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# Retrograde Alteration of Basaltic Rocks in the Þeistareykir High-Temperature Geothermal Field, North-Iceland

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## ABSTRACT

Hydrothermal alteration of basaltic rocks in the geothermal area on Þeistareykir was studied in a drillcore from well ÞR-7 on the edges of the Theistareykir geothermal field, NE Iceland. Emphasis was laid on the study of clay minerals and zeolites formed by hydrothermal alteration. The reservoir rocks in the area are mainly tholeiitic basalt lavas and hyaloclastites, with occasional occurrence of acidic volcanic rocks that are moderately to highly altered. The rock forming minerals have been transformed to clay minerals or sheet silicates and several secondary minerals have been precipitated in vugs and factures. Several different clay minerals were identified in the altered rocks: smectite, chlorite, mixed layer chlorite/smectite, mostly irregular types and irregular chloritic mixed layer sheet silicates. Smectite/illite mixed-layer minerals were also encountered. The clay minerals are mostly poorly crystalline and a regular clay zonation from smectite through mixed layer smectite-chlorite to chlorite, that is common in high-temperature geothermal fields in Iceland, is not observed in the core. The zeolites identified in the core are laumontite, mordenite, wairakite, and the quite rare yugawaralite, previously only encountered in three localities in Iceland. The higher temperature zeolite wairakite is found in the middle of a zone dominated by the lower temperature zeolite laumontite. The dispersion of the secondary minerals does thus not show a very clear zonation of the alteration minerals and correlation with rock temperature is not easily obtained. Some of the clay minerals/ sheet silicates encountered suggest a retrograde alteration of previously formed clay minerals at lower temperatures than the original hydrothermal alteration. The occurrence of zeolites in the core implies a similar development. The rock temperature in well ÞR-7 appears to have been higher at earlier times than at present showing an overprint of lower temperature secondary minerals over a previous high-temperature alteration.

## 1. INTRODUCTION

The Theistareykir high-temperature geothermal area lies in the active zone in northest Iceland within the Theistareykir fissure swarm (Figure 1). Well ÞR-7 is an exploratory well located 5 km from the most active part of the area with numerous fumaroles and boiling mud pots. The active part of the geothermal area lies in the eastern half of the Theistareykir fissure swarm. The geothermal activity covers an area of nearly 10.5 $km^2$, and the most intense activity is on the northwestern and northern slopes of Mount Bæjarfjall and in the pastures extending from there northwards to the western part of Mount Ketilfjall (Figure 2). The thermal area covers nearly 20 $km^2$ if the old alteration in the western part of the swarm is considered a part of the thermal area (Ármannsson et al., 1986, Sæmundsson, 2007). The bedrock in the area is composed of hyaloclastite ridges formed by subglacial eruptions during the Ice Age, interglacial lava flows, and recent lava flows (younger than 10 000 yrs). All the rock formations are basaltic (Figure 2). Acidic rocks are found on the western side of the fissure swarm, from subglacial eruptions up to the last glacial period (Sæmundsson, 2007). Rifting is still active in the fissure swarm (Björnsson et al., 2007). Volcanic activity has been relatively infrequent in the area in recent times. Approximately 14 volcanic eruptions have occurred in the last 10 000 years, but none in the last 2500 years. Large earthquakes (up to M: 6.9) occur mainly north of the area in the Tjörnes Fracture Zone, which is a right–lateral transform fault in the fissure swarm itself (Halldórsson, 2005, Björnsson, 2007). The Tjörnes Fracture Zone strikes northwest, crosscutting the north-striking fractures as it enters into the fissure swarm some 5 km north of the thermal area. The volcanic activity ceases in the fissure swarm as it crosses the Tjörnes Fracture Zone, although its northern part remains seismically active (Ármannsson et al., 1986).

The most active parts of the area are related to active fractures, increasing permeability and enabling geothermal fluids to circulate and reach the surface.

Surveys indicate that a low resistivity structure (<10 Ωm) is located at the depth of 400-600 m elongated in an east-west direction from Mount Bæjarfjall in the east towards Mount Mælifell in the west. Below this low resistivity structure the resistivity increases sharply. Similar structures were detected by gravity and magnetic field studies. This could be interpreted as an east-west trending heat source crossing a north-south tectonic structure. Thus, the distribution of the surface manifestations reflects the direction of vertically permeable faults and fissures rather than that of the heat source (Ármannsson et al., 1986).

Surface exploration in the area started just after 1970 with geological mapping, geophysical exploration and geochemical survey (Gíslason et al., 1984). It was continued with intervals through the next twenty years (Gíslason et al., 1984; Ármannsson et al., 1986; Björnsson et al., 2007).

