UNITED NATIONS UNIVERSITY
UNU-GTP
Geothermal Training Programme

Orkustofnun, Grensasvegur 9,
IS-108 Reykjavik, Iceland

Reports 2016
Number 8

GEOLOGY, HYDROTHERMAL ALTERATION AND GEOLOGICAL STRUCTURES OF WELL HE-59, HELLISHEIDI GEOTHERMAL FIELD, SW- ICELAND

Birhan Abera
Geological Survey of Ethiopia
P.O. Box 2302 Addis Ababa
ETHIOPIA
birhanabera@rocketmail.com

ABSTRACT

Well HE-59 is located in Hellisheidi geothermal field within the Hengill high-temperature geothermal area. It was drilled directionally to a total depth of 2400 m with a western bearing into Mt. Reykjafell. Binocular microscopy, petrographic analysis, X-ray diffraction analysis and fluid inclusion analysis were the major tools used to interpret the cutting samples that were collected from the upper 902 m, but subsequently total circulation loss occurred and cuttings were not retrieved at the surface. Beside these, the study was supported by borehole geophysical data and a surface structural study. The stratigraphy of well HE-59 is represented by dominant sub-glacial eruptions of hyaloclastite and thin layers of interglacial and postglacial basaltic lava flows and intrusions. The hyaloclastite formation is basaltic in composition and characterized by the inter-layering of basaltic tuff, breccia and pillow or glassy basalt. Structural correlation of the well path with the surface faults and fissures shows that the well crosses a nearby, narrow, postglacial volcanic fissure at 900 m and this is evidenced from the gyro survey, circulation losses and lithological and intrusion findings. The alteration zones in this well are challenging, where the hydrothermal mineral distribution and clay analysis show different outlines. However, the combination of the two approaches infers the presence of four alteration zones in the well. These zones are unaltered zones (0-150 m), a smectite-zeolite zone (150-616 m), a chlorite-epidote zone (616-716 m) and an epidote-wollastonite zone (716-902 m). From the temperature logs and circulation losses, four minor and five major aquifers were identified, which are related to geological boundaries and structures. The formation temperature, which is based on the temperature logs before the recovery of the well, together with fluid inclusions study and alteration temperatures indicate a cooling down of the system in this well. However, further temperature logs are necessary as they may change this assumption.

1. INTRODUCTION

Iceland is an island, surrounded by the North-Atlantic Ocean, situated between Greenland and continental Europe, close to the Arctic Circle. The country has a number of active geological areas, where geothermal resources are extensively exploited and supply steam and water both for power generation and different direct use purposes. Hengill is one of the largest high-temperature geothermal areas in Iceland, located in the southwestern part, about 30 km east of Reykjavik. Hellisheidi is one of the production field located within the Hengill geothermal field together with other two production fields and one exploration fields, namely Nesjavellir, Hverahlíd and Bitra respectively (Figure 1) (Franzson et al., 2010a and b; Gasperikova et al., 2015). The Hengill area has three power plants; two of them are situated at Hellisheidi and one at Nesjavellir geothermal field.

