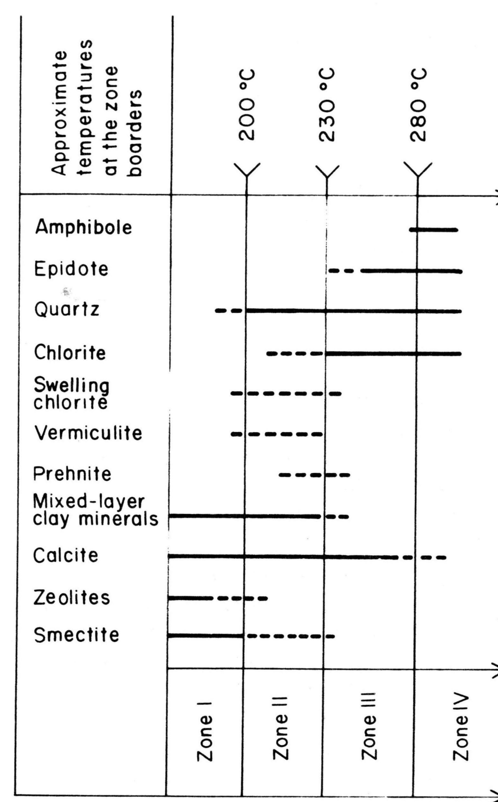

Figure 3. A simplified scheme showing alteration zones appearing in high-temperature areas and the distribution of main alteration minerals within the zones. Rock temperatures at zone borders are also indicated.

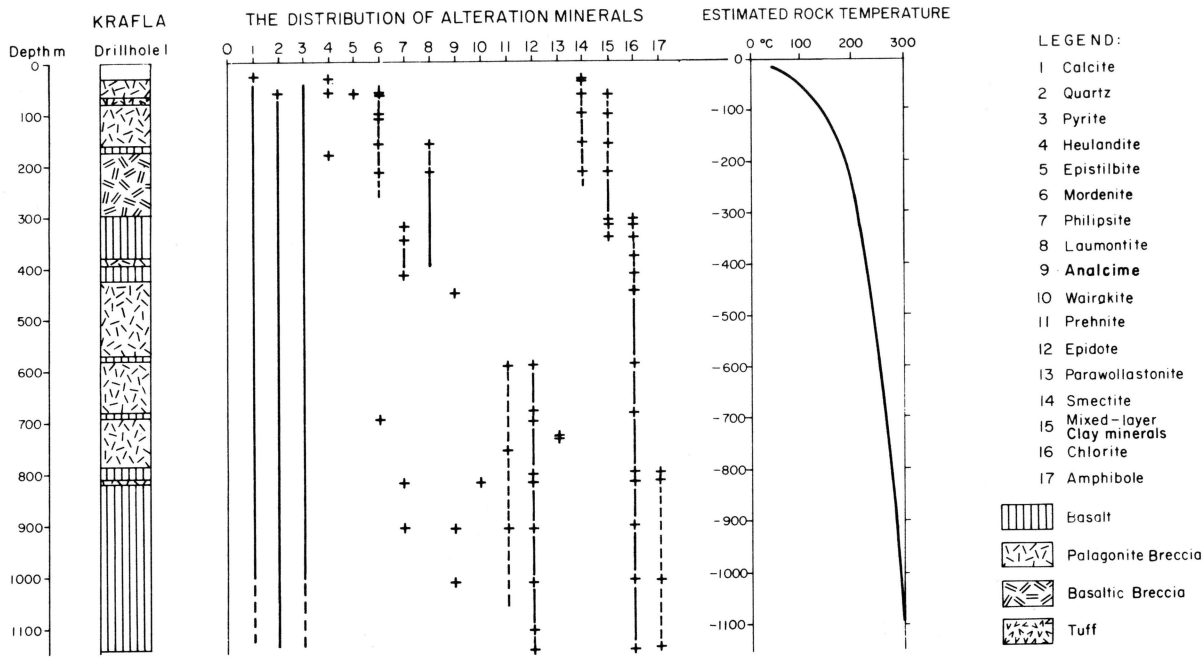

Figure 4. Distribution of alteration minerals with depth in a drill hole (maximum depth 1204 m) in the Krafla area, with a simplified geologic section and estimated rock temperatures.

in the upper levels of the areas. In drill holes where the rock temperature appears 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 a recent publication (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 interstages 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 considered responsible for some of the alteration phenomena observed (for example, the parawollastonite). In the Nesjavellir area (Kristmannsdóttir and Tómasson, 1974) alteration is much less than prevailing temperatures would suggest, and fresh glass is found down to 450 m at rock temperatures of nearly 200°C. Recent migration of the area is clearly the cause of this. At greater depth (1600 m) in this area, smectite is found in rather fresh dolerite intruding basalt. The rock temperatures there exceed 260°C and the smectite occurs below a zone dominated by chlorite. This is mainly due to less permeability in the intrusives. Thin basalt horizons between the dolerite are more heavily altered.