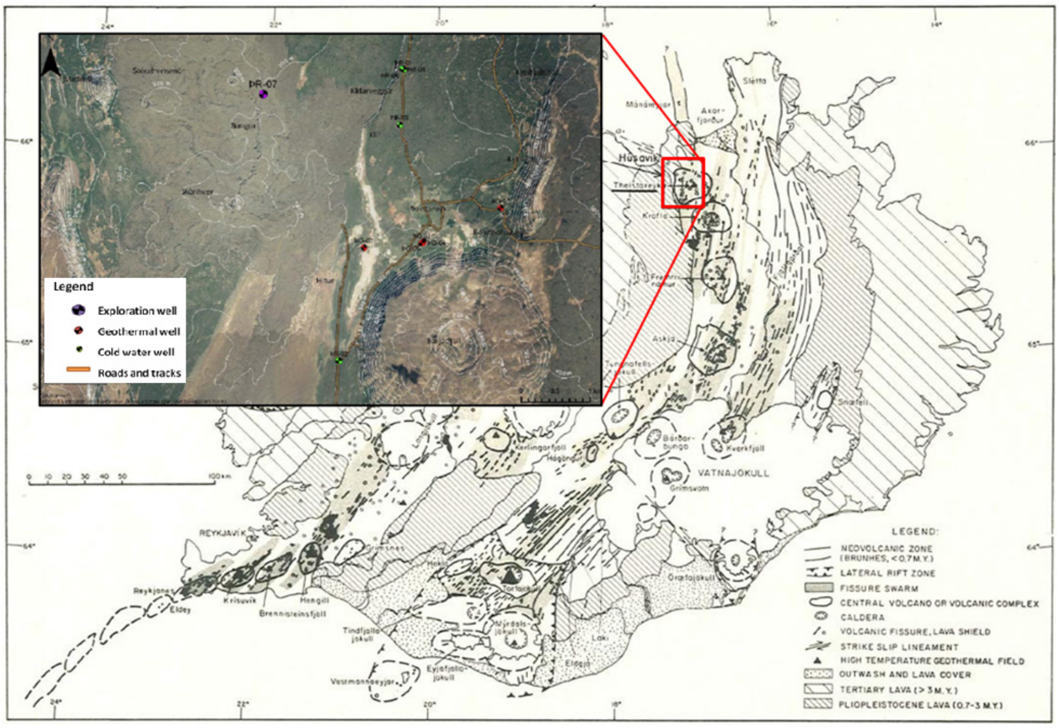


**Figure 1: Outline of geology of Iceland showing the study area and the location of Theistareykir (compiled by Sæmundsson, 1979) and of the drill sight ÞR-07 (Lacasse et al., 2007).**

The aim of the drilling of well ÞR-7 was to explore the extension and borders of the area. The depth of the well is only 458.1 m, but the aim was to drill to 600 m depth (Lacasse et al., 2007). Drilling started in 2002. Besides well ÞR-7, which is an exploration well, five geothermal wells have been drilled in the Theistareykir geothermal area. Well ÞG-1 was drilled down to a depth of 1953 m in 2002 reaching a maximum temperature around 332°C. It was followed by well ÞG-2 of 1723 m depth in 2004 and its temperature is around 242°C and ÞG-3 of 757 m depth in 2006, with a temperature of 380°C. In 2007 two additional geothermal wells were drilled, ÞG-4 and ÞG-5. ÞG-4 is 839 m deep with a temperature of 320°C, ÞG-5 is 847 m deep with a temperature of 259°C. The maximum temperature of the wells decreases with increasing distance from the volcanic caldera (Bæjarfjall).

## 2. GEOTHERMAL ALTERATION AND HYDROTHERMAL MINERALS

Hydrothermal alteration results from an interaction of the primary rocks and hot water and steam causing dissolution of primary minerals, replacement and precipitation of new minerals and changes in permeability (Henley and Ellis, 1983). Generally, the primary minerals formed at the highest temperature have the least stability by hydrothermal alteration (Stefánsson et al., 2001). Basaltic glass is the most unstable phase and the first to be altered. The hydrothermal alteration in geothermal fields shows zoning by increased temperature and depth in terms of special index minerals. The index minerals are different in different reservoir rocks (Kristmannsdóttir, 1985). Lowering of the reservoir temperature may also be demonstrated by retrograde alteration and overprint of mineralization formed by lower temperature alteration over mineralization formed by older high temperature alteration.

The intensity or degree of alteration depends on several factors such as: permeability (related to gas content and hydrology of system), temperature, duration of activity, rock composition, pressure, hydrothermal fluid composition (pH value, gas concentration, vapor- or water dominated, magmatic, meteoric), number of superimposed hydrothermal systems (overprinting of alteration), and hydrology (Kristmannsdóttir, 1975a; Browne, 1978; Reyes, 2000; Franzson, 2008). The special features of the alteration in Icelandic geothermal areas are the result of the bedrock being dominantly basaltic hyaloclastites and lavas. Whereas, some alteration minerals may be the same or almost the same as high temperature geothermal fields elsewhere in the world, others in turn, are completely different. This applies to the clay minerals, which were first described when the high temperature geothermal systems of Reykjanes and Nesjavellir were first investigated by deep drilling (Kristmannsdóttir and Tómasson, 1974; Kristmannsdóttir, 1976). The zeolites formed in Icelandic geothermal areas are dominantly calcium zeolites, in contrast to more common sodium and potassium zeolites in more acidic volcanic and sedimentary reservoir rocks (Kristmannsdóttir and Tómasson, 1978). Temperature and permeability play the most important role in the stability of most hydrothermal minerals. In the case of low temperature geothermal fields, alteration may be more complex and it is often difficult to separate geothermal alteration due to present activity of regional alteration from older high temperature alteration.

## 3. WELL ÞR-07

Well ÞR-07 is a shallow exploration drill hole with a total depth of 458.1 meters cored from 3 m depth to the bottom. It is located on the 2,500 years B.P. Þeistareykjahraun lava flow (Figure 3) (Lacasse et al., 2007). The well is cold to about 175 m depth, where the temperature increases sharply to a maximum temperature of 180°C near the bottom of the hole (Figure 4). The intermediate temperature inversion at 374-404 m corresponds to a succession of lava flow units characterized by a vesicular and oxidized upper part (Lacasse et al., 2007).

Several lava flow units were identified in the core (Lacasse et al., 2007). The most vesicular cuttings (lapilli, scoria) may have a pyroclastic origin due to a more explosive character of the eruption. Phenocrysts of plagioclase, pyroxene, and rare olivine occur in the rocks. The amount of phenocrysts varies in cuttings and can fill up to 30-40% of the rock volume. Phenocrysts generally occur in the central part of the lava flow units, where cooling was slow and allowed crystals to grow. Fine grained matrix is mainly observed at the top and bottom of the lava flow units where rapid cooling has occurred. The rock texture is therefore aphyric with no phenocrysts. Rock alteration is heterogeneous along the 150 m depth interval and is illustrated by variation in the angle of fracture at the ends of the cuttings, by Fe oxidization and palagonitization of basaltic glass. The reddish surface coating is evidence of a state of oxidization (Lacasse et al., 2007).