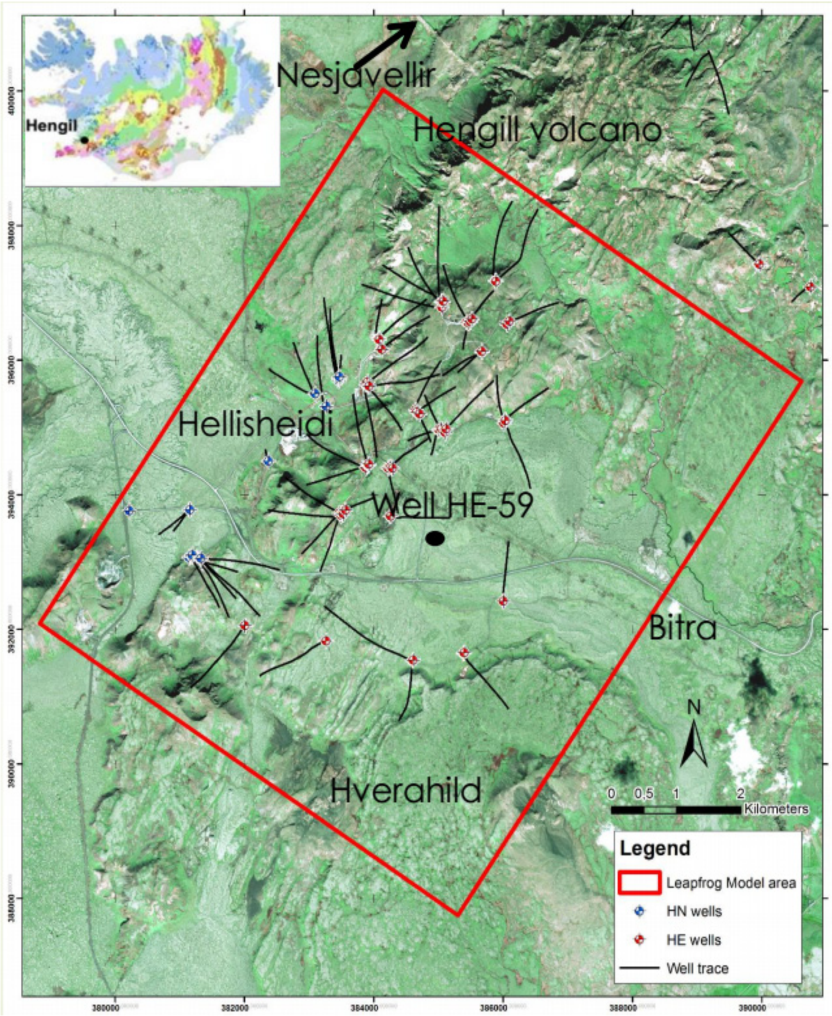


FIGURE 1: Map of Hengill area showing the four geothermal fields and location of well HE-59 (modified from Gunnarsdóttir, and Bastien, 2016)

Hellisheidi power plant is located in the southern part of Hengill volcanic complex, comprising a total of 59 deep (1300-3300 m) exploration and production wells which are currently producing about 303 MWe, and 133 MWth (Hardarson et al., 2015). Hengill geothermal area is within the SW rift zone of Iceland and has a size of 110 km^2, with a capacity of about 5500 GWh/y for 50 years (Franzson et al., 2010).

Surface thermal manifestations (Figure 2) in the area, are controlled by fractures and the central volcano and mainly found close to the volcanic fissures (Gasperikova et al., 2015). These include fumaroles, hot springs and altered ground.

Well HE- 59 is situated to the southern part of Hellisheidi geothermal field (Figure 1). The well is drilled to a total depth of 2400 m directionally aimed at intersecting volcanic fissures to the west. The objective of the well was to increase and keep up the production power capacity of the Hellisheidi power plant (make-up well).

This paper summarizes the results of geological, hydrothermal alteration and structural relationships in well HE-59.

2. GEOLOGY AND GEOTHERMAL SYSTEMS OF ICELAND

Geologically, Iceland is young and on the diverging Mid-Atlantic Ridge, which was created about 60 million years ago along the diverging American and the Eurasian plates, after the northwestwardly migration of Greenland, Eurasia and NE Atlantic plates over the Iceland plume (Sigmundsson, 2006). The continuous plate migration over the stationary mantle plume resulted in the complicated pattern of the present Icelandic rift zones, where rift jumps leave fossil rifts to the west and new ones forming to the east (Hardarson et al., 1997). The Icelandic volcanic rift zones (Reykjanes, Western Volcanic Zone, Eastern Volcanic Zone, and Northern Volcanic Zone) extend from Reykjanes peninsula in the southwest to the north through the country and divide into two parallel branches in southern Iceland (Figure 3). The rift zones are 40-50 km wide with5-15 km wide en-echelon arrays and up to 200 km long volcanic fissure swarms (Saemundsson 1979; Sigmundsson, 2006). It has a general trend of NE-SW and N-S in the northern part.

