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Borehole Geology and Hydrothermal Alteration of Well HE-24, Hellisheidi Geothermal Field, SW-Iceland

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ABSTRACT

Well HE-24 is located in the Hellisheidi high temperature field, a part of the Hengill central volcano in SW-Iceland. It is a vertical well reaching a total depth of 2587 m. The well was drilled with targeting a 5000 years old NE-SW trending volcanic fissure. The lithology of well HE-24 comprises basaltic hyaloclastite formations and dyke intrusions. Different alteration zones were identified in the well; zone of no alteration, smectite-zeolite, mixed layer clay, chlorite, chlorite-epidote and epidote-actinolite zone. These zones depict a trend from a cold groundwater system down to 244 m through a cap rock and into a high temperature system. Based on mineral sequence deposition and comparison between hydrothermal alteration mineral and formation temperature the geothermal system appears to have cooled, particularly in the upper 700-800 m of the well. Feed points were found in the well and categorized into weak, moderate and large aquifers. Some of these are located in the production part and are mostly associated with intrusions while others are located above the production part, and they are mostly associated with stratification boundaries.

1. INTRODUCTION

The Mid-Atlantic ridge, a constructive plate margin appears above sea-level in Iceland, one of few countries in the world attaining an increase in its surface area due to the creation of new lithosphere by sea floor spreading. The newly created lithosphere occurring at the plate boundaries is characterized by high heat flow due to volcanic activity and extensional tectonics. This active zone of volcanism and tectonism across Iceland strikes roughly NE-SW. The rock sequence within this active rift zone consists of interglacial lavas and sub-glacial hyaloclastites with an age of less than 0.7 million years (Björnsson et.al., 1986). The active geothermal areas in Iceland are distinguished as low-temperature areas and high temperature areas. The low-temperature areas are located outside the volcanic rift zone and have reservoir temperatures lower than 150°C at 1 km depth. High temperature fields, on the other hand, are confined to the active rift zone and characterized by reservoir temperatures of more than 200°C at a depth of 1 km (Bödvarsson and Pálmason, 1961). One of the largest high temperature geothermal areas in Iceland is found within the Hengill central volcano about 30 km east of Reykjavik, the capital city of Iceland. Hellisheidi field where well HE 24 is located is a part of the Hengill geothermal area.

The data on the geology and alteration of the well were collected from cutting analysis using binocular microscope, thin section petrography, X-ray diffraction analysis, fluid inclusion geothermometry, and geophysical logs.

2. GEOLOGICAL OUTLINE

2.1. Regional Geology

Iceland is located where the astenospheric flow under the NE Atlantic plate boundary interacts and mixes with a deep seated mantle plume. The buoyancy of the Iceland plume leads to a dynamic uplift of the Iceland plateau, and high volcanic productivity over the plume produces a relatively thick crust. Because the lithosphere tends to break up above the mantle plume and the plume has been moving east relative to the plate boundary the main volcanic belts in Iceland are displaced eastward relative to the crest zone of the Mid Atlantic Ridge.

Vertical sections of the volcanic sequence in Iceland expose up to 1500 m thick pile of volcanic rocks below which lies at least another 2 – 5 km thick sequence of extrusives. The exposed volcanic pile is built predominantly of basalts (80-85%), while acidic rocks, including intermediate rocks constitute about 10%. The amount of sediments of volcanic origin is in the order of 5-10% in a typical Tertiary lava pile but much higher in Quaternary rocks (Saemundsson, 1979).

2.2. Hengill Volcanic System

The Hellisheidi high temperature field is part of the Hengill volcanic system. This volcanic system includes about 60-100 km long NNE-trending fissure swarm with normal faults, fissures, frequent magma intrusions and a central volcano (Figure 1). Exploration started in the Hengill system in 1985 with a well drilled at Kolvidarholl and followed by a well at Olkelduhals in 1995 (Franzson et al., 2005).