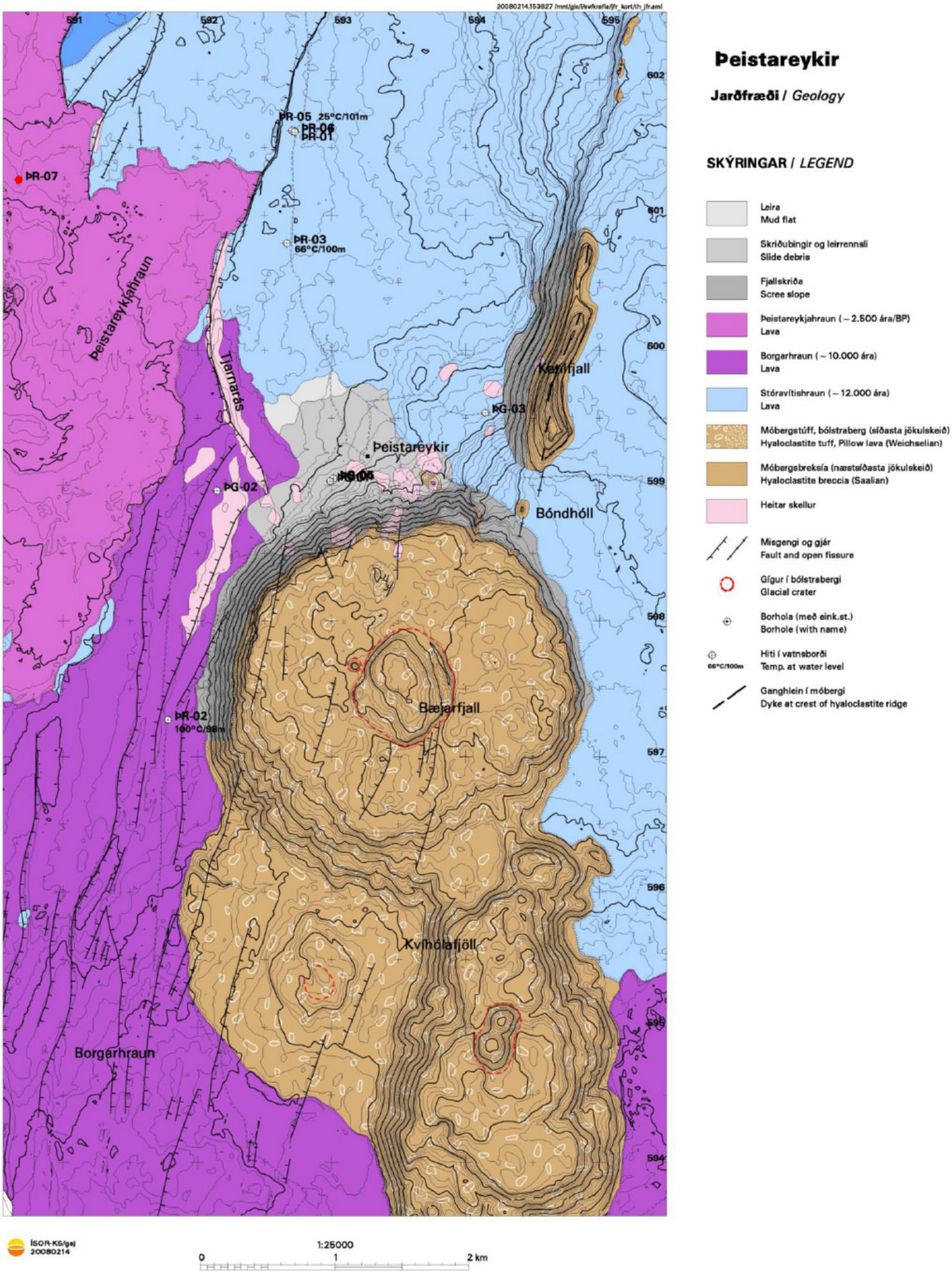


**Figure 2: Geological map of the research area (Sæmundsson, 2007).**

Below 153 m depth the rock types observed in the core from ÞR-7 can be subdivided into 4 main categories that include volcaniclastic sandstone, "fresh" basalt, altered volcanic breccia, and altered basalt. Volcaniclastic sandstone occurs along the 173-186 m and 200-205 m depth intervals. The dark grey to dark brown sedimentary rock is generally well sorted, stratified, and poorly consolidated (Lacasse et al., 2007). The unconsolidated state of the rock has resulted in poor core recovery, as low as 35%, with fragments falling down to the bottom of the hole and disturbing core drilling. Relatively less altered basalt occurs along the 151-170 m and 190-200 m depth intervals. It is medium to dark grey in color and has few vesicles up to 1.5 cm in diameter. The matrix is fine grained and bears occasional large phenocrysts of plagioclase up to 6 mm in size and rare phenocrysts of pyroxene and olivine (Lacasse et al., 2007). Volcanic breccia, including tuff horizons, is by far the dominant rock type and represents almost one third of the whole sequence that was drilled at site ÞR-07. The volcanic breccia is mainly originated from subglacial eruptions forming hyaloclastite (móberg) accumulation up to 40-50 m thick, e.g. between 255 and 304 m depth and between 320 and 362 m depth (Lacasse et al., 2007).