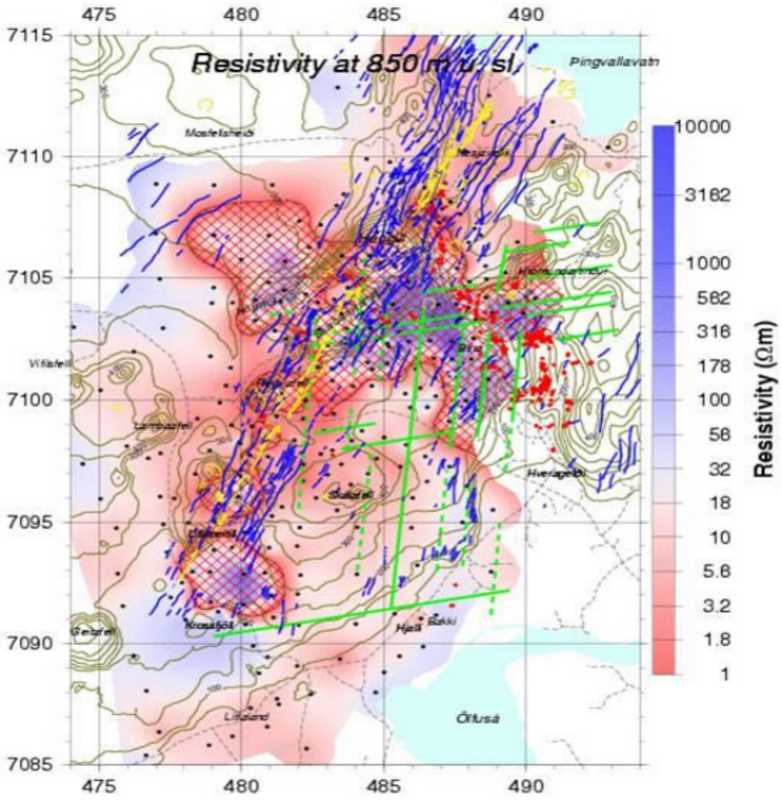


FIGURE 2: Resistivity at 850 m b.s.l. according to TEM surveys. High resistivity cores are shown with red, crossed lines. Surface geothermal springs as red dots. Postglacial surface fissure swarms and faults as blue lines. Green lines are fissures and faults defined by earthquake locations and yellow lines are postglacial fissures (Árnason, 2007)

Iceland is mainly made up of basaltic volcanic products of subglacial (hyaloclastites and pillow lavas), interglacial (lava flows) and postglacial (fissure eruptions) volcanic origin. Subglacial eruptions (eruptions under glacier ice), are the results of glacial periods during the last 3 Ma. According to Saemundsson (1979), the Icelandic volcanic pile is grouped into four stratigraphic series as Tertiary (> 3.3 Ma), Plio Pleistocene (0.8-3.3 Ma), Upper Pleistocene (0.8 Ma-11,000 yrs) and Postglacial (<11,000 yrs). The main rock type in Iceland is basalt, which covers 80-85% of the country, while intermediate-acidic rocks and sedimentary rocks cover 10% and 5-10% respectively. The oldest rock on the surface is dated to16 million years old and located in the northwest and east parts of the country (Hardarson et al., 1997).

Geothermal systems in Iceland are classified as high- and low-temperature geothermal systems. High-temperature geothermal systems (>200°C at 1 km depth), are confined to active volcanism and rifting areas, while low-temperature geothermal systems (< 150°C at 1 km depth) are found outside the rift zones (Figure 3) within the Tertiary and Quaternary formations (Arnórsson et al., 2008). The Icelandic high-temperature geothermal systems have a heat source from magmatic intrusions while stratigraphic boundaries, faults and fractures are means of permeability. However, the heat source of low-temperature areas is crustal heat being conducted and convected upwards (Arnórsson et al., 2008; Franzson et al., 2010b).