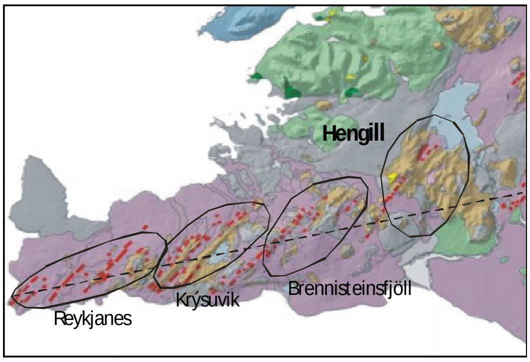

Figure 1. Simplified geological map of SW-Iceland showing volcanic zone, fissure systems and location of Hengill volcanic system.

The rock sequence of the Hengill central volcano predominantly consists of hyaloclastites and lava series. Hyaloclastites formed in subglacial eruptions are formations of relatively limited horizontal extent which makes them of limited use as marker horizons. Lava series are seen to bank up against the volcano in the western part, as lavas are a feature of lowland accumulation. Unusually large faults delineate the western margin of the fissure swarm and indicate the termination of volcanic activity west of Hengill area. This may furthermore have the implication that the high temperature reservoir deepens sharply west of the faults (Franzson et al., 2005).

Fault and major fractures strike mostly NNE-SSW and are conspicuous in the east and west marking the boundaries of the fault and fissure zone of the volcano. Post glacial volcanism includes three fissure eruptions of 9000, 5000 and 2000 years. The fissures can be traced further to the north, through Nesjavellir field and into Lake Thingvallavatn (Saemundsson, 1995).

2.2. Geophysics

Aeromagnetic, gravity and DC-resistivity surveys were carried out between 1975 and 1986. These delineated a 110 km^2 low resistivity area at 200 m b.s.l. and furthermore showed a negative and transverse magnetic anomaly coherent with the most thermally active grounds (Björnsson et al., 1986). The resistivity map was revised between 1986 and 2000, by applying the central loop transient electromagnetic sounding method (TEM). These data imply that despite being widespread, the resistivity anomaly is complex and affected by processes such as faulting, shearing and spreading (Árnason and Magnússon, 2001).

3. BOREHOLE GEOLOGY

Skardsmýrarfjall mountain is part of the Hellisheidi geothermal field. Geologically Skardsmýrarfjall consists of hyaloclastites and post glacial lava. The mountain is succeeded by 5000 years volcanic fissures trending NNE and SSW. The well HE-24 is sited beside the volcanic fissure and meant to cut through the feeder of that eruption. The well is vertical and is aimed at exploring the deeper part of the reservoir. The well reached 2500m depth. The cutting samples on which the geological data are based on are taken at 2m interval during drilling and studied with binocular, petrographic and fluid inclusion microscopes. The cutting analysis was aided by geophysical lithological logs.

3.1. Stratigraphy

The stratigraphy of well HE-24 is shown in Appendix 1. It is divided into a number of rock types mainly depending on the crystallinity of the rock. Basaltic tuff composed of volcanic glass, basaltic breccia which is a mixture of partially crystallized basalt and volcanic glass, glassy basalt, which often is interpreted as pillow basalt, is mostly made up of partially crystallized rock with minor amounts of volcanic glass, and finally crystallized (fine to coarse grained) basalt, which forms either sub-aerial lavas or intrusions. The volcanic products are in most cases very porous, while intrusions are dense. Porphyritic or aphyric character of the rock is very useful in separating one volcanic formation from another.

The description of the rock formation of well HE-24 is mostly based on the binocular microscope and aided by petrographic thin section analysis. The stratigraphy of the well consists predominantly of alternating sequence of sub-glacial hyaloclastites and basaltic intrusive rocks. Intrusive rocks are mostly characterized by relatively low alteration compared to the surrounding rock, compact nature, and sometimes marked by oxidation at their margin. Intrusions usually show relatively high peaks value in neutron-neutron and resistivity logs (Franzson et al., 2005).