Table 2. Chemical analyses of basalts and hyaloclastites from drill holes in the Reykjanes high temperature area.

	Samples (see notes)			
Constituents	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_2O_3	11.83	13.01	11.18	10.59
Fe_2O_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_2O	2.05	2.88	2.86	2.22
K_2O	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

Notes: (1) basalt, depth 1300 m, drill hole No. 8; (2) basaltic hyaloclastite, depth 306 m, drill hole 8; (3) basaltic fragments in palagonite breccia, depth 466 m, drill hole 3; (4) glassy matrix in the same breccia as (3).

LOW-TEMPERATURE GEOTHERMAL AREAS

The low-temperature 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 alteration due to hydrothermal action in this temperature range is well within that of the smectite-zeolite zone of the high-temperature geothermal areas.

In Figure 5 results of mineralogical investigation are summarized, mainly of the Reykir and Reykjavík geothermal areas (Tómasson and Kristmannsdóttir, 1974), but comparison to other known areas shows closely similar results (unpub. results). In the areas studied, tholeiitic basalts and hyaloclastites are the dominant rocks.

As seen from Figure 5, four alteration zones have been distinguished after the dominant zeolites. Chabazite is dominant in the coolest and least altered strata. Opal and 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

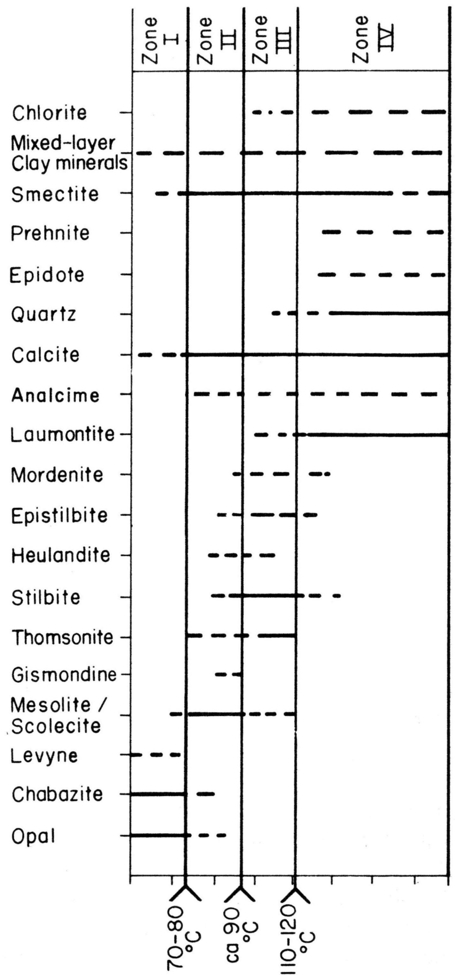

Figure 5. Zeolite zones found in the Reykjavík and Reykir low-temperature areas and the occurrence of other alteration minerals. The rock temperatures of the zone borders are very approximate in this figure.

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.

Retrograde 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 some smectite are sometimes found together through most of a 2000 m deep drill hole (for example, some of the Reykir drill holes) and can either be accompanied by mixed-layer minerals or not. Careful examination of the chlorite (Kristmannsdóttir, unpub. data) have in many cases shown a beginning retrograde 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 others the clay mineral zones appear fairly regularly, with chlorite dominant from approximately 125°C. Also, signs of retrograde alteration are commonly shown here 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 highly 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. Those schemes are based on the assumption that temperature, depth, permeability, and age of the geothermal system are the main controlling factors of the alteration and are valid only for basaltic rocks. As seen from the data presented, the alteration found in rocks from low-temperature areas is of 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, for example, contact metamorphism from central volcanoes (Reykir, Reykjavík). In other cases this explanation lacks any strong support. The 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 have been obtained from the high-temperature areas, and the mineral zones and rock temperatures within them are considered to be better established. Comparison with results from geothermal areas elsewhere (Muffler, and White, 1969; Seki, 1969; Miyashiro, 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.

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