Basaltic rock also occurs as altered individual flow units between 362 m and 425 m depth, with their upper part being vesicular and reddish in color due to oxidization and their lower part being fine grained, non vesicular, and enriched in smectites. This rock sequence has the largest amygdules with macroscopic secondary mineralization (e.g. zeolite) of low to moderate temperatures (Lacasse et al., 2007). In all samples the rock type is olivine tholeiite basalt of varying alteration rate and the type of secondary minerals.

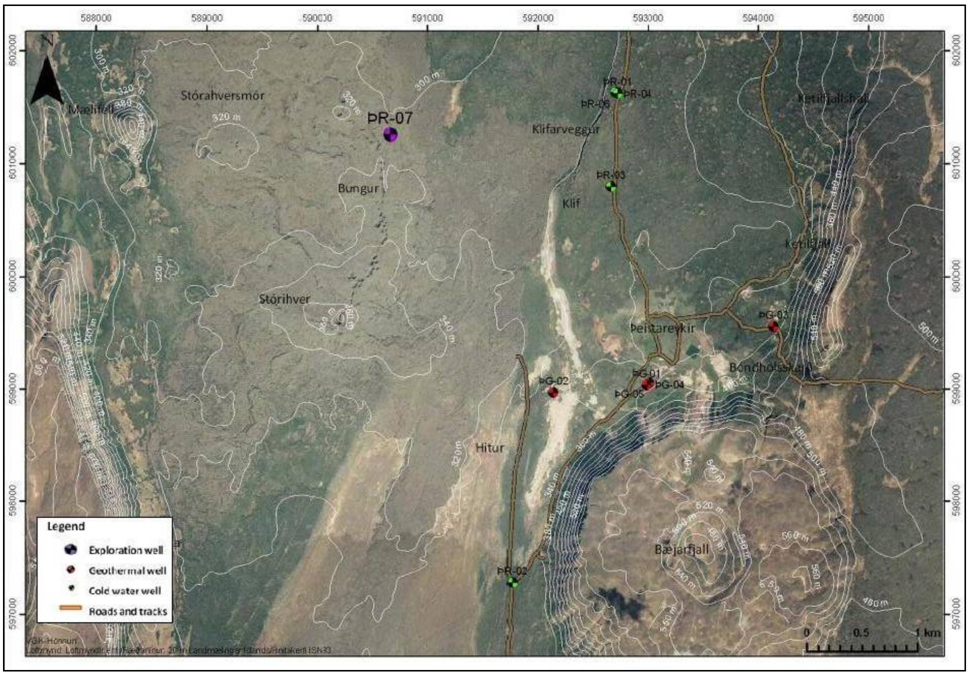


**Figure 3: Photo from the area and location map of the drill site ÞR-07(Laccasse et al., 2007).**

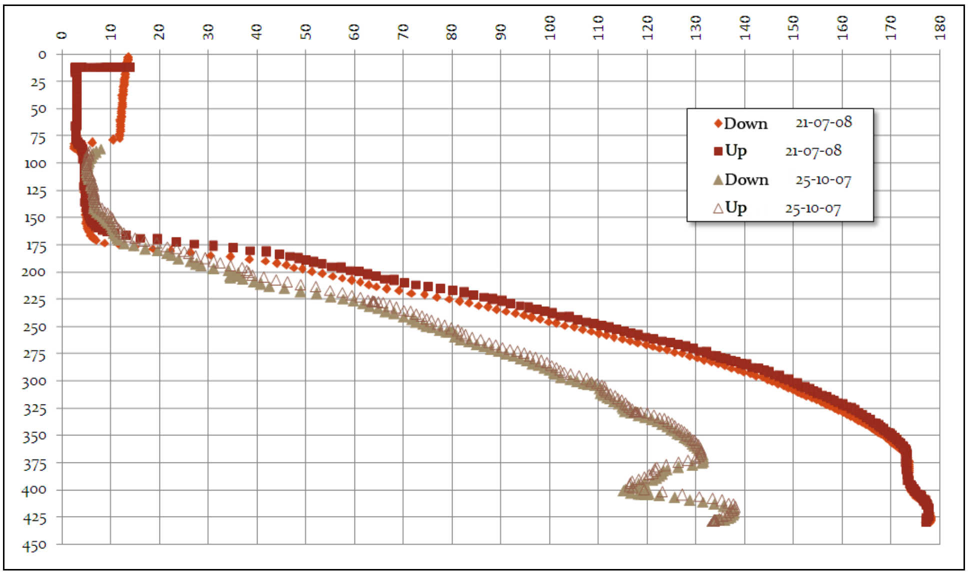


**Figure 4: Temperature logging of borehole ÞR-07 (Lacasse et al., 2007).**

## 4. ALTERATION MINERALS

In amygdules and fractures of the bedrock generation of the minerals is clearly visible. The clay minerals/sheet silicates appear first, secondly quartz and/or zeolite appear, and finally calcite appears (Figures 5 and 6**)**.

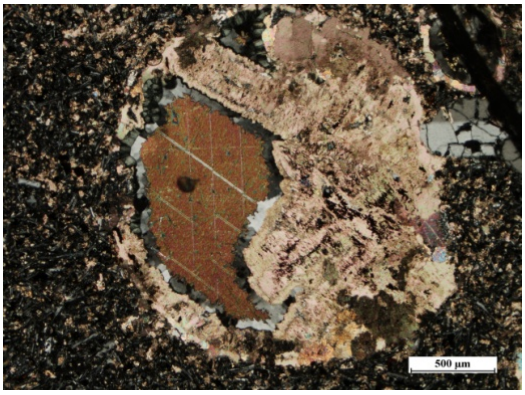

**Figure 5: Clay minerals and zeolite in amygdules, at 458 m depth.**

### 4.1 XRD Analysis of Secondary Minerals in Amygdules and Fractures

The zeolites identified in the ÞR-7 core are laumontite, yugawaralite, mordenite, and wairakite. Other minerals identified were quartz and calcite, which are found together with the zeolites. Laumontite is the most common zeolite and was identified both in amygdules and fractures.

