



## **BOREHOLE GEOLOGY AND HYDROTHERMAL ALTERATIONS OF WELL HE-39, HELLISHEIDI GEOTHERMAL FIELD, SW-ICELAND**

**Peter Kiranga Mbia**

Geothermal Development Company – GDC  
P.O. Box 100746-00101,  
Nairobi  
KENYA  
*pmbia@gdc.co.ke*

### **ABSTRACT**

Well HE-39 is located on Mt. Skardsmýrarfjall in the northern part of the Hellisheidi high-temperature field in the southern sector of the Hengill central volcano in SW-Iceland. It is a directional well with a total measured depth of 3055.5 m. The well was drilled with the aim of targeting 2000 and 5000 year old NE-SW trending volcanic fissures and to explore the geothermal system northeast of Mt. Skardsmýrarfjall. Drilling started on 13<sup>th</sup> October 2007 and was completed on 15<sup>th</sup> April 2008. The lithology of the well consists of basaltic hyaloclastite formations, basaltic lava flows and dyke intrusions. This report describes the uppermost 1000 m of the well, analysed as a part of this UNU-GTP project. Geophysical and drilling data indicate that permeability in the well is related to lithological contacts, intrusives, boundaries, and major faults and fractures. Aquifers in the top 1000 m of the well are related to stratigraphic and intrusive boundaries. Hydrothermal alteration in the well is controlled by temperature, rock type and permeability. The mineral assemblage showed the evolution of the hydrothermal system from low- to high-temperature conditions followed by cooling, which is evidenced by the precipitation of calcite at later stages. Mineralogical examination revealed five zones of hydrothermal alteration beneath a zone of unaltered rocks, associated with zeolite-smectite (<200°C), mixed layer clays (200-230°C), chlorite (230-240°C), chlorite-epidote (>240°C) and epidote-actinolite (>260°C). In general, this study shows that there are three successive stages within the history of the geothermal system: a progressive heating, a later cooling episode and finally a probable renewed heating phase, which may relate to the two Holocene fissure eruptions. An attempt to compare alteration sequences of wells OW-909, OW-901, OW-902 and OW-903 from Olkaria, Kenya revealed four hydrothermal alteration zones beneath an unaltered zone, the zeolite-chlorite zone, illite-chlorite zone, epidote-illite-chlorite zone and garnet-biotite-actinolite zone.

## **1. INTRODUCTION**

### **1.1 The study area**

HE-39 is located in the northern part of Mt. Skardsmýrarfjall in the Hengill geothermal field. It is a directional well with a total measured depth of 3055.5 m. This well was designed as a production well

with an aim of intersecting 2000 and 5000 year old volcanic fissures and to explore the geothermal conditions below the little known Innstidalur valley (Figure 1). The Hengill area is located in SW-Iceland (Figure 2) within the western branch of the active volcanic zone (e.g. Saemundsson, 1979). It is one of the largest geothermal areas in Iceland, covering about 110 km<sup>2</sup>. Large scale utilization of the geothermal resource started in 1990, when Reykjavik Energy commissioned a 100 MWt hot water plant at Nesjavellir, north of Mt. Hengill, to be used for space heating of the capital city, Reykjavik, and the surrounding communities. Since then, hot water production has been increased to 290 MWt (Árnason et al., 2010). The electricity generation at Nesjavellir started in 1998 when a 60 MWe power plant came online. Production was expanded in 2001 (30 MWe) and in 2005 (30 MWe) to the present capacity of 120 MWe. In 2006, the first phase of the Hellisheidi power plant, built and operated by Reykjavik Energy south of Mt. Hengill, was commissioned with an installed capacity of 90 MWe. The Hellisheidi plant was expanded in 2007 (33 MWe) and in 2008 (90 MWe) and is now generating 213 MWe. In other words, the total installed power production capacity in the Hengill geothermal area is 333 MWe. Geothermal exploration in the Hengill region had been intermittently going on from the 1940s until the 1980s when it was intensified for the preparation of the Nesjavellir plant. This geological report describes the uppermost 1000 m of well HE-39, which was studied in correlation with HE-37, located on the same pad. In addition, the results from Mt. Skarðsmýrarfjall were compared to wells located in the Olkaria geothermal field (Kenya) within the East African rift system. This report is a fulfilment of a six months training course at the UNU Geothermal Training Programme in Iceland in 2010.

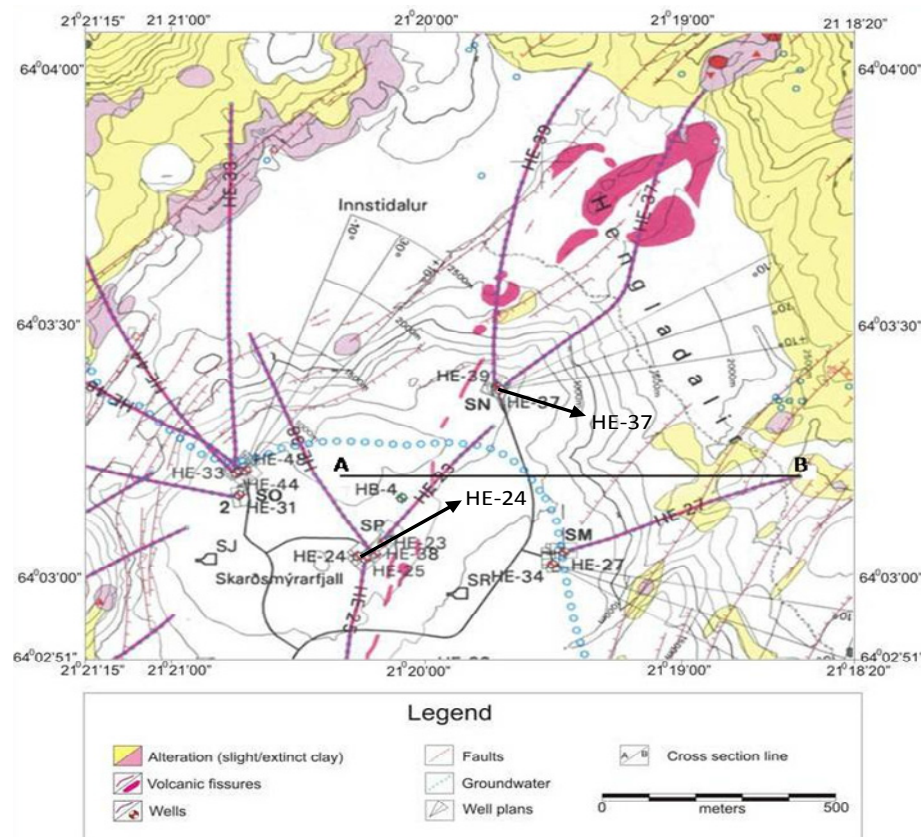


FIGURE 1: Location of wells HE-39 and HE-37 on Skarðsmýrarfjall in Hellisheidi, Hengill field (Gebrehiwot, 2010)

This report is a fulfilment of a six months training course at the UNU Geothermal Training Programme in Iceland in 2010.

## 2. GEOLOGICAL AND TECTONIC SETTINGS OF THE HENGILL AREA

### 2.1 Main aspects of tectonics and geology of Iceland

Iceland is unique in its location astride the diverging Mid-Atlantic Ridge and, furthermore, is located on top of a mantle plume (Saemundsson, 1979; Hardarson et al., 1997). This constructive plate margin appears above sea-level in Iceland, one of the few countries in the world attaining an increase in its surface area due to the creation of new lithosphere by sea floor spreading. It lies astride one of

the Earth's major fault lines, the Mid-Atlantic Ridge, which is the boundary between the North American and the Eurasian tectonic plates which move apart at an average rate of 2 cm per year (e.g. Saemundsson, 1979). Iceland resides on a mantle plume and has been formed in frequent volcanic eruptions continually from Miocene time to the present. This explains why this part of the ridge rises above sea level and formed an island with an area of 103,000 km<sup>2</sup>. The currently active zone of rifting and volcanism crosses Iceland from southwest to northeast, as indicated in Figure 2. Volcanic eruptions are very frequent within this zone and take place typically every few years. The Icelandic crust is, therefore, very young on the geological time scale. Rocks on the surface range in age from zero, near recently active volcanoes, to 15-16 million years in the coastal areas furthest away from the volcanic zone in the east and the west (e.g. Saemundsson, 1979; Hardarson et al., 1997).

Iceland is rich in geothermal resources due to the volcanic activity, and heat flow through the crust is several times higher than the world average. More than 200 volcanoes are located within the active volcanic zones stretching through the country from the southwest to the northeast, and at least 30 of them have erupted since the country was settled a thousand years ago. In this volcanic zone, there are at least 20 high-temperature areas containing steam fields with underground temperatures reaching 200°C within 1,000 m depth. These areas are linked to the active volcanic systems (Hardarson et al., 1997).

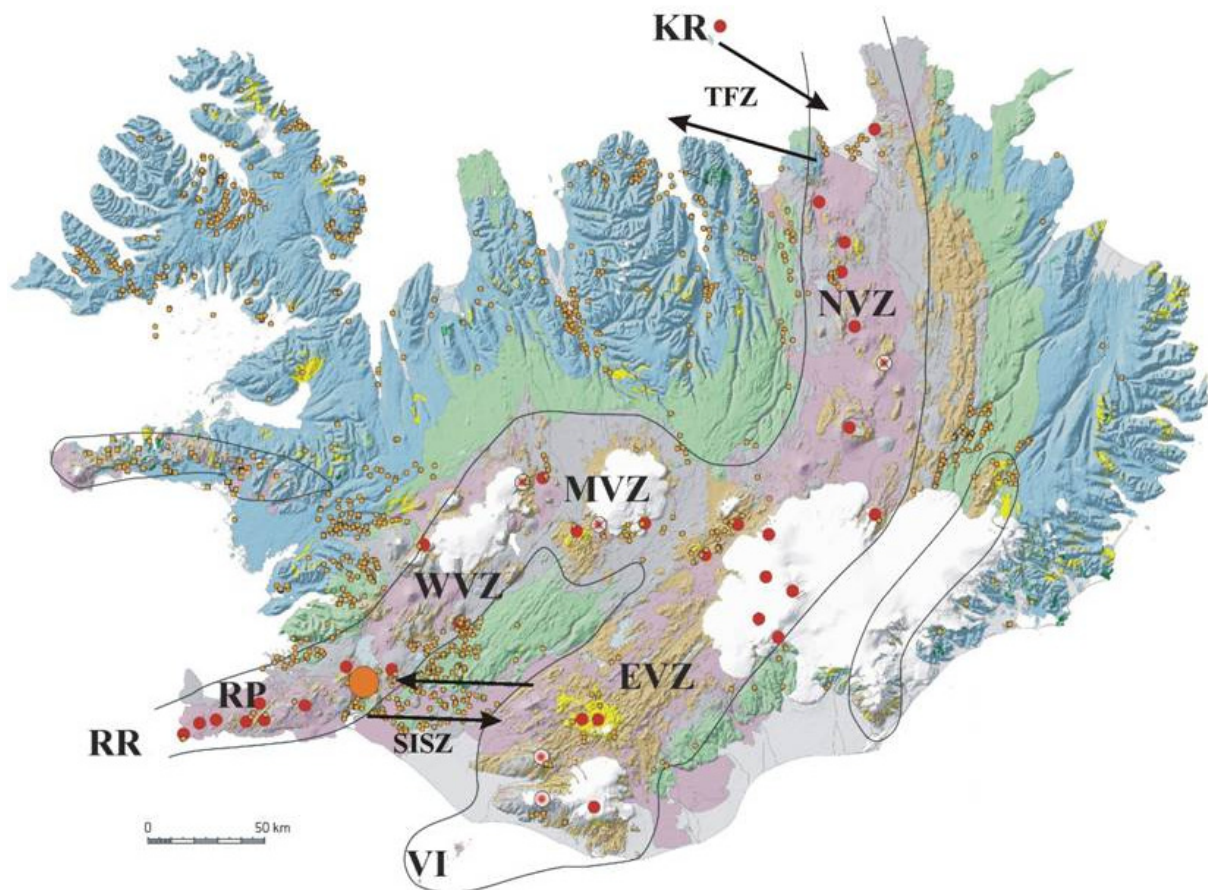


FIGURE 2: Geological map of Iceland showing location of the active volcanic zones and transform faults. RP=Reykjanes Peninsula; WVZ=Western Volcanic zone; MVZ=Mid-Iceland Volcanic Zone; NVZ=Northern Volcanic Zone; EVZ=Eastern Volcanic zone; VI=Vestmanneyjar Islands.

SISZ=South Iceland Seismic Zone; TFZ=Tjörnes Fracture Zone; Orange circle represents the approximate location of the Hengill volcanic system (modified from Jóhannesson and Saemundsson, 1999)

## 2.2 Geological structure and volcanic succession of Hengill geothermal field

The Hengill volcanic system is located in the southern end of the western volcanic zone (WVZ) of Iceland (Figure 2). It is at the triple junction of the WVZ, the Reykjanes peninsula (RP), which is the landward extension of the Reykjanes spreading ridge, and the south Iceland seismic zone (SISZ), which is a transform zone, transferring part of the crustal spreading from the WVZ to the eastern volcanic zone (Hardarson et al., 2009). The volcanic products in the Hengill area are mainly basalts but some acidic rocks occur on the surface southwest of Mt. Hengill; acidic rocks are also found as intrusives in boreholes. The Hengill geothermal field is divided into at least five geothermal fields: Nesjavellir, Hellisheidi, Hengladalur, Hverahlid and Ölkelduháls (Figure 3).