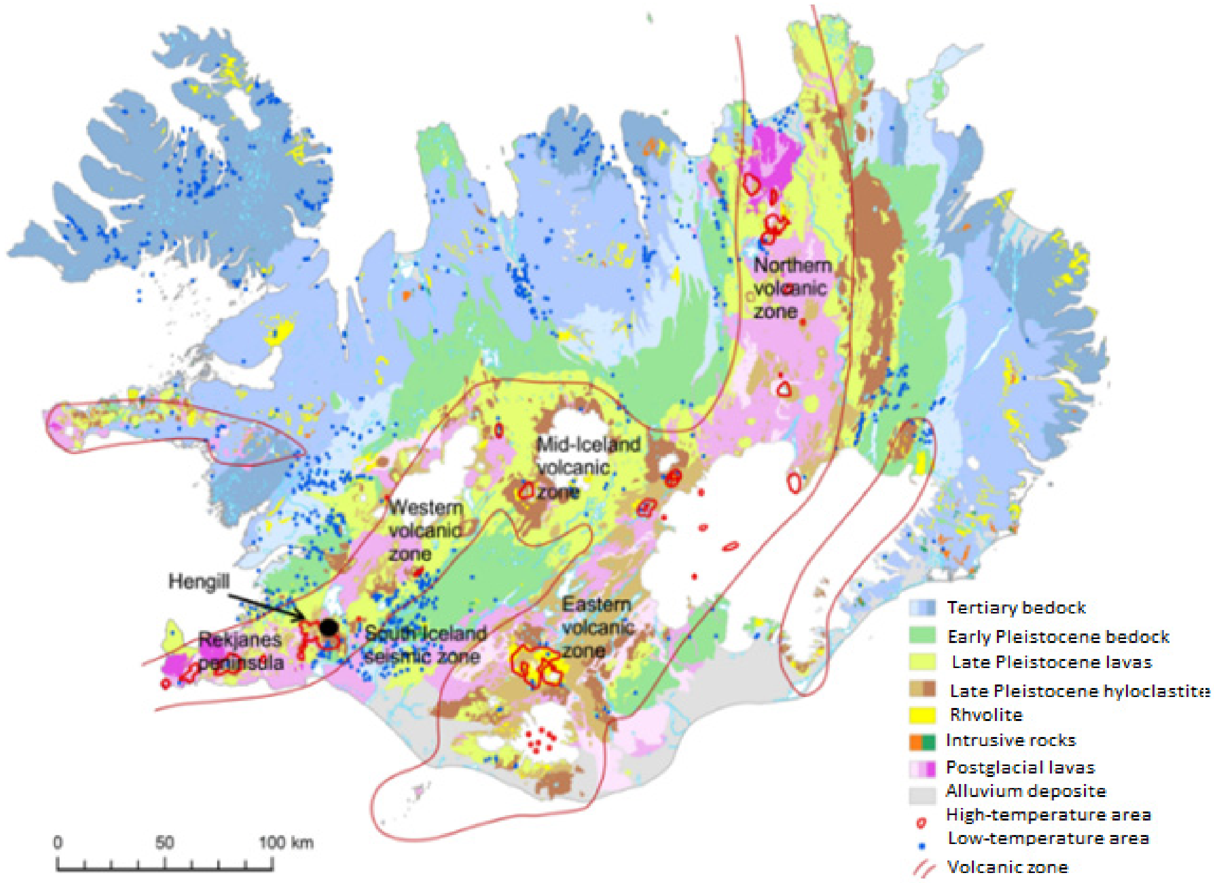


FIGURE 3: Geological and geothermal map of Iceland
(modified from Hjartarson and Saemundsson, 2014)

3. GEOLOGY AND TECTONIC SETTING OF THE HENGILL-HELLISHEIDI AREA

About 0.4 Ma year old, Hengill central volcano is situated between the American and Eurasian diverging plate boundary, in the middle of the Western Volcanic Zone (Figure 3). It is a place where the three active tectonic zones; the Reykjanes Peninsula, the Western Volcanic Zone and the South Iceland Seismic Transform Zone form a triple junction (Gunnlaugsson and Gíslason, 2005; Franzson et al., 2005) which results in active tectonism, volcanism and seismic activity in the area. Hengill volcano is represented by elevated, dominant subglacial hyaloclastites (mostly consisting of pillow basalts, breccia and tuff), interglacial lava flows and postglacial eruptions of 9000, 5000 and 2000 years along NE-SW trending fissure swarms (Franzson et al., 2005). The Hengill fissure swarm is 60-70 km long to the north and south of the central volcano and 5-10 km wide. These are the main outflow zones for the geothermal system and the main drilling targets in the Hellisheidi geothermal field (Franzson et al., 2005). Tectonically, Hengill area is active and dominated by several NE-SW striking minor and well identified major normal faults, which are tilted to the east and west with a total down throw of 200 to 250 m (Hardarson et al., 2009; Hardarson et al., 2015; Helgadóttir et al., 2010; Franzson et al., 2005).

