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NESJAVELLIR

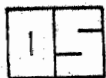
Hydrothermal alteration in
a high temperature area

Hrefna Kristmannsdóttir and Jens Tómasson

Prepared for the International Symposium
on Water-Rock Interaction
Prague september 1974

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ABSTRACT

The Nesjavellir high-temperature thermal area in south-west Iceland has been investigated for several years. The present paper gives results of the mineralogical investigations.

The area lies in an active volcanic area. North-east south-west going faults and fissures penetrate all the rock formations. Dominating rocks are hyaloclastics and basalts. The highest temperature reached is 284°C at 850 md. The geothermal water is low chlorine water. The degree and magnitude of alteration is much less than would be expected at so high temperatures. This indicate recent changes in the geothermal area.

NESJAVELLIR

Hydrothermal alteration in a high-temperature area

I. INTRODUCTION

Nesjavellir is situated in Hengill high-temperature geothermal area in South West Iceland (see fig. 1). The Hengill area is one of the biggest of 17 active high-temperature areas in Iceland, which are all situated within the active volcanic zones in Iceland (fig. 1). The Hengill area (Saemundsson, 1967) is divided into several subareas and one of them is the Nesjavellir area lying in the North Western part (fig. 2). The outline of Nesjavellir's surface geology is shown on fig. 2. The youngest rocks are postglacial lavas and Nesjahraun lava is only about 2000 years old. Subglacial rocks are dominant in the area and they form elongated ridges lying in the main tectonic direction. The area is very active tectonically with many faults and fissures going from North East to South West. Also the youngest rocks in the area are penetrated by faults and fissures. The thermal activity on the surface is shown on the map in fig. 2. Three of the drillholes 1, 2 and 4 are situated within the area of visible thermal activity. The two others, 3 and 5, are situated outside to the North East. From geophysical measurements we know that the border of the thermal area (to 1000 m depth) lies about 4 km north of drillhole 5. The temperature gradient is much steeper in the holes which are situated within the area of visible thermal activity. In drillhole 4 (fig. 3) a temperature of 255°C is reached at 400 m depth. At the same depth

in drillhole 3 the temperature is 165°C. In the deepest drillhole 5, the highest temperature is 284°C at a depth of 850 m, but beneath, the temperature decreases to between 250-270°C. The geothermal water has meteoric origin. It is alkaline (see table 1) with very low Cl⁻ and rather low total content of dissolved solids. The chloride content is as low as in the vapour dominated areas.

II. OUTLINE OF THE SUBSURFACE GEOLOGY

The geologic section through the drillholes in the uppermost 1000 m is shown in fig. 4. Beneath the uppermost 1-3 lavafloes the section down to 400-500 m is dominated by hyaloclastic breccias and tuffs. Beneath that depth in drillholes 3 and 5 basalts and tuffaceous sediments and hyaloclastites alternate in approximately equal amount to about 1450 m. In the interval 1450 to 1800 m depth dolerite dykes dominate the profile.

III. ALTERATION

There are three main factors controlling the degree of alteration in this area, the temperature, the rock type and the water circulation. The rock types have varying susceptibility to alteration, depending on the degree of crystallisation and mineral composition. The most easily altered rocks are the glassy breccias and tuffs, but in the drillholes, horizons with fresh glass are found down to 500 m. The glass becomes at first palagonitized (hydrated and oxidized) and, where heavily altered, replaced by clay minerals.

Olivine is the first mineral to alter, first to iddingsitic aggregates and later it is completely replaced by clay minerals. Pyroxene is also altered to clay minerals. This alteration is rarely completed. The plagioclase is nearly unaffected by alteration. The opaque minerals have not been investigated in detail.

In fig. 5 and 6 the types and distribution of secondary minerals are shown, together with simplified geologic sections and thermal gradients through the drillholes.

Zeolites are found down to at least 1000 m depth and to temperatures above 250°C. Analchime is found from the uppermost section down to the bottom of the zeolite zone. Heulandite is found at 100-500 m (100-200°C). Mordenite is found from 100-800 m and Laumontite at 300-900 m, mostly at 800-900 m. Traces of stilbite and wairakite are found in drillhole 5. Calcite is found above the zeolites and is concentrated alternatively with zeolites.

Silica minerals. Opal is one of the first secondary minerals to appear. The depth at which it is replaced by quartz seems to be dependent on the temperature gradient in the holes (see fig. 5-6). Quartz is then stable to the bottom of the holes.