The Hengill volcanic system is currently active while its predecessors, the Graendalur and Hveragerdi systems, are now extinct in terms of volcanic activity but are still active seismically and host geothermal reservoirs. Structurally, the Hengill system is dominated by a large NE-SW striking fault/fissure swarm which is, however, intersected in places by easterly striking features which may play an important role in the permeability of the geothermal field (e.g. Árnason and Magnússon, 2001; Hardarson et al., 2007). The volcano is mainly comprised of hyaloclastite formations which erupted beneath the ice sheet of the last glacial age, forming a mountain complex rising up to some 600 m elevation at Mt. Skarðsmýrarfjall. Interglacial lavas, on the other hand, flowed down and accumulated in the surrounding lowlands. The age of the volcano has been estimated to be slightly older or around 400,000 years old (Franzson et al., 2005).

Hyaloclastites form when magma is quenched during eruptions into the base of a glacier, or during submarine eruptions, and piles up into a heap above the orifice, mostly as pillow basalts, breccias and tuffs. Although of relatively high porosity, these formations tend to have low permeability, especially when they have been hydrothermally altered. Most of the rock formations are basaltic in composition, ranging from picrite to tholeiite; occasionally evolved rocks are seen, especially as intrusive bodies. The Hellisheidi field is within the Hengill central volcanic system where volcanism is most intense, and where hyaloclastites have formed highlands. Interglacial lavas, however, when erupting in the highlands, flow downhill and accumulate on the lowlands surrounding the volcano (Franzson et al., 2005).

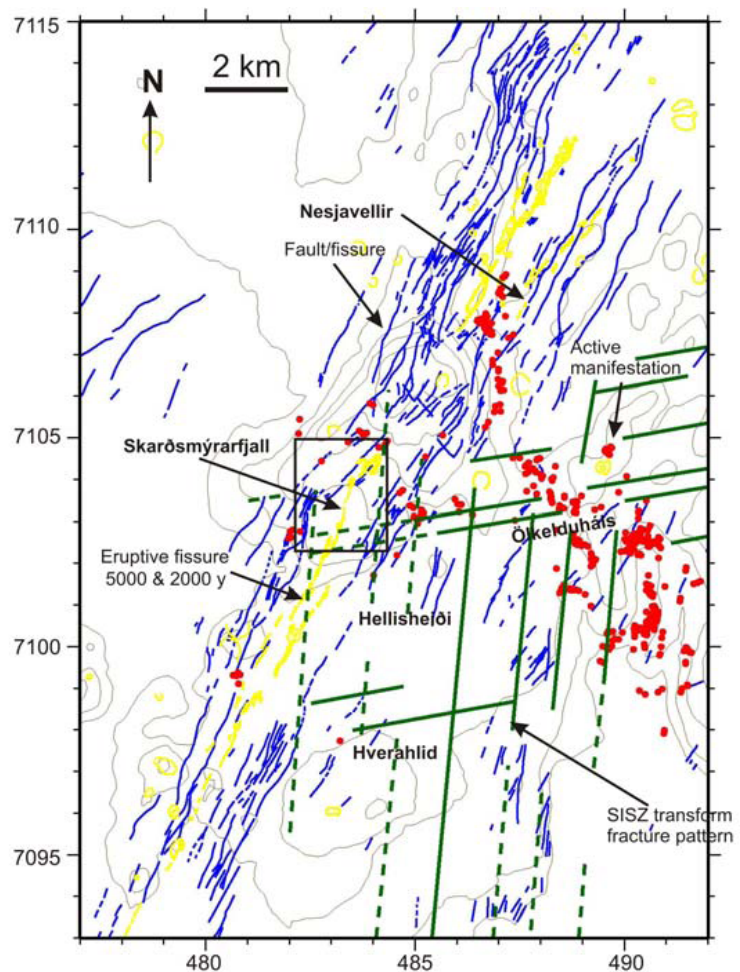


FIGURE 3: The Hengill volcanic system with fissure swarm, and a central volcano, including geothermal manifestations, topography, transform faults, and Postglacial eruptive fissures (from Árnason et al., 2010)

### 3. SURFACE EXPLORATION

#### 3.1 Surface geology

The geology of the Hengill volcanic system has been intensely studied. The main component of the volcanic system is the 3-5 km wide and at least 40 km long fissure swarm, with active rifting and maximum volcanic accumulation, in the central part of the Hengill volcano (Figure 3). The fissure swarm is within a depression or a graben structure, with large faults showing a total throw on the western side of more than 300 m (e.g. Franzson et al., 2010). The faults on the eastern side have not been located accurately but are assumed to have an overall similar throw taken up by a greater number of step-faults (Franzson et al., 2010). The largest part of the volcano is built up of hyaloclastite formations erupted during glacial times, while minor interglacial lavas erupted in the highlands and flowed to the surrounding lowlands. Intermediate and acid rocks are found on the western flanks of the volcano, but have also been found as intrusives in the drill holes throughout the geothermal fields.

Faults and major fractures mostly strike NE-SW and are conspicuous in the east and west, marking the boundaries of the volcano's fault and fissure zone. Postglacial volcanism includes three fissure eruptions, aged 9000, 5000, and 2000 years (Figure 1). The fissures can be traced to the north, through the Nesjavellir field and into Lake Thingvallavatn (Saemundsson, 1995a). The latter two eruptions play an integral role in the explored part of the Hengill geothermal system. Surface geothermal alteration (Saemundsson, 1995b) is extensive and most common in the Hengill table mountain in the centre of the volcanic complex; but is also evidenced throughout the volcano (Figures 1 and 3). Most of the alteration patches show a clear relationship to tectonic faults and fissures (Franzson et al., 2010).

#### 3.2 Geophysical exploration

Several geophysical exploration methods were used to define the structures and the characteristics of the geothermal systems in the Hengill area, including Bouguer gravity surveys, aeromagnetic surveys, seismic refraction and passive seismic surveys. The most informative method in defining the geothermal reservoir in the Hengill area is, however, resistivity (Figure 4). The methods used include Schlumberger and dipole-dipole surveys (Björnsson and Hersir, 1981). In 1987, the TEM method was applied and, to date, some 280 TEM soundings have been made in the Hengill area (e.g. Árnason et al., 2010; Franzson et al., 2010).

Árnason et al. (2000) related the resistivity structures to variations in hydrothermal alteration, where the low-temperature clay-rich outer margins of the high-temperature reservoir are characterised by low-resistivity and the underlying higher resistivity is associated with the formation of chlorite and less conductive alteration

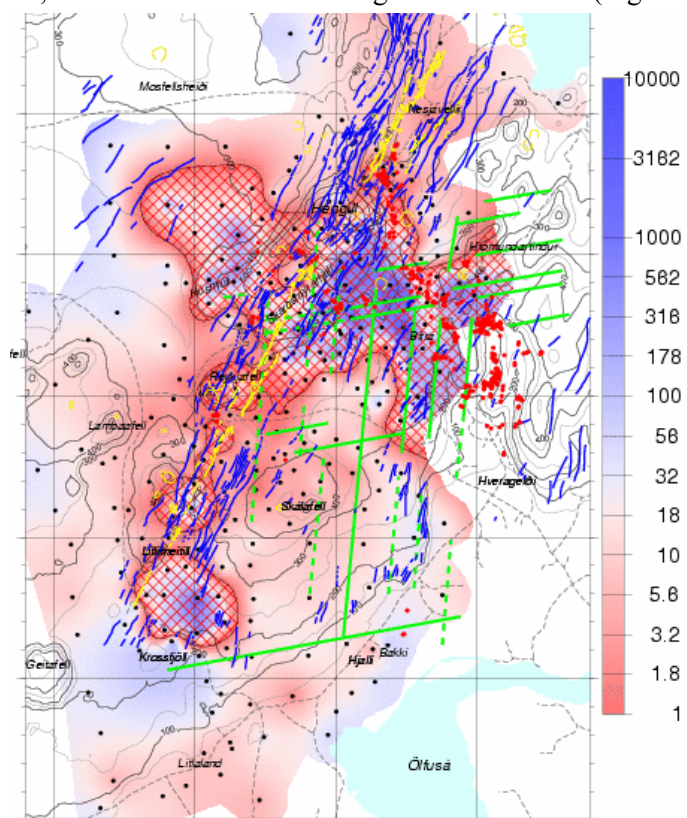


FIGURE 4: Resistivity map of the Hengill central volcano at 850 m b.s.l. showing a high-resistivity core below the main low-resistivity layer, indicating alteration temperatures above 220°C (Árnason et al., 2010) in the Hengill area at 1000 m b.s.l. according to TEM data (Árnason and Magnússon, 2001)

assemblages. Figure 4 shows the resistivity at 850 m b.s.l. in the Hengill area. High resistivity shows some relationship to the dominant NNE-SSW alignment of the fissure swarm. A broad WNW-ESE structure crosses Hengill from Húsmúli in the west to Bitra and Hveragerdi in the east. These structures have been confirmed by temperature dependent alteration zonation in drillholes, but present formation temperatures have been variable (Árnason and Magnusson, 2001).

#### 4. BOREHOLE GEOLOGY

Before embarking on well siting and subsequent drilling, geological, geophysical and geochemical surface explorations must be performed to earmark the resource area. The vertical and horizontal extents of the geothermal reservoir, its thermal and hydrological characteristics, and the structures controlling the flow of the geothermal fluids must be fully confirmed before drilling a well into the geothermal resource area.

##### 4.1 Materials and analytical methodologies

The geological data is chiefly based on cutting analyses from samples taken at 2 m intervals in well HE-39, where the delay time of the cuttings in the well has been corrected for. The geophysical logs (caliper, neutron-neutron, natural gamma, and resistivity) were also extensively analysed to make the geological interpretation as accurate as possible. This report describes the uppermost 1000 m of the well where about 500 samples were analysed. This forms the foundation of the description of the subsurface geology, distribution of the alteration minerals and the alteration sequences in the well.

The cuttings, which were drilled and crushed by the drilling bit at the bottom assembly, were carried to the surface by mud, water or air and collected at the shakers. These samples were labelled with depth, name of the well and date collected and then stored in 125 ml plastic containers. After thorough washing, the samples were analysed wet to enhance the visibility using a binocular microscope. Drill cutting analysis of rock samples is a visual method of describing the rock and pore characteristics. Unlike core samples, the interpretation of a cutting analysis is far more difficult as there are several complications regarding the collection of cuttings which have to be accounted for. For instance, the composition of the cutting samples may not represent the actual rock penetrated as drilling softer, more brittle, more readily cleaved, or finer-grained minerals may result in their depletion in a sample during collection, or previously drilled units may be incorporated into a sample. The time required for samples to reach the surface must be compensated for; otherwise interpretation errors are produced as drilling depth is likely to be greater than the actual depth from which the sample came from (e.g. Low, 1977). Interpretation becomes even more difficult as cutting size decreases with increasing depth and becomes finer grained. Twenty three thin sections, selected from specific depths and based on the alteration of the rock samples, were prepared and studied using a Leitz-Wetzlar model petrographic microscope. For clay analyses, samples were selected and run through XRD-equipment. Fluid inclusions were identified from specific depths (mostly quartz and calcite were selected for the fluid inclusion studies) and were analysed using a fluid inclusion microscope. In addition to these analyses, geophysical logs give information on the structure, physical properties and performance of the geothermal system penetrated by the well (e.g. Stefánsson and Steingrímsson, 1990). Because of the difference in electrical properties between different formations, the resistivity logs will show lithological variations clearly. The natural gamma log detects the gamma radiation from rocks due to isotopes even though these isotopes are found in very small quantities. The count rate measured by a gamma ray tool at each depth in a borehole is related to the concentration of the radioactive isotopes  $^{40}\text{K}$ ,  $^{238}\text{U}$  and  $^{232}\text{Th}$  in the formation outside the well, and defines a quantity that is called the radioactivity of that formation (e.g. Stefánsson and Steingrímsson, 1990). This log is especially helpful in identifying intermediate to acid intrusives as these rocks contain elevated concentrations of the above isotopes compared to basaltic rocks. The neutron logs are used in porosity

investigations and can be related to the porosity of the formation while the caliper logs measure the diameter of the well. Geophysical, drilling, and borehole geological data were computed using the Log Plot (Rock Ware, Inc) software for correlation of these parameters.

## 4.2 Drilling

Well HE-39 is a directional well with a total measured depth of 3055.5 m. The well was drilled to explore the northern extent of large eruptive Postglacial fissures and to investigate the geothermal conditions under the little known Innstidalur valley in the Hengill graben (Figure 1). It is a wide diameter type well (Table 1). The well is located on Mt. Skardsmýrarfjall in the northern sector of Hellisheidi in the southern sector of Hengill high-temperature geothermal field at ISN 93 coordinates: X = 385863.359 and Y = 397175.338 at an elevation of 563 m a.s.l.

TABLE 1: Casing depths and program of well HE-39

Drill rig & KRB	Hole size (")	Maximum depth (m)	Casing depth (m) RKB	Casing diameter (")
Sleipnir (5.8 m)	26	99	95.4	22½"
Sleipnir (5.8 m)	21	305	303.4	18⅝"
Sleipnir (5.8 m)	17½"	780.5	750	13⅜"
Týr (7.6 m)	12¼"	3055.5	3055.5	9⅝"

Drilling of the well started on October 13<sup>th</sup> 2007 and was completed on 15<sup>th</sup> April 2008. As indicated in Figure 5, drilling was performed in three stages: the first and second phases used the rig Sleipnir and the final section, the production zone, was drilled by the rig Týr. The first section (pre-drilling phase) was performed with a 26" drill bit to a depth of 99 m and was cased with 22½" casing (Table 1). The water level was encountered at 73 m. About 33 m<sup>3</sup> of cement was used to anchor the surface casing.

*First phase:* Drilling of a 21" hole proceeded with mud as the drilling fluid, but at 167 m depth about 5-6 l/s of the drilling fluid was lost to a fractured formation and in an effort to reduce the loss, mica was added to the fluid. However, at a depth of 260 m, further loss of circulation was experienced (40 l/s) and the drilling fluid was changed to water and several gel pills were added. Gradually, the circulation loss decreased and drilling was continued using mud. Drilling was stopped at 305 m depth and geophysical logs and a temperature profile were performed before the 18⅝" casing was installed and cemented (Table 1). About 36 m<sup>3</sup> of cement was used to cement this section.