4. HYDROTHERMAL ALTERATION

4.1. Primary Rock Minerals

The primary minerals in the rocks penetrated by well HE-24 are characterized by the abundance of glass, olivine, plagioclase, pyroxene and opaques (Table 1). The replacement of the mineral can best be studied by petrographic thin section analysis. The primary minerals first start to alter intensively in this well below 478 m depth.

4.2. Distribution of Hydrothermal Minerals

The most common hydrothermal alteration minerals in well HE-24 are quartz, calcite, and pyrite, low temperature minerals such as the zeolite group, smectite and chlorite (Appendix 2). Calcite is of special importance as it is deposited closest to the present time in the geothermal system. Temperature of calcite deposition is relatively difficult to determine, experience has shown that this mineral disappears at temperatures above 290^{o}C (Franzson, 2000, Krismannsdottir, 1979).

Table 1: Primary rock minerals and their product as found in well HE-24

Relative susceptibility	Primary rock minerals	Alteration mineral products
Most susceptible	Glass	clay, calcite, quartz
↓	Olivine	clay, calcite, sphene
	Plagioclase	clay, albite, calcite, quartz, wairakite, epidote
	Pyroxene	clay, actinolite, sphene
Least susceptible	Opaque	sphene, sulfides (pyrite)

4.3. Vein and Vesicles Fillings

The rocks encountered in the well are generally porous with a number of veins. Porosity can be classified into several types such as intergranular, joint and vesicular or vug type. Vesicular is common in Iceland where basaltic rocks predominate (Browne, 1984). These open voids become gradually filled with increasing alteration where limonite, siderite, and low temperature zeolite are found in the upper part and mostly clay, calcite, quartz, wairakite and epidote filling the vesicles in higher alteration. Hydrothermal alteration mineral deposition is mostly found in vesicles and veins. Voids are abundant in the hyaloclastites.

4.4. Alteration Mineral Zonation

In the geothermal areas, the study of altered basaltic rocks shows that the sequence of mineral assemblages relates to increased temperature and depth. The most common alteration minerals are the clay minerals. Other hydrothermal minerals present are silica, feldspar, calc-silicates, zeolites, carbonates, iron oxide, iron sulfides, sulfate, and sulfides (Browne, 1978). Below the hydrothermal alteration has been divided into temperature dependant zones as practiced in Iceland.

Unaltered zone (0-244 m)

The formations down to 244 m depth contain no alteration that is related to hydrothermal. XRD analysis show hardly any indication of smectite and the only mineral precipitations are limonite and siderite, both of which relate more cold groundwater conditions. The Skardsmýrarfjall formation belongs to this zone.

Smectite-zeolite zone (244-616 m)

The upper boundary of this zone coincides with the first occurrence of zeolites (including thomsonite, chabazite, scolesite) at about 244 m depth. XRD signature of smectite is still weak and remains so until below 446 m where it becomes stronger. Experience and data have confirmed that smectite starts to form below 200°C (Kristmannsdóttir, 1979).

Mixed layer clay zone (616-672 m)

The upper boundary is set by the first analysis of mixed layered clay at 620 m depth and the lower boundary is determined by the first appearance of chlorite at 672 m. The temperature assessment of this zone is 200-230°C (Browne, 1978, Kristmannsdóttir, 1979). Petrographic evidence shows the mixed layered clays as high coloured and very pleochroic clays.

Chlorite zone (672-1074 m)

The upper boundary of this zone is marked by the first appearance of chlorite in the XRD analysis at 672 m and the lower boundary is marked by the first appearance of epidote at 1074 m depth. Chlorite is identified petrographically as low-colour and non-pleochroic radial clays. With XRD-analysis chlorite is identified with peaks appearing at 14 and 7 Å, although the chlorite is considered unstable as the 7 Å peak collapses on heating. Chlorite has been estimated as forming at a minimum temperature of 230°C (Browne, 1978; Franzson, 1987).

Chlorite-epidote zone (1074-1172 m)

The upper boundary of this zone is characterized by the appearance of epidote. Other minerals in the zone include quartz, wollastonite and sometimes prehnite. The upper boundary of the zone is believed to conform to 240-250°C (Kristmannsdóttir, 1979).