Prehnite and epidote. Prehnite is found in drillhole 3 continuously below 700 m but in drillhole 5 it is found below 1200 m with epidote. Epidote is only found in the deepest drillhole No. 5 and occurs first at 1100 m in small amounts. Most of the dolerite in the deepest part of the hole is nearly unaltered but between the dykes there are thin horizons where epidote and other high temperature minerals are concentrated. Probably these horizons are thin layers of heavily altered basalts.

Other minerals. Pyrite is unevenly distributed and found in greatest concentration in the uppermost parts of the holes. Haematite is found with clay minerals in the glass and olivine pseudomorphs in the uppermost 100 m of the section. Gyrolite is found associated with zeolites, mainly at 250-600 m and also in one sample at 1500 m. Traces of reyerite are also found in a few samples.

Clay minerals. Smectite minerals dominate down to 800 m depth. Randomly mixed-layer minerals, mainly of chlorite-smectite and smectite-illite are found together with the smectites from about 150 m. Chlorite is found from 600 m and is dominant from 1000 m down to the dolerite at 1450-1500 m. In the dolerite zone smectite minerals become dominant again but in the heavily altered horizons chlorite is found.

In table 2 the main groups of clay minerals are shown and the results from x-ray methods, differential thermal analysis and infrared spectroscopy are compared.

The smectite minerals are identified as iron-rich saponite, which is the type of smectite found to be dominant in altered subsurface basalts from Icelandic geothermal fields (Kristmannsdóttir, in prep.). Most of the minerals are green in colour but some are yellow to brownish. Some have faint pleochroism. The birefringence is variable, medium to high. Smectites with different optical properties give very similar x-ray diffraction patterns. Smectites from different depth levels or different drillholes show however slightly different spacings for $d(001)$ because of different cations occupying the interlayer spaces. The DTA curves are very similar to curves of iron-rich saponites described from Japan (Sudo, 1957,

Miyamoto, 1957). The smectites are found (by DTA) to be commonly interlayered by chloritic interlayers. In the infra-red spectra of the smectites the absorption bands due to interlayer water appear at distinctly lower frequency than for saponite (Farmer, 1958). This might be caused by a high degree of Fe substitution in octahedral positions (jfr. subst. in nontronite, Farmer & Russell, 1967). The structure of the minerals is completely destroyed by 6 N HCl, leaving an amorphous residue.

The chlorites are found to be iron-rich varieties, from the optical properties, infra-red data (jfr. Hayashi and Oinuma, 1965 and 1967) and partial chemical analysis. They are green in colour with low birefringence. The "swelling chlorites" have higher birefringence. The DTA analysis of the chlorites and "swelling chlorites" show very similar results. Traces of structural bound water are found in both, but are more significant in the "swelling chlorites". Dehydroxylation occurs at approximately 600°C and sometimes in two steps showing a shoulder peak appearing at 575-595°C and a main peak at 600-610°C. The "swelling chlorites" dehydroxylate at a slightly lower temperature than the normal chlorites. The second endothermic peak due to dehydration of the mica layer in the chlorites is very low or missing. By further heating above 600°C to approximately 920-950°C there appears to be a gradual breakdown of the structure. The absorption bands in the infra-red spectra of all the chlorites and "pseudochlorites" appear at similar frequencies. When compared with the infra-red absorption spectra of chlorites described by Hayashi and Oinuma (1965, 1967) they resemble the spectra obtained from Fe and Fe, Mg chlorites. Treatment of the chlorite with 6 N HCl initiated only slight dissolution of the brucite layers.

The mixed-layer minerals are very variable according to x-ray diffraction results. Their optical properties are much like those of the smectites, but are even more variable. The DTA curves for most of the mixed-layer minerals are very similar to those for the smectites. The smectite-illite mixed-layer minerals give however distinctly different curves. The DTA analysis shows that there is a gradation from smectites not or slightly interlayered with chloritic layers to smectites with a large amount of interlayers. The infra-red spectras of the mixed-layer minerals are close to those of the smectites, but can have some intermediate features between that of the smectites and that of chlorites.

IV. DISCUSSION

There are not many high-temperature areas that have been investigated thoroughly so far in Iceland. Reykjanes (Tómasson and Kristmannsdóttir, 1972) and Hveragerdi which is also a subarea of the Hengill area (Sigvaldason, 1963) have been investigated and Námafjall (Gíslason, G. in prep.) is one of the areas being investigated now.

The main factors one would expect to govern the alteration of rocks in a high temperature geothermal area are rock type (including the age of the rock) water composition and the temperature and water-circulation system.