*Second phase:* The second section of the well was drilled with the same rig to a total depth of 780 m, with a 17½" bit and mud motor but the kick-off point started at 324 m with an inclination target of 30°+/-3° and azimuth of 0° +/-15° at the end of the section. Several gyros and geophysical logs were run before the 13⅜" production casing was installed and cemented.

*Third phase:* On October 30<sup>th</sup>, the 23<sup>rd</sup> working day, Sleipnir, the rig was shifted to another area in Skardsmýrarfjall. Six months later, the rig Týr was rigged up and drilled a 12¼" hole to 3055.5m depth. This section was characterised by several intermittent-to-total circulation losses from 1675 m to the bottom of the well even though air drilling was adopted in an effort to recover the circulation. At 2948 m, the drilling string got stuck in the hole and all efforts were carried out to un-do the string which eventually got loose. Reaming was done later and several gyros and geophysical logs were performed before drilling proceeded. Eventually, the drilling speed became very slow accompanied by high torque which forced the drilling team to terminate the drilling operations at 3055.5 m depth (Table 3). Reaming and cleaning of the hole was performed before final geophysical logs and gyros were run. The drilling of the well took more time than was stipulated due to a winter break,

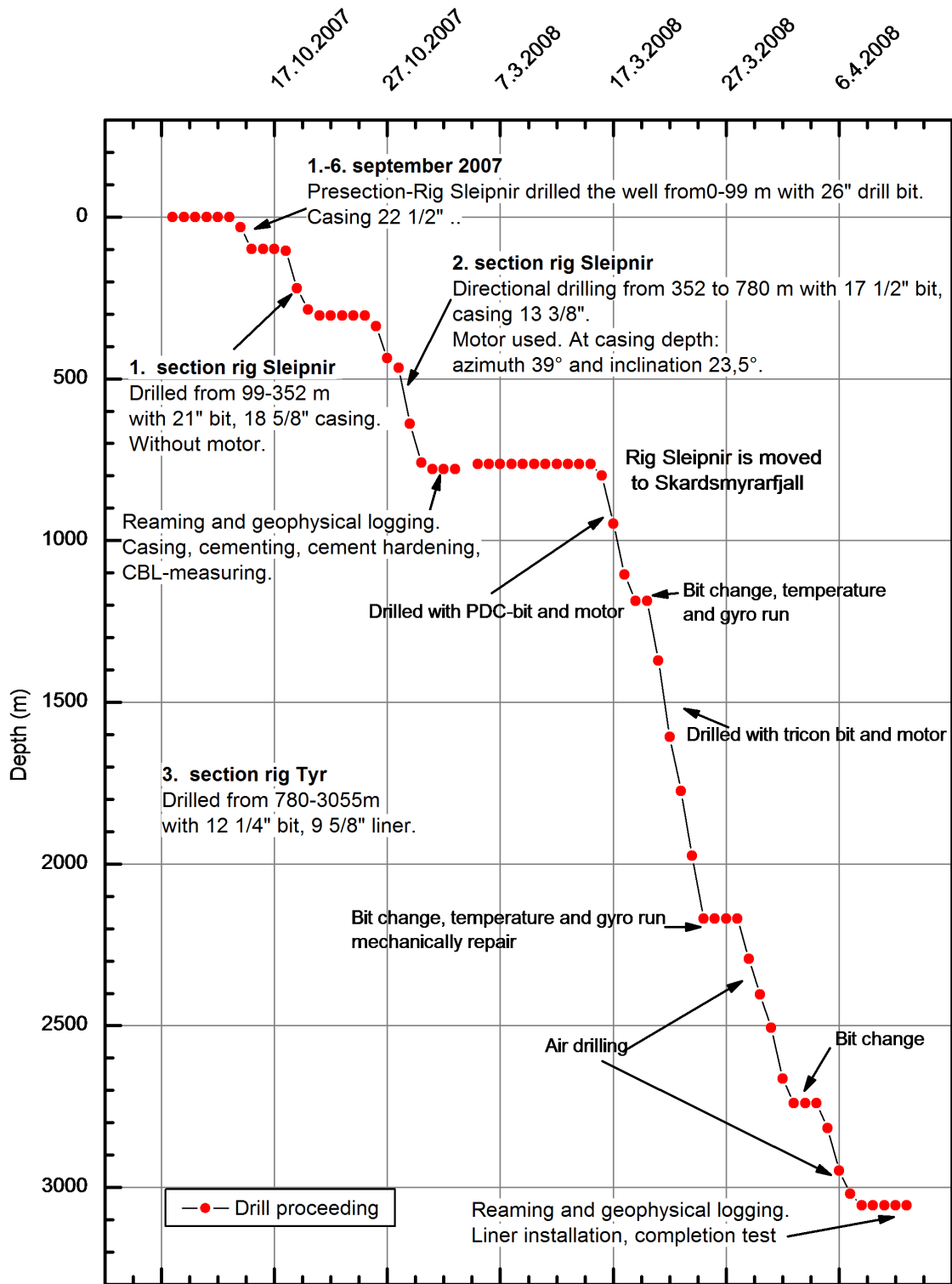


FIGURE 5: Drilling progress of well HE-39

changeover of the rigs and several geophysical and gyro runs which were performed during drilling. When 9 5/8" liners were fitted, the procedures for stimulating the well started and completion tests were done before the rig was released on April 15<sup>th</sup>, 2008. Gyro measurements showed that the inclination angle of the well at 2670 m was 29.5°, which was within the targeted range, whereas the azimuth was 30.5° NE at the same depth, which was well outside the target of 0° +/- 15°. The drilling progress of the well HE-39 is shown in Figure 5.



### 4.3 Stratigraphy

The main rock types that comprise the geology of the upper 1000 m of well HE-39 are hyaloclastite formations and basaltic intrusions. This classification is mainly based on the crystalline and/or textural character of the rock which shows either porphyritic or aphyric characteristics, shown by binocular and petrographic analyses. The rock types include basaltic tuff or volcanic glass, glassy basalt, or pillow basalt containing predominantly crystallized rock with minor amounts of volcanic glass, basaltic breccias, a mixture of partially crystallized basalt and fine- to medium-grained crystallized basalt which forms either lava or intrusions. These volcanic rocks are variably altered depending on the hydrothermal activities and the porosity of the rock formations. The intrusive rocks encountered are moderately fresh and well crystallized. A simplified vertical section of the geological formations from the surface to 1000 m depth is shown in Figure 6 along with the alteration minerals and alteration zones. The locations of intrusions and aquifers are indicated. The stratigraphy of the well, along with geophysical logs, is shown in Figure 7.

#### **Skardsmýrarfjall formation (12-304 m)**

The Skardsmýrarfjall formation covers the upper part of the well and consists of hyaloclastic tuff, glassy basalt (pillow lava) and basaltic breccia of olivine tholeiite composition.

*Basaltic breccia (12-20 m):* These breccias are dark grey mixtures of fresh, glassy fragments of basalt and tuffs. Crystalline fragments are porphyritic with plagioclase phenocrysts. The breccia is oxidized and common alteration minerals are siderite and limonite fillings in vugs and vesicles. The oxidation is due to the interaction of surface groundwater with the rocks.

*Pillow basalt (20-104 m):* Greyish to yellowish brown porphyritic rock. The phenocrysts are plagioclase, olivine and magnetite. The unit is relatively fine-grained except for very small oxidation tints on vesicular walls; it is fresh, porous crystalline glassy basalt of olivine tholeiite composition. The original porosity of the unit is reduced by clays being deposited in vesicles. Alteration minerals present are siderite (radiating carbonates), limonite and some fine-grained clays.

*Basaltic tuff (104-140 m):* This hyaloclastites tuff unit is brownish yellow in colour, fine grained with glassy fragments. It is highly porous, foamy and with minor plagioclase and olivine phenocrysts. Minor oxidized tints. Limonite, siderite and minor amounts of clays are the main alteration minerals. Small calcite veins were also identified.

*Pillow basalt (140-304 m):* This hyaloclastite is dark grey, porous and partially crystalline, predominately glassy or consisting of fine- to medium-grained porphyritic rock. The phenocrysts consist of plagioclase and pyroxenes with olivine and opaque minerals in the groundmass.

#### **Hyaloclastite formation I (304-326 m)**

This formation occurs below the Skardsmýrarfjall formation and consists predominantly of aphyric basaltic tuff. The glass within this formation is relatively dark or greenish in colour as a result of alteration. It is mostly dominated by low temperature hydrothermal minerals such as mesolite, scolecite and stilbite. Pyrite and calcite appear in this section which may indicate permeability.

#### **Hyaloclastite formation II (326-376 m)**

This hyaloclastite formation consists of basaltic tuff which is generally greenish grey in colour, porous and has plagioclase and pyroxenes occurring as phenocrysts. The intensity of alteration within the unit is moderate with low-temperature zeolites such as stilbite, mesolite/scolecite in addition to clays. Calcite occurs in vugs and vesicles. Pyrite contents continue to increase. Minor veins are filled with calcite, and clays were also identified.

#### **Sediments (376-396 m)**

This is a thin layer of tuff rich sediments which are silty and very fine-grained in texture.

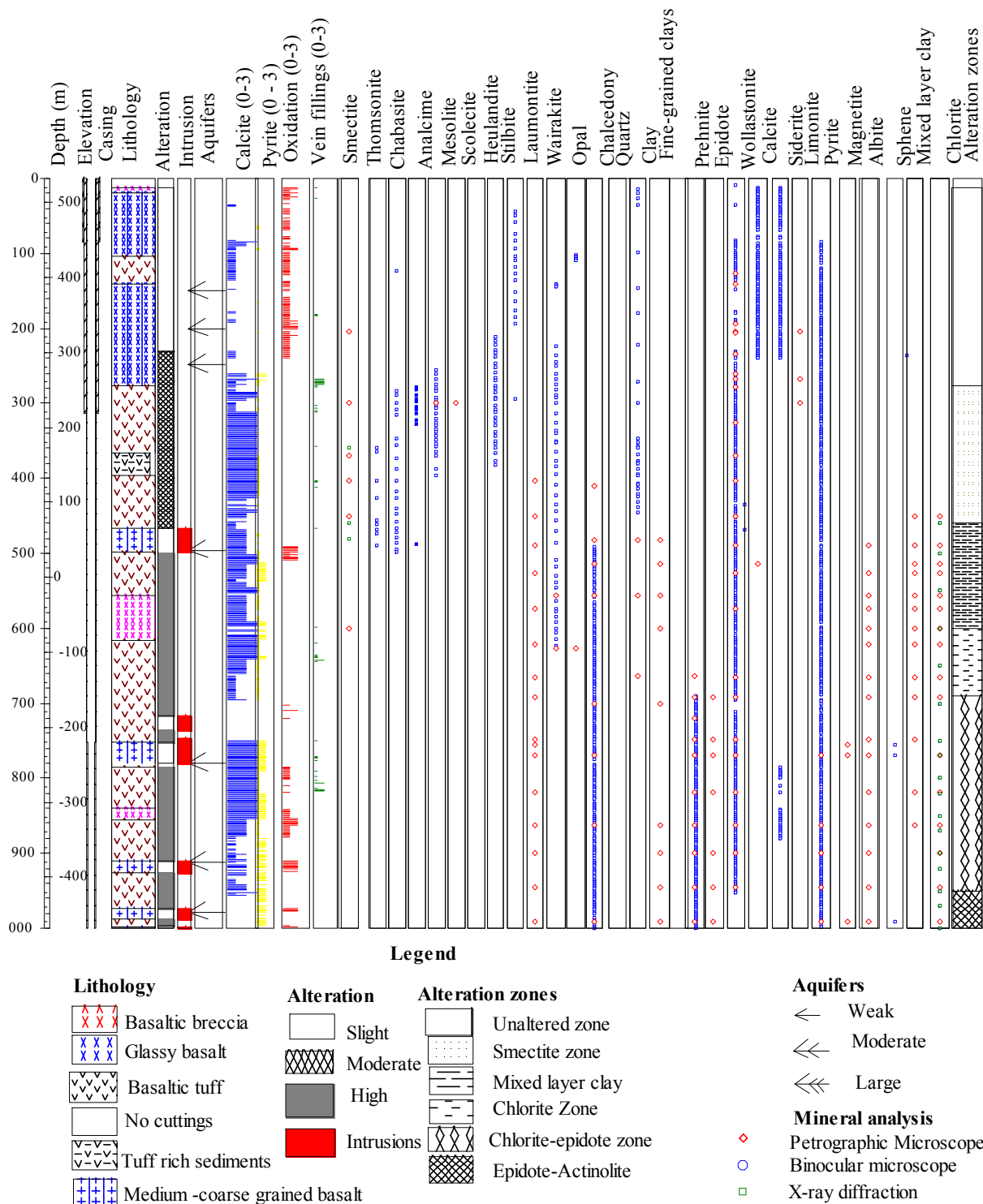


FIGURE 6: Simplified stratigraphic section and distribution of hydrothermal alteration minerals in the top 1000 m of well HE-39

**Hyaloclastite formation III (396-616 m)**

This formation is aphyric and consists predominantly of basaltic tuff and basaltic breccia with fresh, medium-grained crystalline basalt occurring as an intrusion. The main difference between the two hyaloclastite formations is the texture, being porphyritic and aphyric, respectively. Chalcedony, zeolites (like mesolite/scolecite, stilbite), quartz and wairakite were the identified hydrothermal minerals. The basaltic breccia occurs as a mixture of glassy fragments with partly crystallized basalt