In some samples, laumontite appears with calcite and in one sample also with yugawaralite and quartz. Yugawaralite is also a quite common zeolite in the amygdules of the core. Mordenite is found in one sample, as well as wairakite. Two more minerals were identified: calcite was found to be dispersed in samples from top to bottom and quartz was found in samples taken from a depth of 330 m, down to the bottom. The zeolite yugawaralite is a very rare zeolite in Iceland (Figure 7). It has only been found in three localities before: in eastern Iceland, in the Snæfellsnes peninsula and in Hvalfjördur in the south west part of Iceland (Barrer et al., 1965; Sigurdsson, 1970; Jakobsson, 1988, Weisenberger and Selbekk, 2008). In the studied well yugawaralite is not the most common mineral, but is by no means rare and appears in well crystalline aggregates.

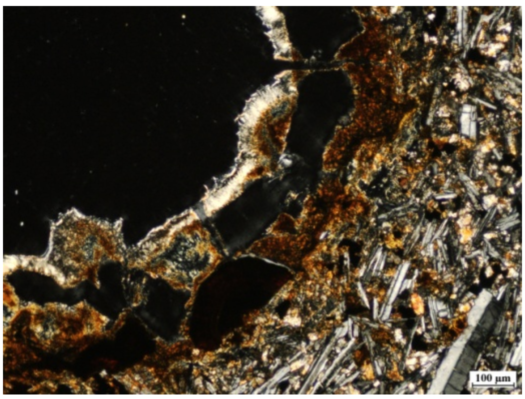

**Figure 6: Clay minerals in amygdules, at 458 m depth.**

### 4.2 XRD Analysis of Clay Minerals

No clay minerals were encountered in the uppermost 200 m of the core (Jónsson, 2008). Smectite is one of the principal phases present in clay samples K06, K07, K13 and K25. As demonstrated in Figure 8, the d(001) peaks are at about 14 Å in the untreated samples, at 17 Å in glycolated samples and break down to about 10 Å by heating to 560°C. Well defined chlorite is identified in a few samples with d(001) at about 14.7 Å in untreated, glycolated and heated samples (Figure 9). The d(002) peak is at 7.25 in untreated and glycolated samples, but disappears after heating at 560°C. In several samples the chlorite is associated with mixed-layer minerals of different kinds and breaks down completely by heating to 550°C. Samples of a mixed-layer minerals of smectite and chlorite which break down into two different components when heated are also encountered (Figure 10). The minerals are often poorly crystalline and not pure components of any single type of mineral and thus interpretations of XRD patterns may be complex. Some of the minerals appear to be the result of retrograde change of minerals formed previously at higher temperature conditions. This is shown in Figure 10 where the main peak at 14.5 Å in the untreated sample swells to 15.7 Å and breaks down to 12.5 and 14.3 Å after heating. Higher order peaks are also clearly visible in untreated and glycolated samples. Another example of a mixed-layer mineral is shown in Figure 11 where the untreated peak has a shoulder at 14 Å and the glycolated peak does not swell to 17 Å, which means it is not a regular smectite even though a low peak occurs at 10 Å after heating. Part of the substance (e.g. chlorite) does not swell after glycol saturation. So this is interpreted as a mixed-layer mineral of smectite-illite and poorly heat resistant chlorite. The distribution of clay minerals in well ÞR-7 does not show a progressive zonation from smectite to chlorite through mixed layer minerals of smectites and chlorite (Kristmannsdóttir, 1976). The relicts of such a zonation may be faintly visible, but many of the chlorite samples appear to have been changed by later retrograde alteration and very complex mixed layer minerals are common.

## 5. DISCUSSION

Well ÞR-07 is a shallow exploration drill hole with a total depth of 458.1 m. The drill core primarily consists of breccia, altered basaltic rocks and tuffs with intercalated altered basaltic lava flows.

Low-temperature zeolites occur throughout the stratigraphic section, but no high-temperature minerals were detected except wairakite. Both above and below the wairakite occurrence the dominant zeolite is laumontite which is a typical low-temperature index zeolite. Yugawaralite and mordenite were found as well among the low-temperature index minerals.

Clay alteration in well ÞR-7 shows no distinct progressive zonation. In the first 200 m there are no clays. Below that there are mostly found interbedded mixed layers and smectite. The XRD diffraction patterns demonstrate the complexity of the material and often poorly crystalline form of the minerals. The mineralization, especially of low-temperature minerals like zeolites, laumontite, yugawaralite and mixed-layer clays (and sheet silicates), characterize the lithology in well ÞR-7 at Theistareykir. The mineral assemblage shows that the temperature in the well has not been constant. The clay minerals appear to have formed at higher temperature and later been modified during retrograde alteration. The sequence of the other secondary minerals also points to an overprint of low temperature over higher-temperature minerals, but this is not always clearly demonstrated. Calcite is, by petrographic study, found to crystallize later than quartz and the high-temperature zeolite wairakite is found in the middle of the zone dominated by low-temperature zeolites. Any age relation between wairakite and the lower-temperature zeolites could not be established as wairakite was the only zeolite identified in the actual sample.

The study of the core samples strongly indicates former higher temperatures and subsequent drop in temperature in this part of the area. The alteration pattern indicates that the present temperature is lower than the temperature in the past. Dramatic changes in surface activity have been observed in the Theistareykir area during the time of exploration (Ármannsson et al., 2000). The present study indicates that there have been considerable changes in the activity at depth as well. These results strongly suggest that no drilling should be performed beyond this border zone of the active high-temperature area.