Epidote-actinolite zone (>1172m)

The upper boundary of this zone is marked by the first appearance of actinolite. Actinolite was first identified from petrographic thin section at 1172 m depth and binocular microscope at 1176 m. This mineral is mainly found as an alteration of pyroxene. Actinolite appears to form at a minimum of about 280°C (Kristmanndóttir, 1979).

4.5. Mineral Deposition Sequence

The mineral sequences deposited from the geothermal system in to vesicles and veins were studied petrographically. The depositional minerals were found mostly in vesicles and veins. The alteration mineral assemblages change from low temperature minerals such as zeolites to moderate-high temperature minerals with increasing depth, such as quartz, wairakite, prehnite, wollastonite and actinolite.

Clay and calcite are the most common minerals participating in the mineral sequence in this well. The fine grained clay is mostly found as thin lining in the wall of the vesicles and veins, associated or deposited after chalcedony, which is also found near the boundary of veins and vesicles. Coarse grained clay is found especially filling in the veins or vesicles.

4.6. Fluid Inclusions

In well HE-24 quartz and calcite crystals were collected, but only calcite crystals were found to contain measurable fluid inclusions. A fluid inclusion study was conducted to assess temperature variation in the geothermal system. The fluid inclusion study in well HE-24 was done with samples collected at a depth around 660 and 2400 m. The homogenization temperature (Th) was identified from 101 primary and secondary inclusions. The range of homogenization temperatures vary from 195°C to 285°C at 660m depth (Figure 2) indicating changes in geothermal conditions from its formation. The wide range of temperatures probably reflect that at this depth is a very high thermal gradient of the cap rock. A few Th measurements were done in fluid inclusions in calcite at 2100 and 2400m depth about 250^{0}C, which is considerably lower than estimated from the presence of actinolite (>280^{0}C) at this depth range. The temperature however conforms with the present formation temperature in the well. Calcite in many cases has been seen to be a mineral depositing at a later stage in the geothermal system at Hellisheidi. Further study is underway to study these temperature variations in more detail.

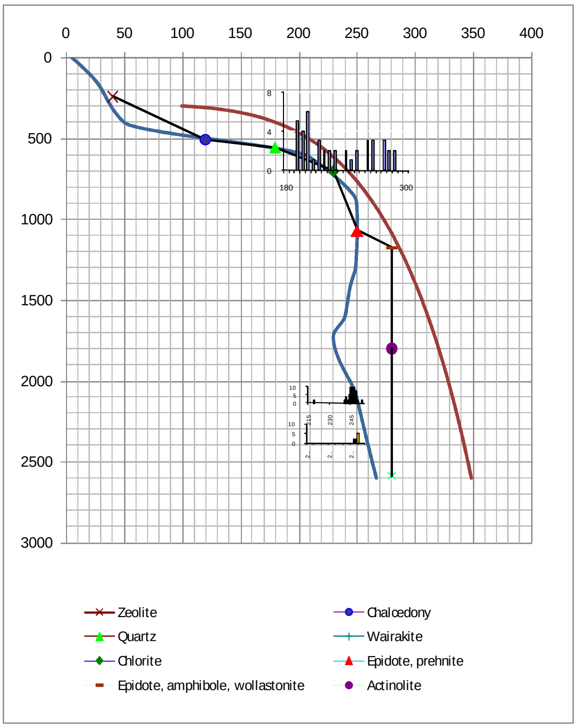

Figure 2: Formation temperature, Alteration temperature and fluid inclusion in calcite and quartz in well HE-24.

5. AQUIFERS

In this well, aquifers (feed points) were identified using various methods such as circulation loss data, temperature logs, intensity of alteration and other geological data. These feed points are divided into three relative sizes of aquifers as large, moderate and small aquifers which are located above and in the production part. In this well, the aquifers are mainly located at stratigraphic boundaries above the production part, while they appear mainly to be related to intrusions in the production part.