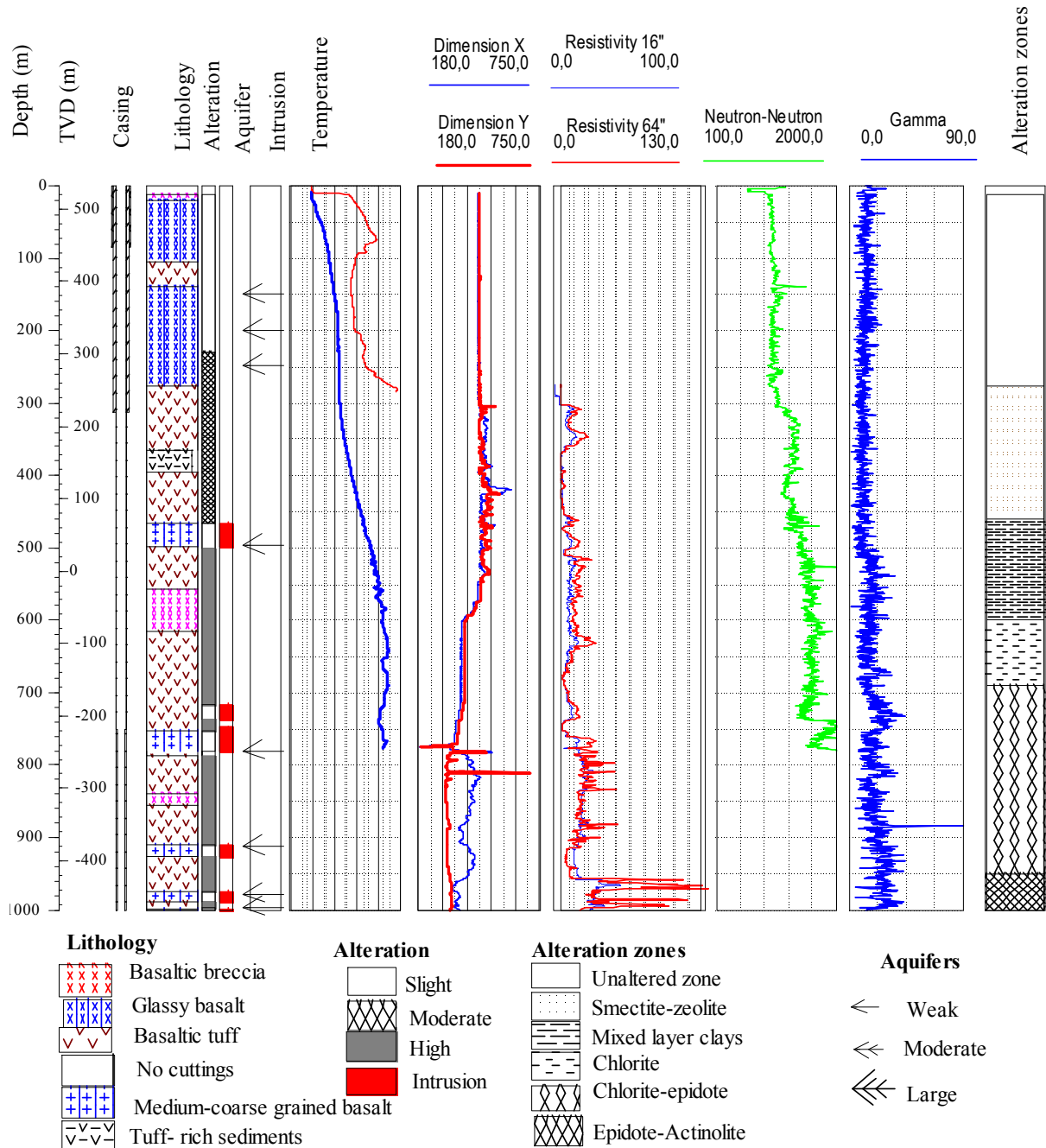


FIGURE 7: Stratigraphic section and geophysical logs of well HE-39 from 0 -1000b m which is generally moderately altered. Calcite and pyrite were also present.

*Crystalline basalt (466-498 m):* Relatively fresh dark grey fine- to medium-grained porphyritic intrusive rock.

*Basaltic tuff (498-556 m):* The formation is light green in colour, and consists of fine-grained and porous volcanic glass. It predominantly shows strong alteration of glassy fragments into wairakite and clay minerals. Pyrite is also present in large amounts.

*Basaltic breccia (556-616 m):* This unit is a mixture of tuffaceous material with crystalline basalt fragments of different textures. It is weakly to moderately altered with wairakite, calcite, limonite and clays as the main alteration minerals. Calcite occurs as a replacement mineral in vugs and phenocrysts. The rock is also veined.

**Hyaloclastite formation IV (616-780 m)**

This hyaloclastite formation comprises mainly basaltic tuff with a major basaltic dyke intrusion from 752 to 780 m. The unit is aphyric to sparsely plagioclase porphyritic and is partly oxidized. The formation is highly altered and is light greenish in colour. The glassy fragments are totally altered into medium-grained clays. Calcite, wollastonite, quartz and clays are the main alteration minerals. It is in this unit, at 690 m depth, that the first appearance of non-crystalline epidote was identified. The crystalline fragments are fresh, unaltered, medium- to coarse-grained basalt. Total loss of circulation was experienced from 780 to 786 m.

**Hyaloclastite formation V (786-840 m)**

This hyaloclastite formation consists of basaltic tuff and basaltic breccia. The unit is generally aphyric and is olivine tholeiitic in composition. Secondary minerals in voids are very common in this unit including chalcedony, quartz, wairakite, epidote, actinolite and calcite. Calcite is being deposited in vugs and vesicles.

**Hyaloclastite formation VI (840-1000 m)**

This hyaloclastite formation is aphyric and consists of basaltic breccia and basaltic tuff which are intruded by medium- to coarse-grained crystalline basalt at 910-926 m, 974-988 m, and from 996 to 1000 m. The tuff fragments are light greenish, and are highly altered volcanic glass. The rock shows significant alteration. Crystalline epidote, actinolite and sphene are the hydrothermal minerals present.

**4.4 Intrusions**

The heat source at Hengill is likely to be magmatic intrusions (e.g. Franzson et al., 2010). Intrusions are common within the different hyaloclastite units and pillow lava formations in the wells and are identified by their massive, tight and compact nature and less altered state than the host rocks. They sometimes have relatively coarser texture compared to the host rock even though they may be fine-grained or aphyric when the intrusions/dykes consolidate at shallow depths. They also show oxidation where the heating effect has been prominent along the boundary with the surrounding wall rocks. The dominant intrusions in the well, occurring at different depth intervals, are fine- to medium-grained rocks as well as intermediate rocks showing elevated peaks in the geophysical logs, especially in the neutron, gamma and resistivity logs. As stipulated by the log plot (Figures 6 and 7), six intrusions were encountered in the uppermost 1000 m of the well at 466-498, 716-736, 746-780, 910-926, 974-988 m and between 998 and 1000 m.

**5. HYDROTHERMAL ALTERATION AND TEMPERATURE DISTRIBUTION**

Hydrothermal alteration is very informative on various aspects of the geothermal system. It indicates the reaction between the reservoir rock and the circulating geothermal fluid, resulting in compositional changes of both the solid and fluid phase as the interaction between rock and fluid usually involves additional and/or removal of major rock-forming components. The factors that usually control alteration in geothermal systems are temperature, rock type, permeability, fluid composition and the duration of fluid-rock interactions (e.g. Browne, 1978). In addition, pressure can also have an important role. Even though the pressure rarely exceeds 200 bars, it may bring about changes in terms of mineral phase equilibria; it controls the depths at which boiling occurs and consequently the separation of vapour and gases (Gebrehiwot, 2010). Boiling zones are often characterised by vein minerals such as quartz, K-feldspar and bladed calcite (Browne and Ellis, 1970; Bargar and Muffler, 1982; Simmons and Christenson, 1994).

Hydrothermal alteration brings about changes in the properties of rocks by changing their texture, porosity and permeability through chemical reactions, or leads to either replacement of the primary

minerals, depletion of some constituents (leaching), or deposition. Access of fluids is an important factor in attaining equilibrium between fluids and the surrounding rocks during hydrothermal alteration. In the upper 1000 m section of the well, all the typical hydrothermal alteration zones were identified, from totally fresh rocks to the epidote-actinolite zone, emphasising the variation with depth of some of the temperature dependant minerals. This alteration was then compared to the present formation temperatures of the system. The hydrothermal minerals used in Iceland for interpretation of alteration temperatures are shown in Table 2 below. Table 3 shows the mineral depositional sequence in well HE-39.

TABLE 2: Some temperature dependent minerals in high temperature areas in Iceland (adopted from Kristmannsdóttir, 1979; Franzson, 1998)

Minerals	Min. temp. (°C)	Max. temp. (°C)
Zeolites	40	120
*Laumontite	120	180
*Wairakite	200	
Smectite		<200
Mixed-layer clay	200	230
Chlorite	230	>300
Calcite	50-100	280-300
Quartz	180	>300
Prehnite	240	>300
Epidote	230-250	>300
Wollastonite	270	>300
Actinolite	280	>300

\*Belongs to the zeolite group

*Siderite* is a form of carbonate which normally forms at temperatures less than 50°C. This normally indicates cold aquifers in the well. It occurs as a small spherically shaped deposition within open spaces at shallow depths above the cap rock of the geothermal system and is thought to belong to the slightly warmer groundwater system. Siderite occurs in association with limonite. It was first identified at 48 m depth in cutting analysis.

*Stilbite* is a transparent framework zeolite and was first found at 212 m depth. In thin section it is characteristically radial and with fan-like aggregates, showing good cleavage. The presence of stilbite indicates temperature in the range of 90-120°C.

*Analcime* is whitish-grey in colour and is characterised by its trapezohedral-sided crystal faces. It was first observed at 212 m in cutting analysis.

*Thomsonite* was observed at shallow depth as acicular radiating crystals, spherical aggregates or clusters of prismatic crystals filling vesicles or veins associated with other zeolites such as scolecite.

*Chabasite* is transparent or white and has a rhombohedra shape. It is mostly found filling vesicles.

*Scolecite and mesolite* are closely related zeolites occurring together as fibrous, acicular and radiating from a common centre. They are characterised by a radial texture that is obvious both in cuttings and in thin section analysis.

*Calcite* is the most abundant and widely distributed hydrothermal mineral, found from 120 to 954 m,

TABLE 3: Sequence of mineral deposition in well HE-39

Depth (m)	Oldest → youngest														
60	No alt														
194	fgc		sti	sco/me											cc
234	fgc			chb			cgc								
278				sco/me											cc
370	fgc			sco/me											
404	fgc	sm					cgc								cc
450	fgc	sm					cgc								cc
490							cgc				qtz				cc
526	fgc					wai	cgc				qtz				cc
574						wai	cgc				qtz				cc
622							cgc				qtz				
666						wai			alb		qtz				cc
692						wai			alb						cc
748							cgc	wo			qtz				cc
818	opa					wai	cgc	wo			qtz	ch			cc
862							cgc	wo			qtz				
900								wo	alb		qtz				cc
946						wai		wo	alb		qtz				cc
992								wo			qtz	ch	pr	epi	cc
								wo			qtz	ch			cc
1020											qtz	ch	pr		act

Explanation: No alt=no alteration, sm=smeectite, fgc=fine-grained clays, sco/mes=scolecite/mesolite, cha=chalcedony, sti=stilbite, qtz=quartz, wai=wairakite, cgc=coarse-grained clays, wo=wollastonite, alb=albite, pr=prehnite, epi=epidote, act= actinolite, cc=calcite and ch=chlorites.

though in varying amounts. It occurs as veins and vesicle fillings in the well, rarely occurring as platy minerals. It also occurs as a replacement of calcium-bearing minerals and volcanic glass. Calcite is white to colourless, occasionally transparent to translucent. In thin section, it is recognized by its perfect cleavage, high birefringence and change of relief with rotation. In cuttings, it is easily determined by dilute HCl acid. Calcite formation can be linked to boiling, dilution and condensation of carbon dioxide in a geothermal system. It can also form during the heating of cooler peripheral fluids (Simmons and Christenson, 1994).

*Pyrite* first appears at 256 m depth and it occurs to 1000 m in varying amounts. It is easily identified in cuttings analysis due to its brass yellow, cubic, euhedral shape. The presence of pyrite indicates high H<sub>2</sub>S content in the formation and often indicates good permeability in the formation.

*Chalcedony* is a low temperature silica mineral which is stable at a temperature range of 100-150°C.

It is usually colourless, grey to greyish blue and semitransparent to translucent with a waxy lustre. It was first identified at 380 m in thin section.

*Opal* was identified in cutting analysis by its pale yellow-brown colour, transparent to sub-translucent. It was found in colour-form clusters in veinlets, and as a cavity filling or lining. It was first found at 224 m, indicating a temperature below 100°C.

*Quartz* was first found at 490 m as euhedral to anhedral colourless to cloudy (milky), glassy to vitreous, transparent to translucent minerals occurring either as an alteration product of chalcedony or precipitated to fill vesicles or veins together with epidote, prehnite, pyrite and calcite. Quartz is colourless in thin section and devoid of twinning, and forms undulatory extinction. It is recognized by its low relief, low birefringence and lack of cleavage or twinning. The appearance of quartz implies a formation temperature of about 180°C.

*Epidote* first appears at 690 m as anhedral yellowish green deposits, but forms crystals at deeper level. Its appearance indicates a formation temperature above 240°C (e.g. Franzson, 1998). Epidote is usually associated with quartz, calcite, wairakite and clays. In thin section, epidote is identified by its high relief, light yellow to green colour having variable pleochroism from weak to moderate depending on the iron content of the mineral.