From recent studies, a narrow NNE-SSW running mini-graben, called Reykjafell mini-graben, has been identified along the western flank of Hengill volcano within the major fissure system (Figure 4 and 11). The mini-graben is 150-400 m wide with down-throws of up to 200 m at depth. Crossing the mini-graben in this area was the main drilling target for several production wells, which proved to be powerful producers (Hardarson et al., 2015).

3.1 Previous studies

3.1.1 Surface studies

Detailed geological mapping, geophysical and geochemical studies carried out on the surface, have revealed the existence of a large geothermal high-temperature anomaly in the Hengill area. The geophysical studies in the area carried out since 1971 include aeromagnetic, gravity and DC-resistivity surveys, seismic refraction and passive seismic surveys (Franzson et al., 2010).

The resistivity surveys (MT and TEM) have identified a 110 km^2 thermal anomaly at 850 m depth (Figure 2) and a low resistivity structure below 4 km depth. The high-resistivity anomaly also shows the dominant NNE-SSW alignment structures (Árnason, 2007; Franzson et al., 2010) (Figure 2).

Geochemical studies from fumarole samples show that the concentration of gases in the area is in equilibrium with mineral buffers at different temperatures. Gas geothermometry studies in the area have revealed a decrease in temperature towards the east (Gunnlaugsson and Gíslason, 2005).

3.1.2 Subsurface studies and hydrogeology

The first exploration well in Hengill geothermal field was drilled in 1985 (Franzson et al., 2005), followed by numerous vertical and later, dominantly directional production and reinjection wells. The directional wells generally have a "kick off point" at approximately 300 m and are subsequently aimed at intersecting major feed zones associated with boundary faults and fissures. The reservoir temperature at Hengill ranges from 200 to 340°C (Haraldsdóttir et al., 2015).

From borehole geology studies, the upper 1000 m b.s.l. in the Hengill area is dominantly hyaloclastites followed by extensive lava successions. These are mostly basaltic with occasional intermediate to acidic intrusives (dikes and/or sills), which are dominant below 800 m b.s.l. The intrusions form heat sources as well as permeability in the reservoir together with major faults (Franzson et al., 2005). The hydrothermal alteration distribution in Hengill reaches up to epidote-amphibole zone. The comparison of this with the formation temperature suggests equilibrium conditions, except some cooling at the western boundary of the Hellisheidi, cooling from the east towards Reykjafell and heating up towards the southern part of the area (Helgadóttir et al., 2010).

According to Franzson et al. (2005), the groundwater model of the area shows fluids from the outer boundaries of the system recharging the upflow. The main recharge channel is deep within the NE-SW fault zone that crosses the Hengill volcano where the permeability is believed to be highest. Higher up under Hengill the upflow divides, with some fluid flows to the NE into the fissure swarm towards Nesjavellir and some to the SW towards Hellisheidi.

4. RESULTS

4.1 Methodology and analytical methods

Binocular analysis: used to analyse cutting samples that were collected at every 2 m interval from well HE-59, to delineate the rock lithology, primary and secondary minerals and alteration, fracture fillings, oxidation and also intrusions. This analysis was carried out by using 'Olympus' binocular microscope.

Thin section analysis: played an important role, next to binocular analysis, which covers the major portion of the overall analysis. The analysis was conducted using 'Leica' petrographic microscope with 4x and 10x magnification power. A total of 11 samples were selected for thin section analysis, where the result added some valuable data on primary and secondary mineral identification, alteration and alteration mineral sequences.

X-ray diffraction analysis (XRD): identifies clay minerals from 14 cutting samples, which were selected from different depths. The objective of these analyses is to outline different zones of clay alteration.

Fluid inclusion analysis: started by selecting appropriate quartz and calcite mineral grains from different depths and subjecting to polishing, so that the inclusions could be clearly seen under the microscope. Then micro thermometry was used to homogenise the temperature of the fluids trapped in the crystal.

Apart from these techniques, maps and GPS were used to track fissures and faults on the surface during structural studies. Software like Log plot and Leapfrog was used to plot geological and drilling logs and to compile the well's data with a 3D Leapfrog model of the area.