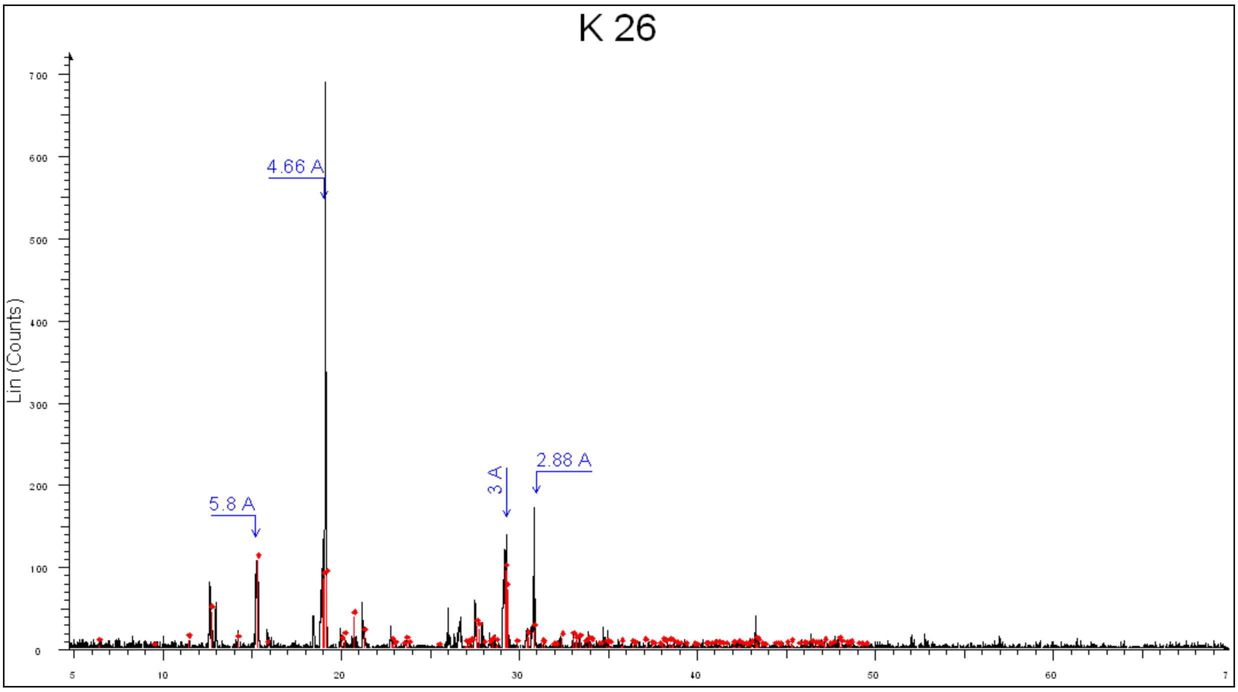


**Figure 7: Sample K26 (Yugawaralite) X-Ray Powder diffraction pattern.**

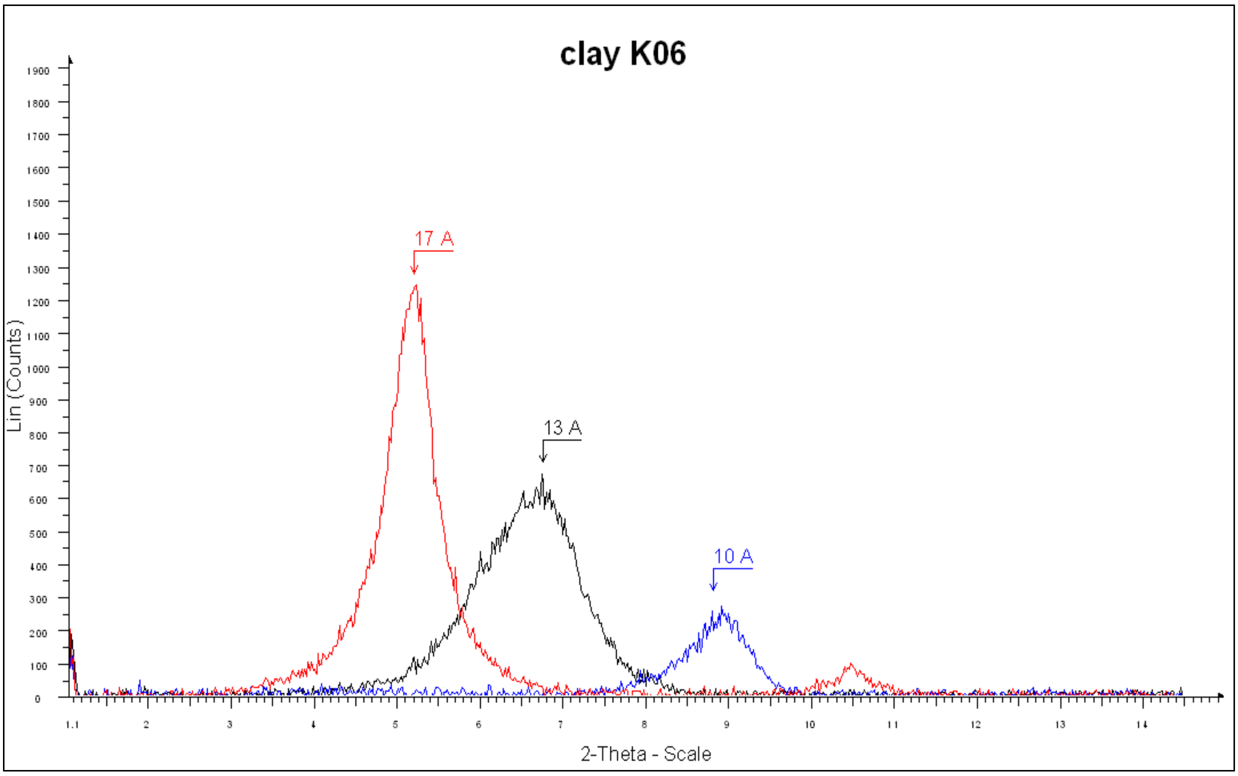


**Figure 8: XRD pattern of a typical smectite in the altered core. The black line shows the untreated sample, the red line the glycolated sample and the blue line shows the pattern after heating the sample over 560°C.**