*Prehnite* is a common mineral in this well and was first identified at 574 m in thin section and occurs in association with chlorite, wollastonite, quartz, and wairakite. It is translucent and partly vitreous with an irregular or uneven fracture and distinct cleavage. Its habit is rounded to nearly spherical in binocular and is differentiated in thin section by its strong birefringence colour and bow-tie structure.

*Wollastonite* is a white to grey mineral occurring as radiating, compact and fibrous aggregates filling vesicles. It rarely occurs as a single crystal and has columnar to acicular habits. It is colourless in thin section with low interference colour of first order grey. It was first observed at 708 m depth. The first appearance of wollastonite indicates a temperature of 270°C and can be stable at temperatures above 300°C (e.g. Franzson, 1998).

*Wairakite* is white to colourless, forms euhedral pseudo-dodecahedral crystals and fills vugs and veins. In thin section, it has a very low relief and typically displays in cross-polar light two perpendicular polysynthetic sets of twin lamella, a distinct feature giving an appearance similar to microcline with poor cleavage (Thompson and Thompson, 1996). It is a high-temperature alteration product compared to other zeolites and is stable above 200°C. It was first observed at 404 m depth.

*Albite* occurs predominantly as an alteration product of plagioclase feldspar. It is white to grey, translucent but usually cloudy and with an equant anhedral to euhedral crystal shape. Plagioclase feldspar twinning disappears and becomes cloudy at higher temperatures forming albite. Albite resembles quartz but it is differentiated by its lower refractive index and its cloudy nature. It was first observed at 490 m depth in thin section analysis.

*Actinolite* is green to grey-green in colour, although the colour varies depending on the amount of iron. It is silky to vitreous, occurring as radiating or fibrous and very compact, or as thin and elongated lath like crystal aggregates. It is colourless, pale green to dark green showing variable pleochroism with moderate relief. It was first observed at 950 m depth in XRD analysis and at 992 m in thin section analysis.

*Sphene* is dark brown or yellow brown (chocolate) in colour and is a common replacement product of opaque minerals. It has a high relief and occurs as irregular anhedral grains.

*The sheet silicates (clay minerals)* are common and abundant alteration products in hydrothermal systems. They are the most dominant minerals in both high- and low-temperature fields in Iceland

(e.g. Kristmannsdóttir, 1979). The crystals are finely crystalline or meta-colloidal and occur in flake like and or dense aggregates of varying types. The typical clay alteration products in Iceland consist of three types: Smectite, mixed-layered clays and chlorite.

*Smectite* is formed in low-temperature environments associated with zeolites, indicating temperatures of less than 200°C.

*Mixed-layer clays* are a complex of smectite and chlorite clays, indicating temperatures between 200 and 300°C. In thin section, the clay appears as a coarse-grained clay mineral, coarser than smectite. Under plane polarized light, the clays show strong pleochroism.

*Chlorite* mostly looks light greenish in cuttings, and represents temperatures of above 230°C (Franzson, 1998). It is associated with high-temperature minerals like epidote, prehnite, wollastonite and wairakite. In thin sections, it is coarse grained and has a light greenish colour in plane light and a grey colour in polarized light. Its texture shows tiny green needles, and sometimes radial forms. XRD analysis showed typical chlorite at 700 m.

## 5.1 Alteration of primary minerals

Primary minerals are crystallized from magma, governed by the physico-chemical conditions under which the magma solidifies. They become unstable in a geothermal environment where there is high permeability, elevated temperatures and intense fluid activity. These minerals undergo chemical reactions with the hydrothermal fluids and readily alter to secondary minerals to become stable under the newly created natural conditions. In short, secondary minerals are formed by replacing primary minerals.

The main primary minerals in Icelandic basaltic rocks are glass (amorphous, quenched liquid), olivine, plagioclase, pyroxene and opaque in order of their susceptibility to alteration, glass being the most unstable of all the other primary minerals. The alteration of volcanic glass and the primary mineral assemblages of the well were studied and are described here below.

*Volcanic glass:* It is amorphous quenched magma and shows a highly vitreous lustre and has good conchoidal fractures. It is the first constituent to be altered and replaced. The replacement products of volcanic glass are zeolites (mordenite, laumontite), cristobalite, quartz, calcite and clays such as montmorillonite (e.g. Browne, 1978).

*Olivine:* It is one of the primary minerals that form basaltic rocks (olivine tholeiite) and is very susceptible to alteration. It is distinguished in thin section by its high birefringence, distinctive irregular fracture pattern, lack of cleavage, and alteration products, usually clay, along fractures. It is completely replaced by calcite and clay at depth.

*Plagioclase:* It is the most abundant mineral occurring in most igneous rocks. In crystalline rocks it is readily identified by its low relief and conspicuous polysynthetic twinning. The untwinned plagioclase (albite) which resembles quartz shows incipient alteration or clouding which is not common in quartz. It also occurs as fine groundmass in rocks exhibiting porphyritic textures. It is observed to be progressively altered as temperature increases and is finally replaced by albite and occasionally by calcite, wairakite, chlorite and epidote.

*Pyroxene:* The dominant pyroxenes that occur in Icelandic basalts are the clinopyroxenes, occurring as phenocrysts and in the groundmass. The pyroxenes resemble olivine but differ by the presence of better cleavage and inclined extinction. Pyroxene is observed to alter to clay as well as to actinolite at higher temperatures.



TABLE 4: Primary rock minerals and their alteration products as found in well HE-39

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, sulphides (pyrite, titanium)

By comparing the formation temperature with the temperature dependant minerals we get a notion of whether the specific area is in equilibrium, cooling down or heating up. Table 4 shows the primary rock minerals and their alteration products found in well HE-39

## 5.2 Vein and vesicle fillings

The rocks encountered in well HE-39 are generally porous with various types of veins (Figure 6). Porosity can be classified as being intergranular, joint and vesicular or of vug type. Vesicular rocks are common in Iceland where basaltic rocks predominate (Browne, 1984). These open voids gradually become filled with increasing alteration where limonite, siderite, clays and low-temperature zeolites are found in the upper part whilst quartz, wairakite and epidote fill the vesicles in high-temperature alteration zones.

## 5.3 Alteration mineral zonation

Some secondary minerals are good geothermometers and are stable at specific temperatures, crystallizing at distinct temperature ranges (e.g. Reyes, 2000). With few exceptions, minerals that provide information on their formation temperatures are those that contain in their structures either (OH) or  $n\text{H}_2\text{O}$ . They include clays, prehnite, zeolites, garnet and amphiboles (e.g. Brown, 1978). The distribution of alteration minerals gives information about formation temperature at the time of deposition. Five zones of hydrothermal alteration were identified in the uppermost 1000 m of well HE-39.

### Unaltered zone (0-304 m)

This zone extends from the surface to 304 m depth and it represents the Skardsmýrarfjall formation. It is composed of fresh rocks with no alteration that could be related to hydrothermal activities. XRD analysis shows hardly any indication of smectite and the only mineral precipitations are minor amounts of limonite, hematite and siderites, which are related to cold groundwater conditions.

### Smectite-zeolites zone (304-460 m)

This zone is characterised by the presence of smectite and zeolites indicating temperatures of less than 200°C and covers an interval from 304 to 460 m in the well. The zeolites present are stilbite, scolecite/mesolite, chabasite and thomsonite. Calcite, pyrite and chalcedony were also identified. Towards the bottom of the zone, zeolites and smectite start to decline while quartz, wairakite and mixed-layer clays start to appear.

### Mixed-layer clays (460-600 m)

This zone indicates a temperature range between 200 and 300°C and extends beneath the smectite-zeolite zone down to 600 m where it occurs with chlorite and illites. These clays are the intermediate products of reactions involving clay mineral end-members in which the different kinds of clay layers alternate with each other. Chalcedony and low-temperature clays are altered into quartz. Albite, wairakite and calcite are also present in this zone.

**Chlorite zone (600-690 m)**

Chlorite is a high-temperature clay mineral which signifies a temperature range of 230-240°C and its first appearance marks the top boundary of this zone. Chlorite appears as a vesicle filling in this section. Pyrite, calcite with chalcedony, wairakite, prehnite, sphene and quartz occur in association with chlorite. Albite occurs as an alteration product of plagioclase feldspars.

**Chlorite-epidote zone (690-950 m)**

This zone is marked by the first appearance of epidote at 690 m depth indicating temperature in excess of 240°C. Epidote occurs mostly as a replacement product of plagioclase and pyroxene.

**Epidote-actinolite zone (>950-1000 m)**

This zone is defined by the first appearance of actinolite at 950 m which indicates a temperature range in excess of 260°C. Actinolite occurs as an alteration product of pyroxene. Quartz, wairakite, prehnite, epidote, wollastonite, pyrite, actinolite and calcite are the main alteration minerals in this zone.

**5.4 Mineral deposition sequences and paragenesis**

Hydrothermal mineralization assemblages depend on the specific evolution and reactions regarding various factors such as temperature, fluid composition, rock type, the interaction between the hydrothermal fluids and the host rock, porosity, permeability and the duration of the interactions. Many of the minerals are formed either as replacement minerals, via alteration or deposition; by studying their depositional sequence in veins and vesicles, one can explore the parent thermal history and relative time scale of alteration minerals within a geothermal system. The sequence of hydrothermal mineral deposition was studied petrographically down to 1000 m using 23 thin sections to deduce the relative time scale of their deposition. The mineral suites varied from low- to high-temperature environments, sometimes with complex assemblages which make interpretation difficult.

Fine-grained clays started appearing as low-temperature minerals, usually occurring as linings inside vesicle walls, partly with chalcedony; these vesicles were later filled with zeolites, mostly scolecite, mesolite and stilbite.

Within the zeolites assemblage, stilbite appears first, followed by scolecite which is then replaced by the high-temperature variety of wairakite. At depth, high-temperature minerals replace low-temperature ones in a sequence of coarse-grained clays, wollastonite, albite, quartz, prehnite, epidote and actinolite. Calcite and clays are present throughout the entire depth. The appearance of calcite at a later stage in the high-temperature mineral sequence may indicate cooling, and probably represents the closest time to the present system.

Generally the sequence of hydrothermal minerals evolves from low-temperature to high-temperature minerals with the deposition of calcite at the end. Table 4 summarizes the hydrothermal sequence in the upper section of the well.

**5.5 Hydrothermal alteration of wells OW-909, OW-901 OW-902 and OW-903, in Olkaria**

An attempt was made to compare the hydrothermal alteration sequence shown by samples from Olkaria, Kenya. Well OW-909 is a production well drilled to a total depth of 2994 m. It is a vertical well with 7" slotted liners from a 1200 m depth casing shoe. Olkaria is situated in the Kenyan rift which is part of the East African rift system that runs from the Afar triple junction at the Gulf of Aden in the North to Beira, Mozambique in the south. The rift is part of a continental divergent plate boundary where spreading occurs as a result of thinning of the continental crust accompanied with the eruption of lavas and associated volcanic activities (Lagat, 2004).

The geology of the greater Olkaria area is dominated by Pleistocene to Holocene comenditic rhyolitic flows on the surface with subsurface tuffs, basalts and minor dolerite and microsyenite intrusives. Major element analyses of rocks from Olkaria Domes indicate their composition to range from basalt through trachyte to rhyolite (Lagat, 2004). Cuttings collected at 2 m intervals from well OW-909 were analysed to the bottom of the well and 26 thin sections were analysed for optical properties of the rock formations.

The lithology of the well is composed of pyroclastic ash (0-26 m), tuffs, rhyolite, trachyte and basalt with minor dolerite intrusions with several intermittent-to-total circulation losses in several intervals like 66-296, 556-558, 826-836, 932-938, 948-960, 1834-1862 and 2454-2472 m depth. The reservoir rock is trachyte with basalt intercalations at depth. The main hydrothermal minerals identified in the well are: calcite, albite, actinolite, chlorite, epidote, fluorite, garnet, illite, mordenite, prehnite, titanite (sphene), quartz, sulphides (pyrite), wairakite, biotite and K-feldspar (adularia). Four hydrothermal alteration zonations were identified in the well below the unaltered zone: zeolite-chlorite zone, illite-chlorite zone, epidote-illite-chlorite zone and garnet-biotite-actinolite zone at depth. This sequence indicates a progressive increase in alteration temperatures with depth. For comparison, Figure 8 shows a cross-section with the distribution of alteration zones in wells OW-901, OW-902 and OW-903.

The mineral sequence of well HE-39 was compared with wells OW-901, OW-902, and OW-903 (Figure 8). Beneath the unaltered zone in well HE-39, a smectite-zeolite zone is seen, which coincides with the zeolite-chlorite zone in the Kenyan wells; mixed-layered clays coincide with the illite-chlorite zone; chlorite and chlorite-epidote zone with epidote-illite-chlorite zone; and garnet-biotite-actinolite coincides with the epidote-actinolite zone (Lagat, 2004). Binocular and petrographic results from well OW-909 show a similar alteration sequence where fine-grained clays, zeolites and smectite are found at shallow depth and are replaced by higher-temperature stable minerals at greater depth like epidote, garnet and actinolite.