6. DISCUSSION

Generally, stratigraphy of well HE-24 consists of hyaloclastites and basaltic intrusions. The volcanic sequence is divided into different units based on the textural differences. The distinction of the volcanic sequences in the well is predominantly based on whether they are porphyritic or aphyric. Hyaloclastite units (sub-glacial eruptions) and subaerial basalts and intrusions were identified in the well.

The geological and hydrothermal alteration study shows that the degree and the intensity of rock alteration and the distribution of mineral alteration increase with depth. Below about 478 m depth, the degree of alteration increases rapidly both on grounds of temperature dependent minerals and alteration intensity.

Temperature has been defined in two ways in the well. Hydrothermal alteration mineral temperature, which was assessed according to the first appearance of the hydrothermal alteration minerals. The second one is the formation temperature which was determined by calculations based on the temperature measurements during the heating-up period. The alteration temperature curve of the well shows a progressive temperature increase with depth. The alteration mineral assemblage shows a trend, where low temperature minerals like zeolites forms in the upper part of the well and are gradually replaced by the moderate temperature minerals like chalcedony, quartz and wairakite which in turn give way to a higher-temperature mineral assemblages like chlorite, prehnite, epidote, wollastonite, actinolite and garnet in the lower part of the of well. The correlation of hydrothermal alteration, formation, and boiling point temperature curves is shown in Figure 4.

The mineral deposition sequence shows that low temperature zeolites form at an early stage of depositional sequence and in the later stage moderate temperature minerals such as quartz and wairakite are deposited in veins and vesicles. In the lower part of the well high temperature minerals such as wollastonite and actinolite precipitate. The clay minerals on the other hand are sensitive to changes in temperature and are found to become more crystalline with depth. In petrographic thin sections the clay minerals deposited in vesicles are observed to be either fine grained clay which usually is found as a thin layer lining the voids and vesicles and coarse grained clay usually as a chlorite and mixed layer clay, similarly deposited in the veins and vesicles. In this well, calcite is predominantly deposited in the last stage of the mineral sequences in the well. Data from the Hellisheidi geothermal field indicate that the last deposition of calcite might be associated with cooling in the later stages of the geothermal system (Franzson, 2000).

The aquifers in the production part down to 1200 m mostly relate to a basaltic intrusion. Feed points below 758 m are believed to be associated with a vertical dyke, possibly the feeder to the 5000 years old eruption. The rock, where the feed points appear, is heavily oxidized and is interpreted as a contact aureole adjacent to the dyke. Below this, the aquifer is located within the relatively fresh intrusive bodies.

7. CONCLUSIONS

The following conclusions can be deduced:

- Stratigraphy of the first 1200 m of well HE-24 consists of sub-glacial hyaloclastite formations and basaltic intrusion.

- According to the distribution of alteration minerals, one un-altered zone and five alteration zones were identified. Un-altered zone, smectite-zeolite zone (<200°C), mixed layer zone clay (200-230°C), chlorite zone (230-250°C), chlorite-epidote zone (>250°C) and epidote-actinolite zone (>280°C).

- According to circulation loss data, temperature logs, and intensity of alteration three relative sizes of aquifers are distinguished located above and in the production part.

- By studying the hydrothermal alteration minerals, it was found that the temperature rises rapidly at about 472-672 m depth with the appearance of zeolites, quarts, wairakite and mixed layered clays, while the temperature gradient is lower in the fairly thick chlorite zone at 672-1072 m depth. Below 1072 m depth the alteration increases again with the deposition of epidote, wollastonite, actinolite and garnet.

- Comparison of alteration mineral temperature and measured temperature shows that the geothermal system has cooled in the upper 700 to 800 m of the well, while cooling appears to be minor 750- 1200 m depth. In the lowermost parts of the wells, especially below 1600 m the reservoir appears to be cooling again.