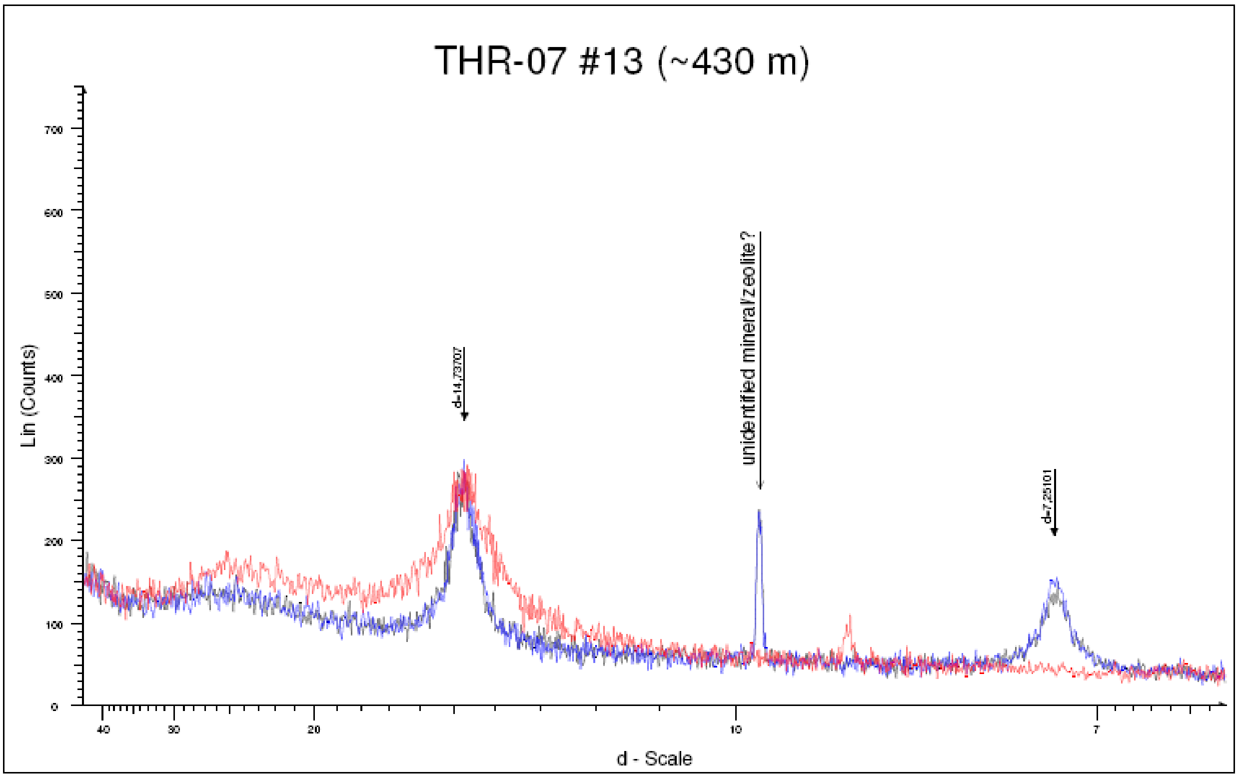


**Figure 9: XRD pattern of chlorite in a sample (13#) at m depth. The red line line shows the untreated sample and the blue line the glycolated sample.**