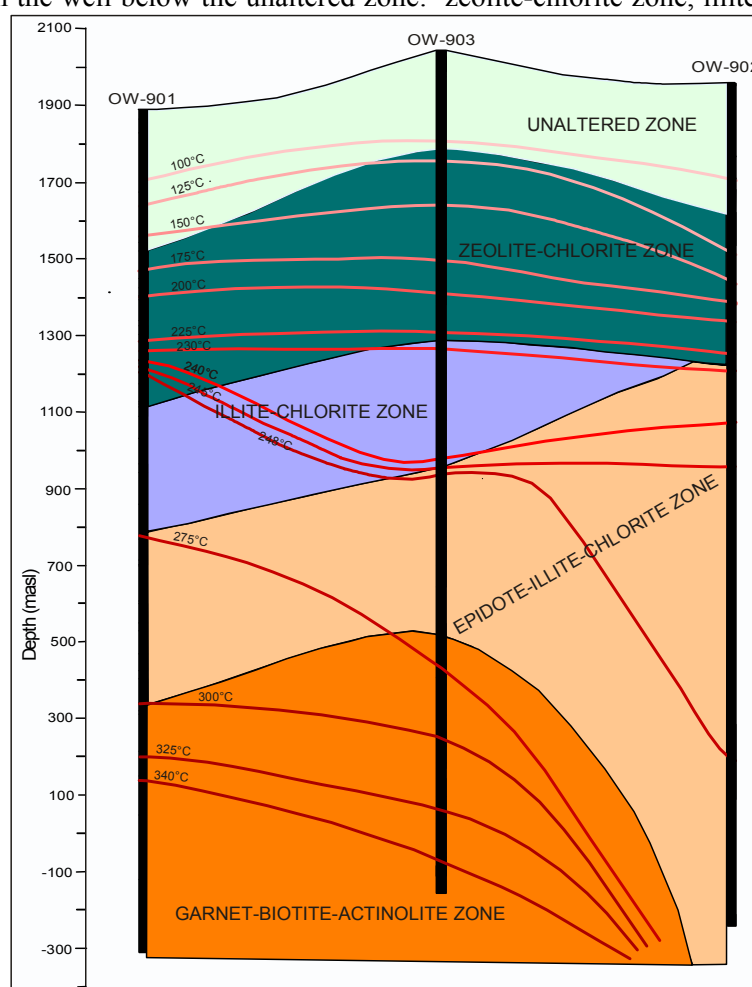


FIGURE 8: Distribution of alteration zones and measured formation temperature isotherms with depth across wells OW-901, OW-903 and OW-902 in Olkaria Domes, Kenya (from Lagat, 2004)

## 5.6 Fluid inclusion geothermometry

When hydrothermal minerals grow, or recrystallize, in a fluid environment, tiny growth irregularities trap small amounts of the depositing fluid within the solid crystal. The sealing off of these irregularities yields primary inclusions, or by their later crystallization, perhaps in response to micro fractures, secondary inclusions. If the fluid trapped is a single phase, this will separate into a vapour

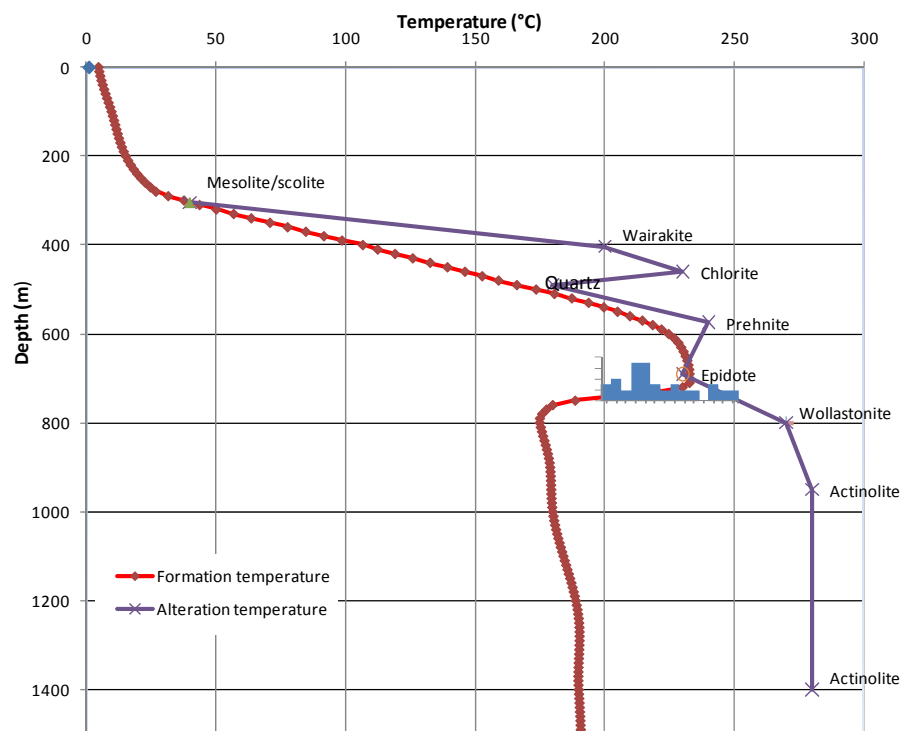


FIGURE 9: Formation temperature, alteration temperature and fluid inclusions in calcite and quartz in well HE-39

(bubble) and a liquid at lower temperatures (two-phase boundary). Heating of an inclusion on a heating stage will restore this fluid to a single phase at its homogenisation temperature; this is, therefore, taken to be its entrapment temperature which is used to determine the thermal history of a reservoir (Franzson, 2010). Fluid may be trapped between the deformed surfaces by either subsequent precipitation or by dissolution–reprecipitation processes, leading to the formation of secondary fluid inclusions (e.g. Goldstein and

Reynolds, 1994). Analysis of fluid inclusions, thus, makes it possible to elucidate temperature and fluid changes during and subsequent to crystal growth. In this study, 42 quartz and calcite crystals were analysed and their homogenization temperatures ( $T_h$ ) were identified as 220-230°C at 738-752 m depth. The results of the fluid inclusion study are shown in Figure 9. The alteration temperatures are considerably higher than the measured formation temperatures, implying that the hydrothermal system has cooled with time. The formation temperature is much higher than the fluid inclusion temperature, implying probable heating of the system.

## 6. AQUIFERS

Aquifers (feed zones) in the well were located using circulation losses, temperature logs, hydrothermal alteration and other relevant drilling data such as the variation in the penetration rate, pressure changes during drilling and circulating fluid temperatures. At least some of the aquifers encountered in the wells can be directly related to margins of intrusions, indicating the dominance of fracture permeability in the geothermal reservoir (Figures 6 and 7). Seven aquifers were identified at 146-150, 200-208, 244-246, 780-786, 910-926, 974-988 and 998-1000 m (Figure 10).

The main source of permeability in the study area is lithological contacts, intrusive boundaries and major faults and fractures. Comparing the locations of the aquifers with detailed geology has shown that feeder zones in Skardsmýrarfjall generally occur along stratigraphic boundaries or are associated with the intrusive boundaries (e.g. Franzson, 2010). No major circulation losses were encountered in the upper section of the well, apart from 780 to 786 m depth.

## 7. DISCUSSION

The uppermost 1000 m of well HE-39 consist of six hyaloclastite formations beneath the Skardsmýrarfjall formation. These hyaloclastite formations are classified on the bases of textural variations and being either aphyric or porphyritic. Six dyke intrusions were also recognized in this section with their fresh, medium- to coarse-grained crystalline fragments in highly altered hyaloclastite formations. 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 500 m depth, the alteration increases rapidly both on the grounds of temperature-dependent minerals and alteration intensity.

Temperature variations in the well have been looked at in two different ways: the hydrothermal alteration temperature, which was assessed according to the first appearance of the different, temperature-dependent alteration minerals; while the formation temperature was determined by calculations based on temperature measurements during the heating-up period. The formation temperature curve of the well shows a progressive temperature increase with depth.

The alteration temperature curve of the well shows a trend where low-temperature minerals, like zeolites, form in the upper part of the well and are gradually replaced by moderate-temperature minerals like chalcedony, quartz and wairakite, which are replaced at greater depth by high-temperature mineral assemblages like chlorite, prehnite, epidote, wollastonite and actinolite. The clay minerals are sensitive to changes in temperature and are found to become more crystalline with depth. According to petrographic analysis, the clays deposited in vesicles were either fine-grained, usually found as thin layers lining the voids and vesicles, or coarse-grained clays occurring as mixed-layer clays and chlorites. Five alteration sequences were identified with the formation of low-temperature zeolites and smectite at early stages of the sequence, indicating formation temperatures below 200°C. Later, in veins and vesicles, moderate temperature minerals were identified such as chalcedony, quartz and wairakite in association with mixed-layer clays, indicating an alteration temperature range of 200-230°C. These moderate temperature sequence minerals decline down the well, giving way to high-temperature minerals like chlorites, prehnite, and wollastonite and later the appearance of epidote and actinolite, which indicate even higher alteration temperatures of more than 260°C. The end of any alteration sequence in the well shows calcite deposition. This implies a progressive heating up of the system followed by later cooling, evidenced by calcite deposition at the final and later stages of the system (Franzson, 2000). Comparison of well HE-39 with HE-37, HE-27 and HE-24 showed a similar stratigraphy even though the hyaloclastite formations occurred at slightly different depths. However, the same hydrothermal alteration mineral sequence was identified in all the wells, as stipulated in Figure 11.

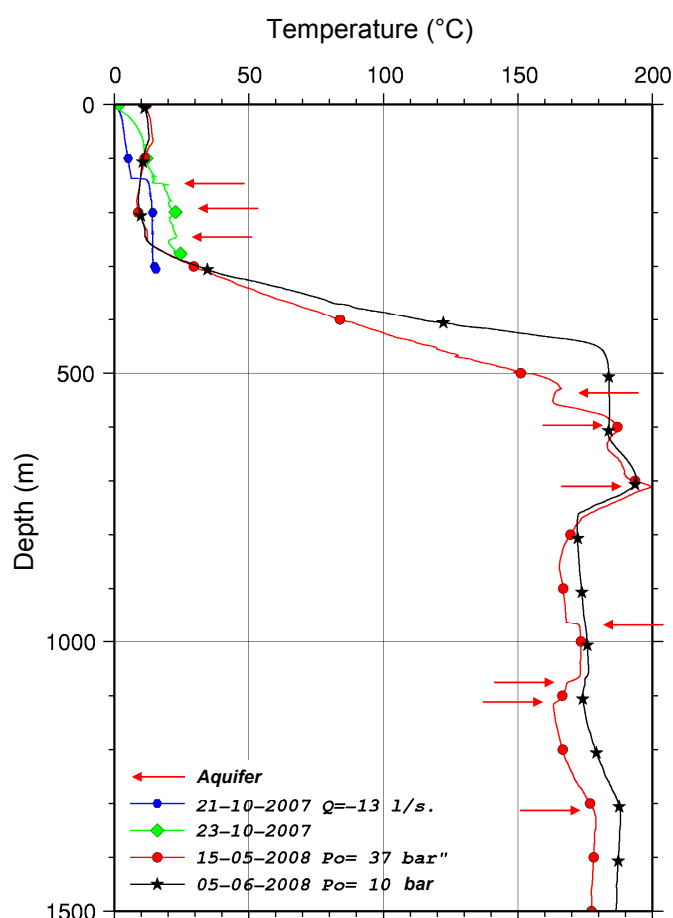


FIGURE 10: Location of the aquifers in the upper 1000 m of well HE-39

The formation temperature curve of the well shows a progressive temperature increase with depth.

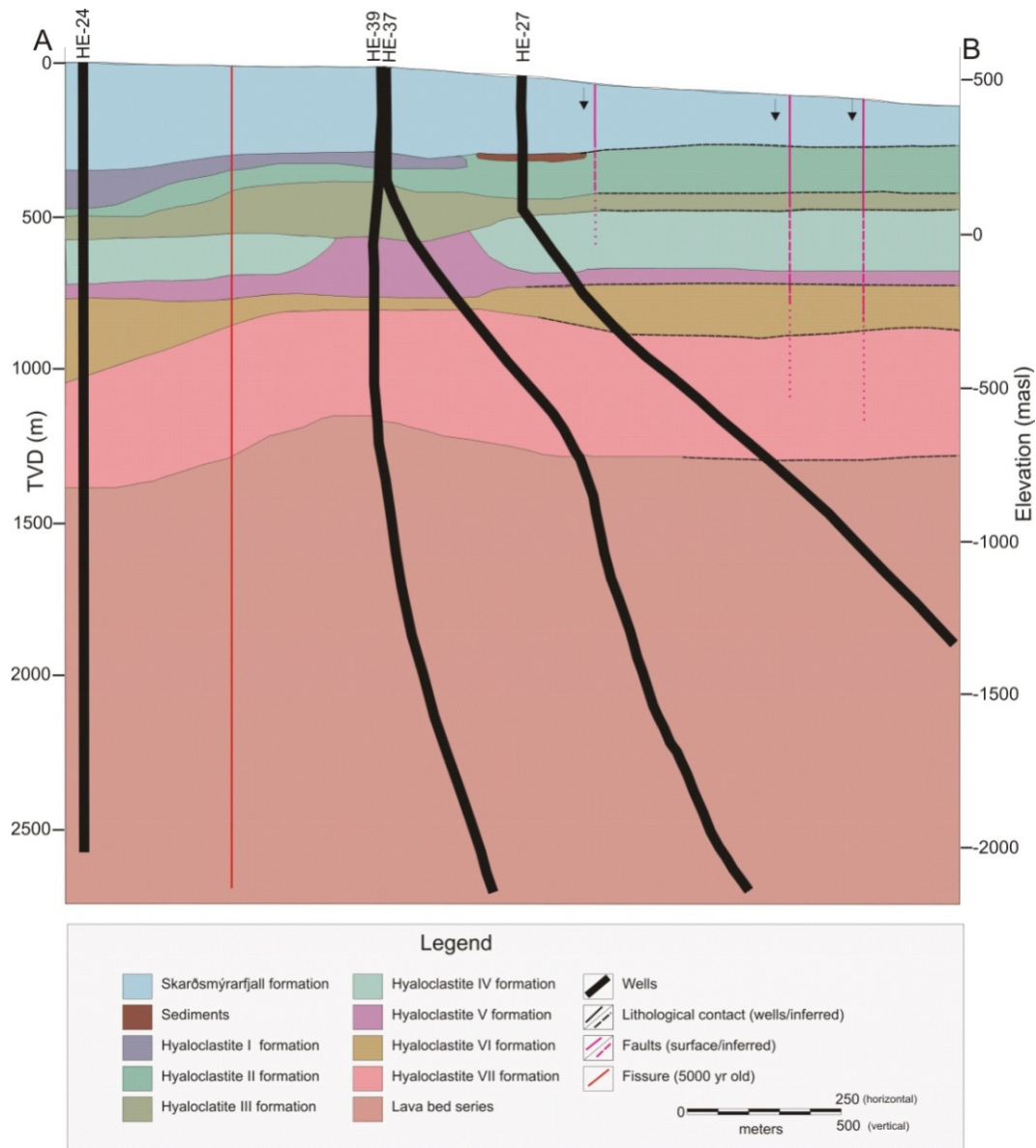


FIGURE 11: Lithological cross-section through wells HE-39, HE-37, HE-24 and HE-27 on Skarðsmýrarfjall, Hellsheiði field (Gebrehiwot, 2010)

## 8. CONCLUSIONS

The following conclusions can be deduced from this study:

1. The main rock types that comprise the subsurface geology of well HE-39 consist of sub-glacial hyaloclastite formations and basaltic intrusions. These hyaloclastite formations include basaltic tuff (volcanic glass), glassy basalt (pillow basalt), basaltic breccia and basaltic and intermediate intrusions which are fine-grained to coarse-grained rocks occurring as dykes.
2. The main sources of permeability in the studied well are, as in most other wells of the Hellsheiði geothermal field, related to lithological contacts, intrusive boundaries, and major faults and fractures.