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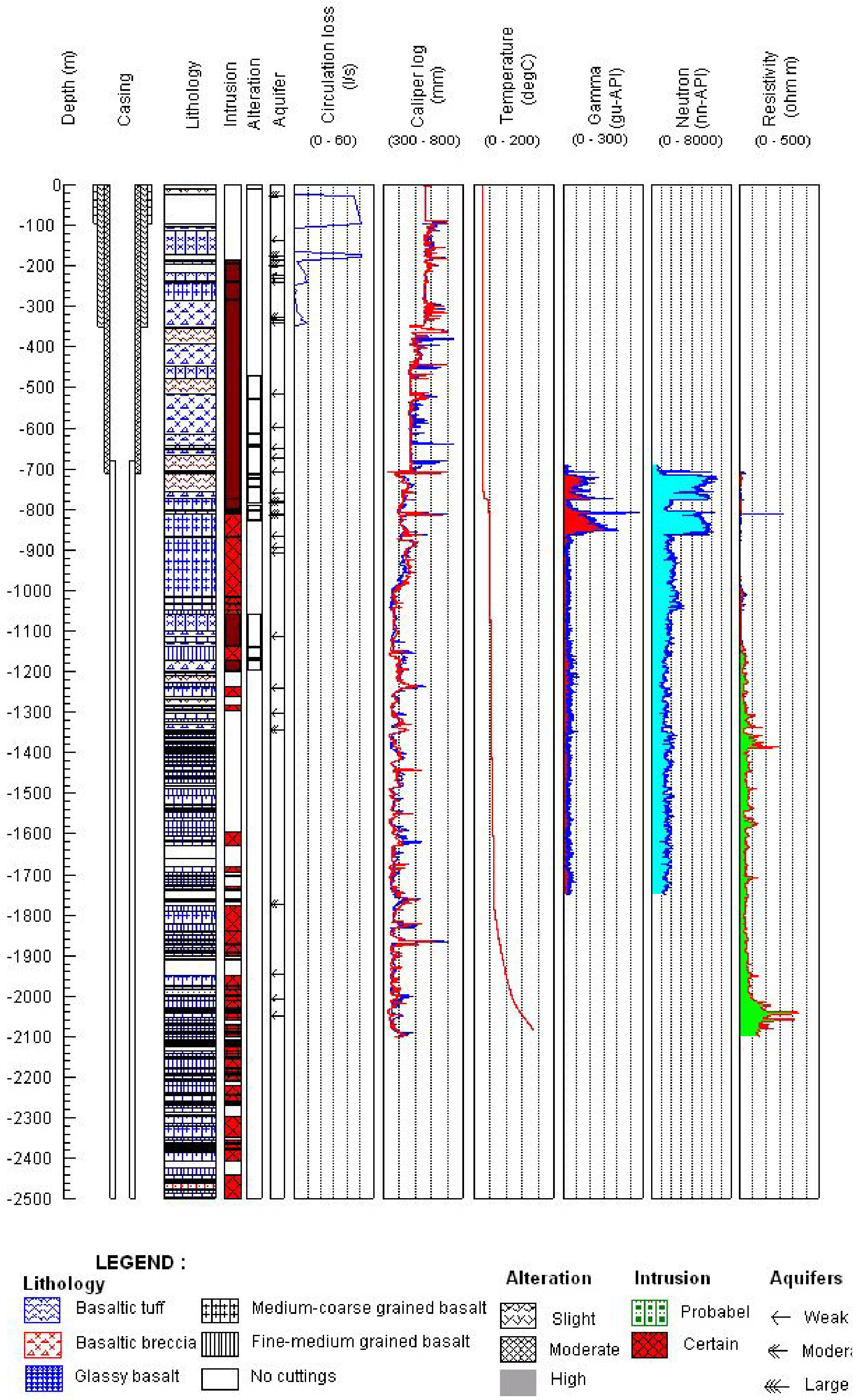
APPENDIX 1: Simplified stratigraphic section and geophysical logs of Well HE-24 (Data from Mortensen et al. 2006)



APPENDIX 2: Distribution of hydrothermal alteration minerals in well HE-24 (Data from Mortensen et. al. 2006 and Koestono 2007)