In all the mentioned areas the rock types and stratigraphy are very similar, consisting of alternating hyaloclastic rocks and basalt lavas. There are some local variations as in drillhole 5 on Nesjavellir where the older rocks are penetrated by younger dolerite intrusions.

The composition of the water is different in the areas. In Reykjanes the water is seawater of origin, nearly neutral or slightly acidic, but Hveragerdi has meteoric originated water, alkaline and with some chloride content (table 1). Nesjavellir and Námafjall have very similar water, alkaline of meteoric origin, with very low chloride content (see table 1).

There is an unsolved problem of how to explain the low chloride content, but this is not considered to be of great importance for the course of alteration. A comparison of the alteration in Námafjall and the Reykjanes areas does not suggest a close correlation between water composition and the degree of alteration in the rocks.

According to earlier investigations the temperature is assumed to be the main factor controlling the degree of alteration. The maximum temperatures reached in Nesjavellir are higher or of the same magnitude as the highest temperatures in the other mentioned areas.

The secondary minerals formed are mainly the same in all areas. The depth and temperature of occurrence are on Nesjavellir often significantly different from the others.

The magnitude of alteration is usually very low in the Nesjavellir area but there are veins with most of the rocks altered to secondary minerals, as a result of higher permeability.

In general the degree of alteration in the Nesjavellir area is much less than one should expect according to temperature. This is expressed by (1) the occurrence of nearly unaltered glass at 450 m depth and to rock

temperature about 200°C, (2) the zeolite zone ranges to unusually high temperature up to 280°C and to the depth of 1000m, (3) the zone of dominant smectite minerals reaches to much higher temperatures than observed in other areas, (4) Epidote-chlorite zone is not clearly defined in the depth range of the holes. Epidote is only found in narrow veins in the deepest drillhole.

The mineral paragenese is obviously not in equilibrium with the present temperature condition in the area.

The temperature has increased too recently for the minerals to get into equilibrium with the new conditions. This means that the geothermal area is migrating to the North.

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Figure captions.

Fig. 1. Geological map of Iceland.

Fig. 2. Geological map of Nesjavellir.

Fig. 3. Temperature in drillholes of Nesjavellir.

Fig. 4. A simplified cross section through the area with the drillholes projected into the profile.

Fig. 5-6. The distribution of secondary minerals. The minerals were identified with optical methods combined with x-ray diffraction analyses. The amount given is volume percentage obtained by point counting in the thin sections made from the drillhole cuttings. Legend for identification of clay minerals and zeolites: a) smectite, b) mixed-layer minerals, c) chlorite, d) swelling chlorite, e) analcime, f) heulandite, g) mordenite, h) laumontite, i) wairakite, j) stilbite.

TABLE 1.

Major component composition of thermal fluids from Nesjavellir and other
High-Temperature areas.

Locality	Temp. °C	pH	SiO ₂	Na ⁺	K ⁺	Ca ⁺⁺	Mg ⁺⁺	*CO ₂	SO ₄ ⁻⁻	S ⁻⁻	Cl ⁻	F ⁻
Nesjavellir Drillhole 5	260	7.1	546.3	164.8	12.6	0.47	0.11	1355	26.2	311.1	17.7	1.03
Námasharó Drillhole 4	260	7.27	531.0	125	23.3	1.14	0.01	78.7	53.1	160.9	25.9	1.2
Hveragerði Drillhole G-3	220	6.8	403	186	18.3	1.6	0.24	98.1	69.0	31.5	153.0	1.2
Reykjanes Drillhole 8	277	6.1	636	9610	1348	1530	16.0	1926	30.8	45.3	19260	0.1

* Total carbonate as CO₂

TABLE 2.

The main groups of clay minerals from drillholes 2, 3 and 5 on Nesjavellir. Comparison of results from the three methods of investigation.