3. Hydrothermal alteration mineralogy is controlled by temperature, rock type, and permeability.
4. Mineralogical examination of the studied well revealed five zones of hydrothermal alteration beneath a zone of unaltered rocks. These zones are the smectite-zeolite zone (<200°C), mixed-layer clays zone (200-230°C), chlorite zone (230-250°C), chlorite-epidote zone (>250°C), and epidote-actinolite zone (>280°C).
5. Based on temperature logs, circulation loss data and intensity of alteration, seven aquifers were identified in the upper part of the well.
6. The sequence of mineral deposition within the wells generally shows the hydrothermal system to have evolved from low- to high-temperature conditions with alteration ranging from fine-grained clays at low temperatures to actinolite at high temperatures. Subsequently, a later cooling stage of the system occurred which resulted in the precipitation of calcite.
7. The fluid inclusion studies for well HE-39 showed progressive heating up of the geothermal system which resulted in higher formation temperatures than the homogenization temperatures.
8. Four hydrothermal alteration zones were identified in wells OW-901, OW-902, OW-903 in Olkaria, Kenya, beneath an unaltered zone: a zeolite-chlorite zone, an illite-chlorite zone, the epidote-illite-chlorite zone and the garnet-biotite-actinolite zone at depth. This sequence indicates a progressive increase in alteration temperatures with depth. Well OW-909 shows a trend of low-temperature minerals like zeolites in the upper part of the well which are progressively replaced by high-temperature hydrothermal minerals such as garnet, epidote and actinolite down the well.

### ACKNOWLEDGEMENTS

I would like to express my gratitude to the United Nations University, Geothermal Training Programme (UNU-GTP) and the Iceland Government for awarding me a scholarship to participate in this borehole specialist course. Special gratitude goes to Dr. Ingvar B. Fridleifsson, the Director, Mr. Lúdvík S. Georgsson, deputy director, Ms. Dorthe H. Holm, Ms. Thórhildur Ísberg and Mr. Markús A.G. Wilde, and all other UNU staff for their assistance, and coordination in achieving this great research. I am indebted to my supervisor, Dr. Björn S. Hardarson, and all ÍSOR geology staff especially Dr. Hjalti Franzson, Ms. Annette Mortensen, Ms. Sandra Snaebjörnsdóttir, Ms. Helga Margrét Helgadóttir, Ms. Christa Feucht and Mr. Sigurdur Sveinn Jónsson for their valuable input and critical comments, especially during data acquisition, processing and interpretation. Special thanks also go to Dr. Gudmundur Ómar Fridleifsson for his extensive field work training at the Geitafell central volcano area.

I extend my appreciation to my employer, the Geothermal Development Company (GDC) for granting me leave to undertake this course. To 2010 UNU-GTP fellows, thank you for the wonderful time we spent together. To my dear wife, Julia, my daughter Lynett and my two sons, Lewis and Alpha, thank you for enduring my absence, for your love, encouragements and your prayers. God made all this possible; glory to His holy name.

## REFERENCES

- Árnason, K., and Magnússon, I.Th., 2001: *Geothermal activity in the Hengill area. Results from resistivity mapping*. Orkustofnun, Reykjavik, report, OS-2001/091 (in Icelandic with English abstract), 250 pp.
- Árnason, K., Eysteinnsson, H., and Hersir G.P., 2010: Joint 1D inversion of TEM and MT data and 3D inversion of MT data in the Hengill area, SW Iceland. *Geothermics*, 39, 13-34.
- Árnason, K., Karlsdóttir, R., Eysteinnsson, H., Flóvenz, Ó.G., and Gudlaugsson, S.Th., 2000: The resistivity structure of high-temperature geothermal systems in Iceland. *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan*, 923-928.
- Bargar, K.E., and Muffler, L.J.P., 1982: *Hydrothermal alteration in research drill hole Y-11 from a vapour-dominated geothermal system at Mud Volcano, Yellowstone National Park, Wyoming*. Wyoming Geol. Assoc. Guidebook, 139-152.
- Björnsson, A., and Hersir, G.P., 1981: Geophysical reconnaissance study of the Hengill high-temperature area, SW-Iceland. *Geoth. Res. Council, Transactions*, 5, 55-58.
- Browne, P.R.L., 1978: Hydrothermal alteration in active geothermal systems. *Annu. Rev. Earth planet. Sci.*, 6, 229-250.
- Browne, P.R.L., 1984: Subsurface stratigraphy and hydrothermal alteration of Eastern section of the Olkaria geothermal field, Kenya. *Proceedings of the 6<sup>th</sup> New Zealand Geothermal Workshop, Geothermal Institute, Auckland, NZ*, 33-41.
- Browne, P.R.L., and Ellis, A.J., 1970: The Ohaki-Broadlands hydrothermal area, New Zealand: Mineralogy and related geochemistry. *Am. Jour. Sci.*, 269, 97-131.
- Franzson, H., 1998: Reservoir geology of the Nesjavellir high-temperature field in SW-Iceland. *Proceedings of the 19<sup>th</sup> Annual PNOG-EDC Geothermal Conference, Manila*, 13-20.
- Franzson, H., 2000: Hydrothermal evolution of the Nesjavellir high-temperature system, Iceland. *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan*, 2075-2080.
- Franzson, H., 2010: *Borehole geology*. UNU-GTP, Iceland, unpublished lecture notes.
- Franzson, H., Árnason, K., Saemundsson, K., Steingrímsson, B., Hardarson, S., and Gunnlaugsson, E., 2010: The Hengill geothermal system, conceptual geological model. *Proceedings of the World Geothermal Congress, 2010, Bali Indonesia*, 9 pp.
- Franzson, H., Kristjánsson, B.R., Gunnarsson, G., Björnsson, G., Hjartarson, A., Steingrímsson, B., Gunnlaugsson, E., and Gíslason G., 2005: The Hengill Hellisheidi geothermal field. Development of a conceptual geothermal model. *Proceedings World Geothermal Congress 2005, Antalya, Turkey*, CD, 7 pp.
- Gebrehiwot, K., 2010: *Sub-surface geology, hydrothermal alteration and geothermal model of Northern Skardsmýrarfjall, Hellisheidi geothermal field, SW Iceland*. University of Iceland, MSc thesis, UNU-GTP, report 5, 65 pp.
- Goldstein, R.H., and Reynolds, T.J., 1994: *Systematics of fluid inclusions in diagenetic minerals*. SEPM Short Course 31, Tulsa, OK, 199 pp.



Hardarson, B.S., Helgadóttir, H.M., and Franzson, H., 2007: *Hellisheidi power plant – the downflow area at Gráuhmúkar*. ISOR – Iceland GeoSurvey, Reykjavík, report ÍSOR-2007/001 (in Icelandic), 29 pp.

Hardarson, B.S., Einarsson, G.M., Franzson, H., and Gunnlaugsson, E., 2009: Volcano-tectonic-geothermal interaction at the Hengill triple junction, SW Iceland. *Geoth. Resour. Council, Transactions*, 33, 49-55.

Hardarson, B.S., Fitton, J.G., Ellam, R.M., and Pringle, M.S., 1997: Rift-relocation – a geochemical and geochronological investigation of a paleo-rift in NW Iceland. *Earth planet. Sci. Lett.*, 153, 181-196.

Hardarson, B.S., Einarsson, M., Kristjánsson, B.R., Gunnarsson, G.E., Helgadóttir, M., Franzson, H., Árnason, K., Ágústsson, K., and Gunnlaugsson, E., 2010: Geothermal reinjection at the Hengill triple junction, SW Iceland. *Proceedings of the World Geothermal Congress 2010 Bali, Indonesia*, 7 pp.

Jóhannesson H., and Saemundsson, K., 1999. *Geological map 1:1.000.000*. Icelandic Institute of Natural History.

Kristmannsdóttir, H., 1979: Alteration of basaltic rocks by hydrothermal activity at 100-300°C. In: Mortland, M.M., and Farmer, V.C. (eds.), *International Clay Conference 1978*. Elsevier Scientific Publishing Co., Amsterdam, 359-367.

Lagat, J.K., 2004: *Geology, hydrothermal alteration and fluid inclusion studies of the Olkaria Domes geothermal field, Kenya*. University of Iceland, MSc thesis, UNU-GTP, Iceland, report 2, 71 pp.

Low, J. W., 1977. Examination of well cuttings and the lithological logs. In: Leroy, L.W., Leroy, D.O., and Raese, J.W. (eds.), *Subsurface geology* (4<sup>th</sup> ed.). Colorado School of Mines, Golden, Colorado, 286–303.

Reyes, A.G., 2000: *Petrology and mineral alteration in hydrothermal systems: from diagenesis to volcanic catastrophes*. UNU-GTP, Iceland report 18-1998, 77 pp.

Saemundsson, K., 1979: Outline of the geology of Iceland. *Jökull*, 29, 7-28.

Saemundsson, K., 1995a: *Hengill, geological map, 1:50.000*. Orkustofnun, Reykjavík.

Saemundsson, K., 1995b: *Geothermal and hydrothermal map of the Hengill area, 1:25,000*. Orkustofnun, Reykjavík.

Simmons, S.F., and Christenson, B.W., 1994: Origins of calcite in a boiling geothermal system. *Am. Science*, 294, 361-400.

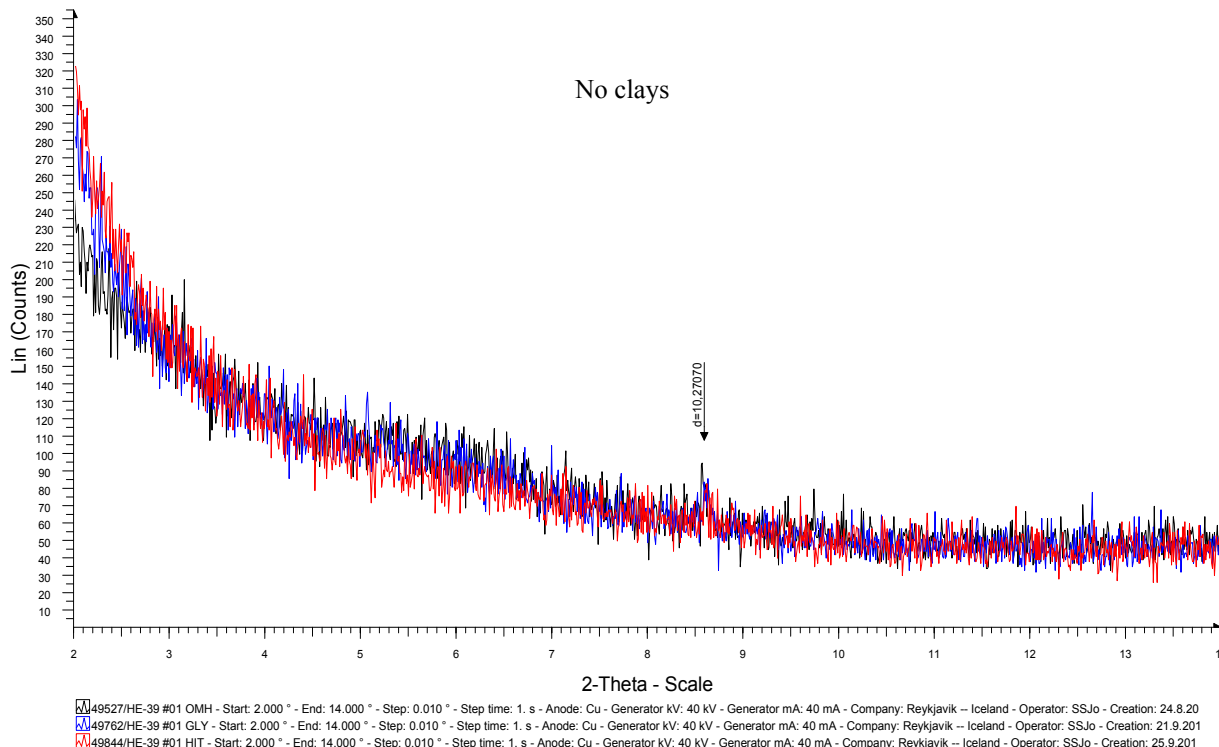
Stefánsson, V., and Steingrímsson, B.S., 1990: *Geothermal logging I, an introduction to techniques and interpretation* (3<sup>rd</sup> edition). Orkustofnun, Reykjavík, report OS-80017/JHD-09, 117 pp.