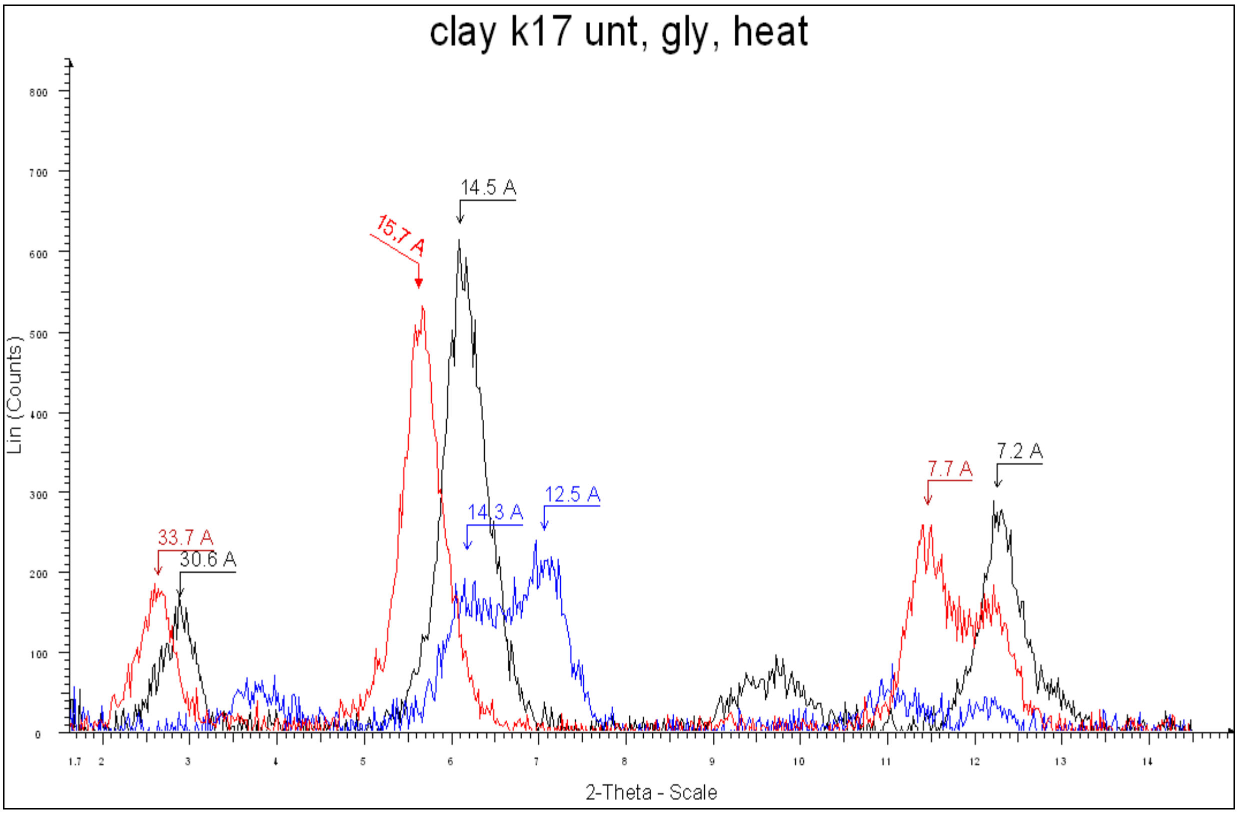


**Figure 10: XRD pattern of mixed-layer minerals. The black line shows the untreated sample, the red line the glycolated sample and the blue line shows the pattern after heating the sample over 560°C.**

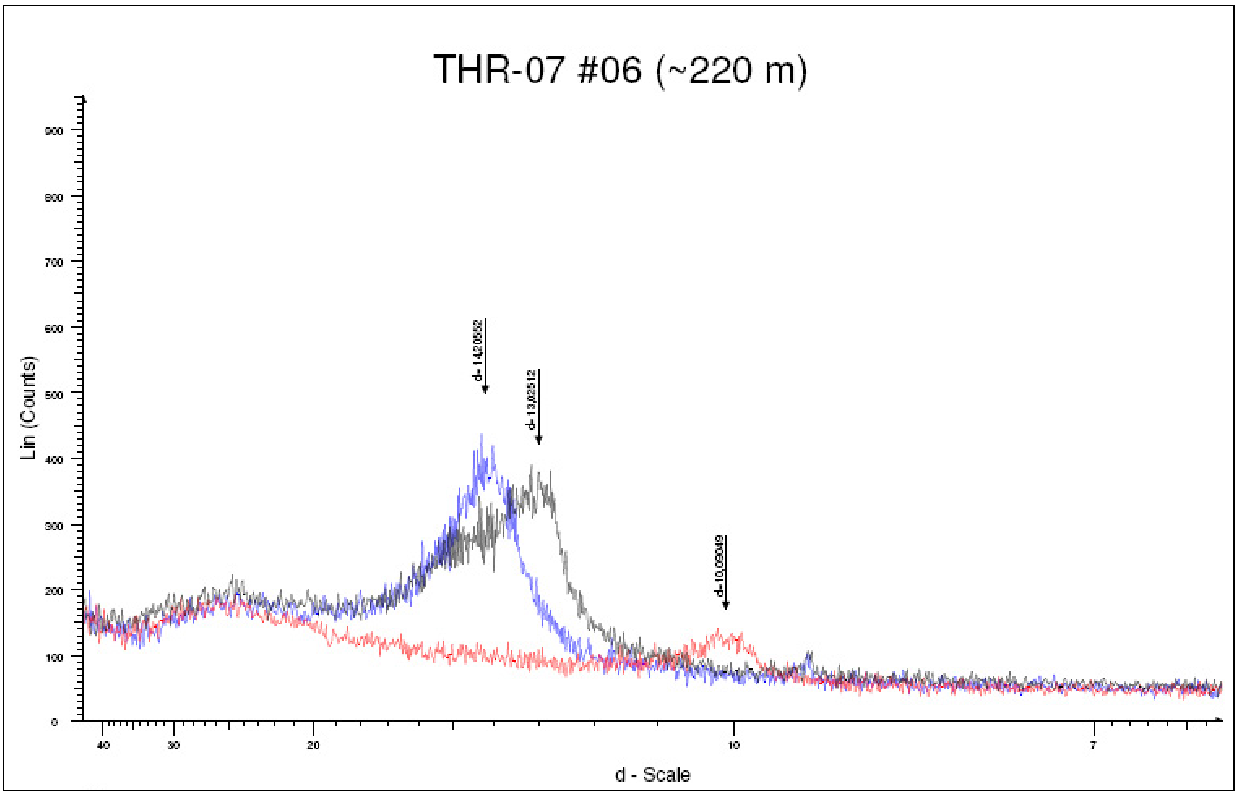


**Figure 11: XRD pattern of mixed-layer (sample #06). The black line shows the untreated sample, the blue line the glycolated sample and the red line shows the pattern after heating the sample over 560°C.**

## 6. CONCLUSION

The main results of the study of the drill core of well ÞR-7 are as follows:

1. The stratigraphy of well ÞR-7 (458 m depth) consists primarily of hyaloclastite rocks like breccia and tuff intercalated with altered basalt.

2. No distinct clay mineral zoning is observed of the kind generally formed in the Icelandic high-temperature geothermal fields. Retrograde alteration is indicated by the irregular mixed-layer structures and thermally unstable chlorites and chlorite.

3. Zeolites are found from ~200-458 m depth. Laumontite is the most common (110-230°C), but yugawaralite (100-120°C), mesolite-scolecite (80-120°C) and wairakite (>180°C) are also found.

4. The zeolite yugawaralite has previously been encountered in only three localities in Iceland.

5. The occurrence of a high-temperature zeolite in the middle of low-temperature zeolite zones point to a later overprint of lower temperature alteration.

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