Mineral group	Characteristics from the x-ray investigation	Characteristics from the differential thermal analysis.	Characteristics from the infra-red spectra.
I. Smectite	Strongly swelling in ethylene glycol, contracts to 9,6 Å after heating.	Main endothermic peak at ca. 160°C	As for smectite.
II. Smectite slightly interlayered	Strongly swelling in ethylene glycol, contracts to 9,6 Å after heating.	Main endothermic peak at ca. 160°C and a lower but distinct at ca. 550°C	As for smectite but slight changes have occurred in the Si-O absorption bands.
a) smectite III. Minerals "intermediate" between smectite and chlorite	Most swell in ethylene glycol from very strongly to slightly.	Main endothermic peak at ca. 160°C and a lower but distinct at ca. 550°C.	Distinct changes in the Si-O bands towards chlorite, but the absorption bands due to OH-stretching vibrations are still smectite-like.
b) chlorite	Swell in ethylene glycol, from very strongly to medium strongly (15 Å).	Dehydroxylation occurs at ca. 590°C. Traces of structural bound water.	As for chlorite. The Si-O bands are however sometimes slightly different from those of group IV chlorite.
IV. Chlorite	Non swelling.	Dehydroxylation occurs at 600-610 C.	As for chlorite.

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Fig. 1.

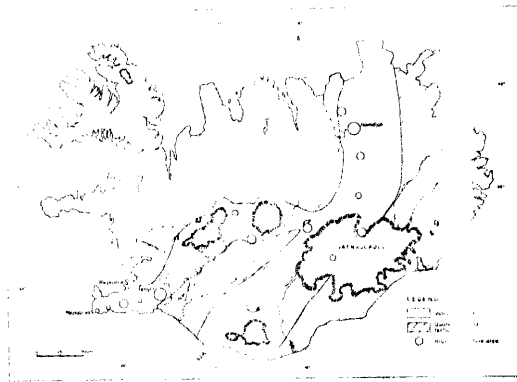


Fig. 2.

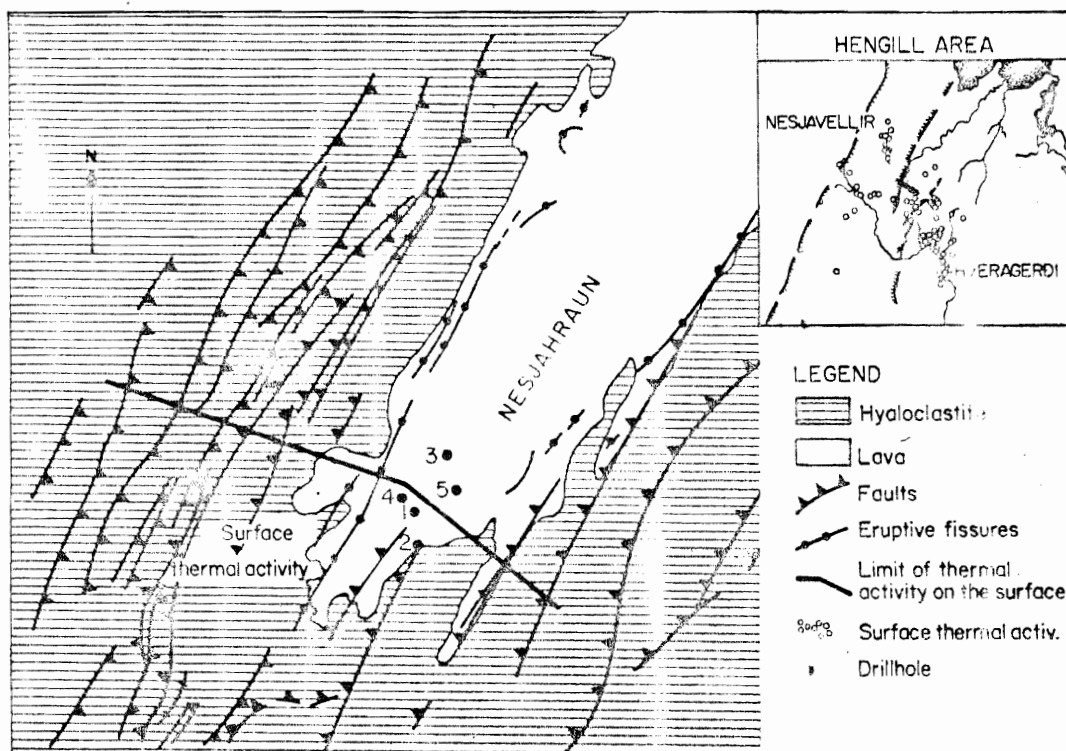


Fig. 3.