Thomson, A.J.B., and Thomson, J.F.H., 1996: *Atlas of alteration. A field and petrographic guide to hydrothermal alteration minerals*. Alpine Press Ltd., Vancouver, BC, 119 pp.

**APPENDIX I: Results of the XRD analysis of clay minerals**

Depth (m)	Untreated (Å)	Heated (Å)	Type of clays
260			No clays
360	14.6	10	Smectite
460	14.3/12.8	10.1/12	Smectite, chlorite, mixed-layer clay
500	27/14.8	14.8	Chlorite, mixed-layer clays
550	31/14.9	12.7	Mixed-layer clays
600	14.8	14.8	Unstable chlorite
650	14.8	14.8 (10Å heated=0)	Unstable chlorite, + illites
700	32. 14.8	14.8	Chlorite, mixed-layer clays
750	32 . 14.8	14.8	Chlorite, mixed-layer clays
770	32. 14.8	14.8 10Å heated=0)	Chlorite, mixed-layer clays +illites
800	14.5	14.5	Unstable chlorite
820	14.5	14.5. (10Å heated=0)	Unstable chlorite
850	14.8	14.8	Unstable chlorite
870	14.8	14.8	Unstable chlorite
900	14.8	14.8	Unstable chlorite
920	14.8	14.8	Unstable chlorite
950	29. 14.4	12	Mixed-layer clays + amphibole
970	14.9	14.9	Unstable chlorite + amphibole
1000	14.9	14.9	Unstable chlorite + amphibole
1020	14.9	14.9	Unstable chlorite + amphibole
1076	14.9	14.9	Unstable chlorite + amphibole
1150	14.6	15	Unstable chlorite + amphibole
1220	15	15	Unstable chlorite + amphibole
1250	14.6	15	Unstable chlorite + amphibole
1300	14.6	15	Unstable chlorite + amphibole
1350	14.8	14.8	Unstable chlorite + amphibole
1412	14.8	14.8	Unstable chlorite + amphibole

**49527/HE-39 #01 OMH**



**FIGURE 1: Pattern 1**

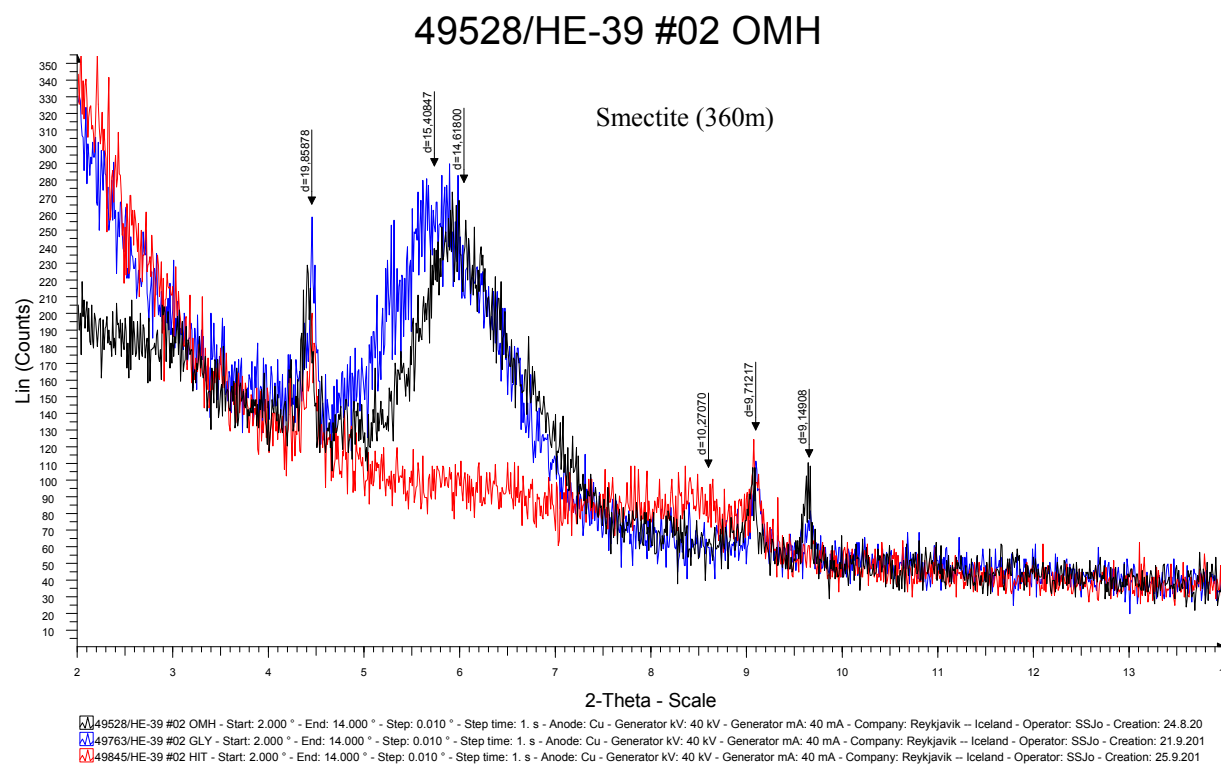


FIGURE 2: Pattern 2

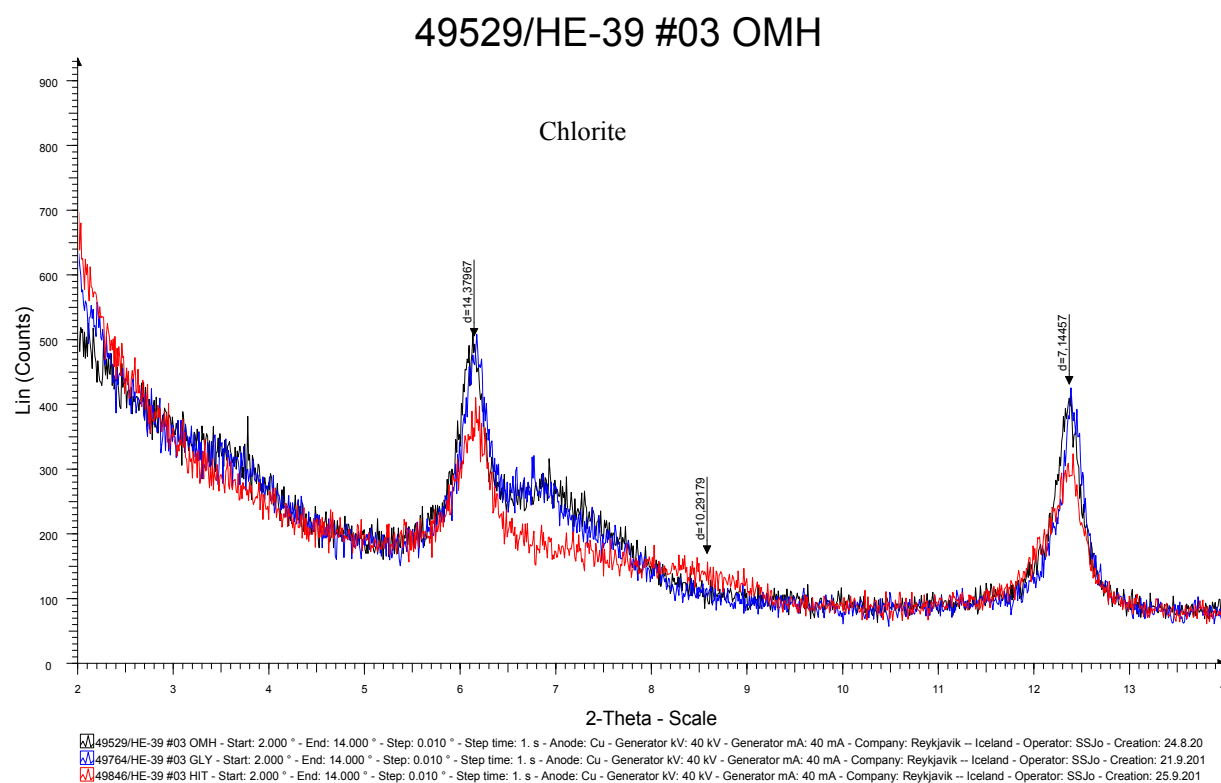


FIGURE 3: Pattern 3

### 49530/HE-39 #04 OMH

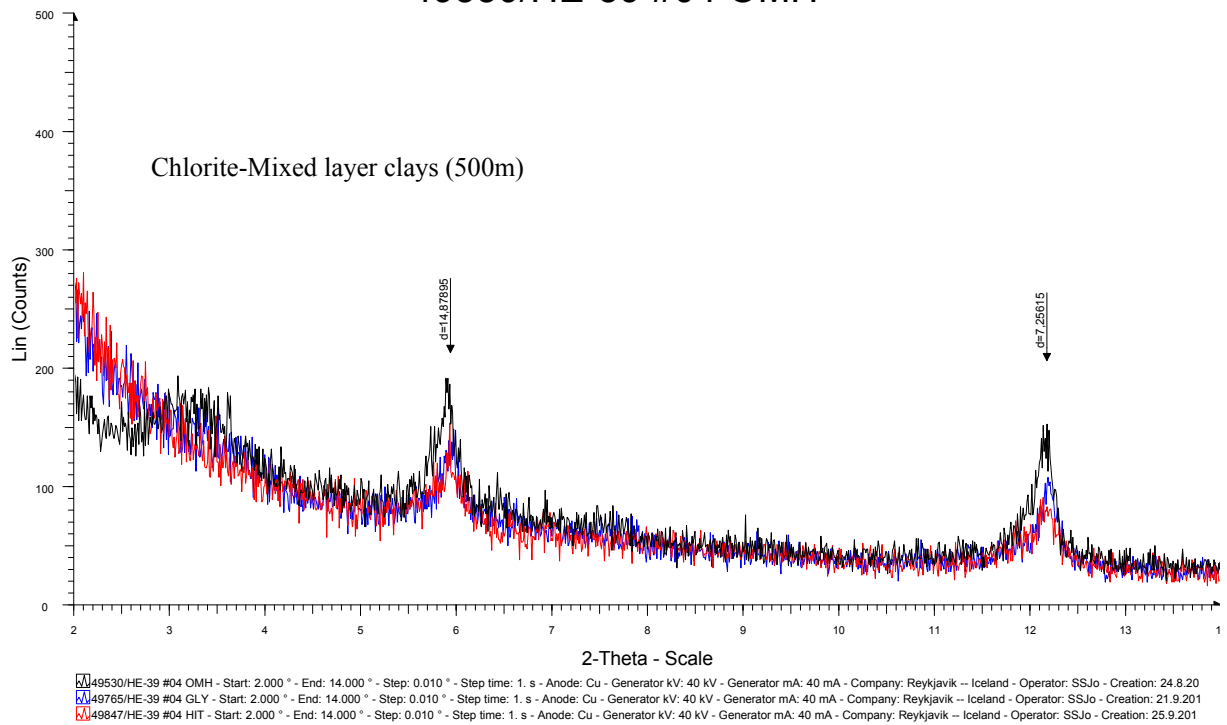


FIGURE 4: Pattern 4

### 49547/HE-39 #21 OMH

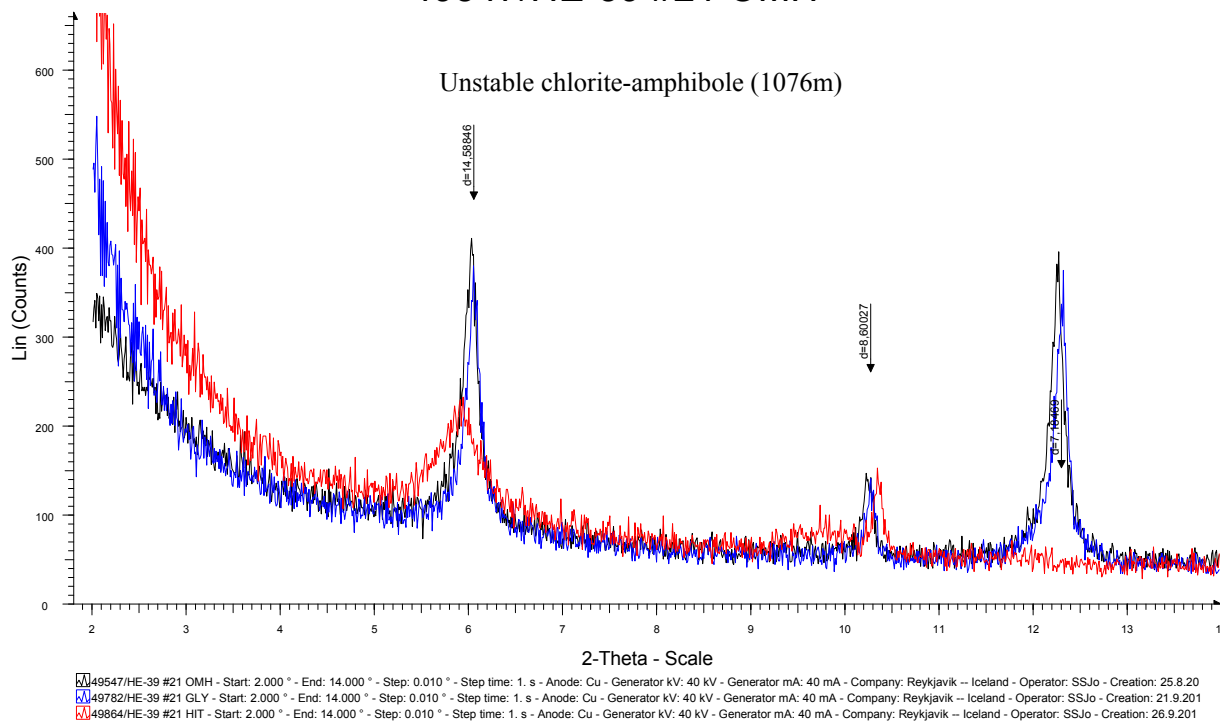


FIGURE 5: Pattern 5