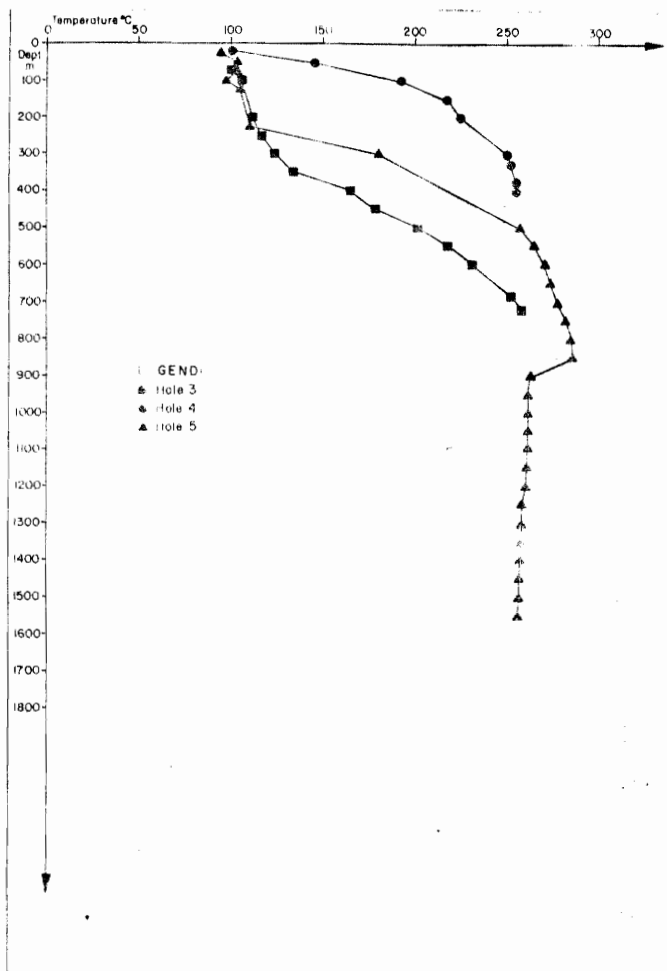


Fig. 4.

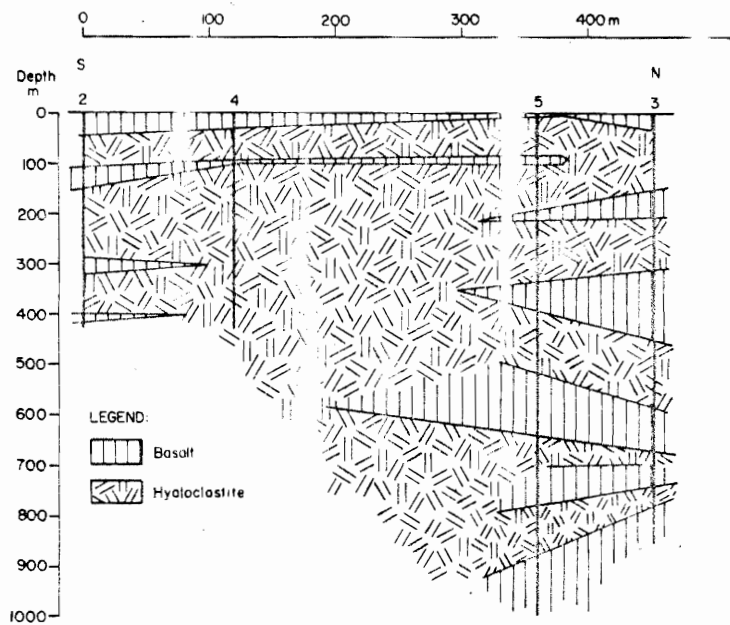


Fig. 5.

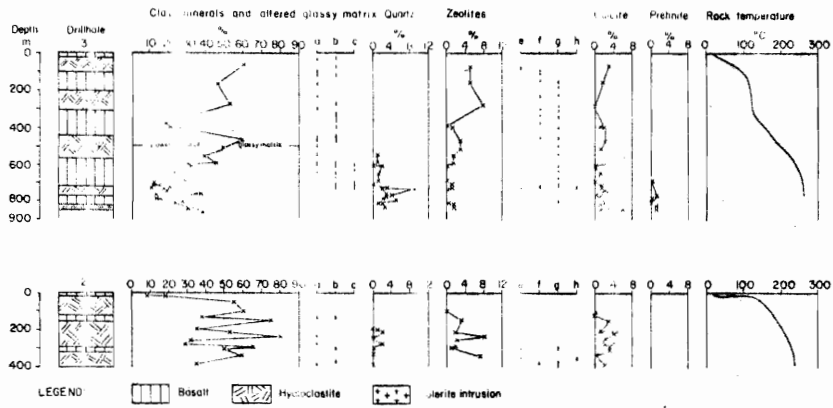


Fig. 6.