4.2 Drilling history of well HE-59

Well HE-59 is a make-up well for the Hellisheidi power plant. It was directed to the southwest towards a mini-graben, which is found in Mt. Reykjafell (Figure 4). Some of the most productive wells on Hellisheidi intersect that mini-graben (Hardarson et al., 2015). The well also transects a 12,300 years old volcanic fissure. Kick off point was planned at 352 m and build-up 3°/30 m, resulting in an inclination of 35° at 700 m. The azimuth was set at 252° (Figure 4). The drilling of HE-59 was achieved in four phases during February and March 2016. Drilling depths, casing depths and drill bits are presented in Table 1. The pre-drilling was done by the rig Nasi (Shcramm T130XD), but phases 1-3 by the rig Thor (Bentec Euro Rig 350).

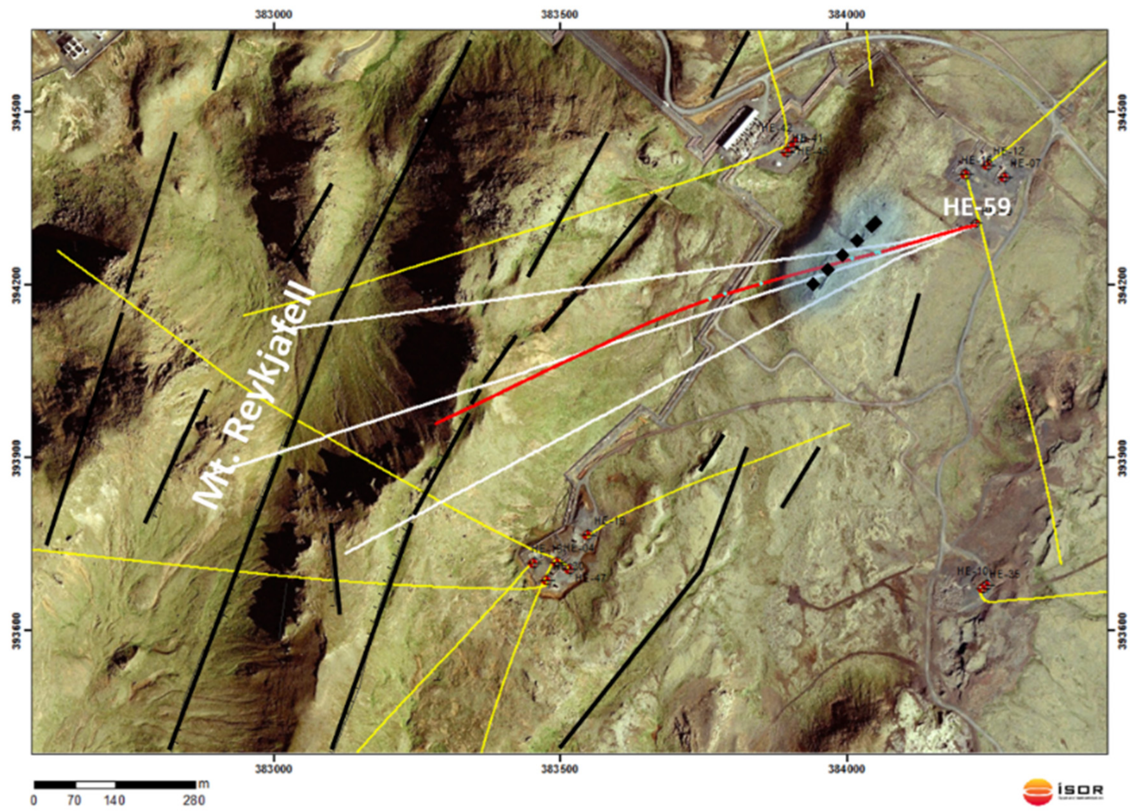


FIGURE 4: The well path of HE-59 extrapolated to the surface (red line). White lines show the planned track and allowed deviation. Yellow lines are nearby wells, black lines represent faults and fissures and black dotted line is the small fissure west of the wheel pad (Helgadóttir et al., 2016)

TABLE 1: Drilling depth, casing depth and drill bits in well HE-59. Depths refer to the platform of Thor, 9 m above ground level (Helgadóttir et al., 2016)

Rig (Drill pad)	Phase	Drill bit	Depth (m)	Casing depth (m)	Casing Diameter
Nasi (1.9 m)	Pre-drilling	26"	114.7	113.7	18⅝"
Thór (9 m)	1. phase	17½"	317	314.2	13⅜"
Thór (9 m)	2. phase	12¼"	800	798.7	9⅝"
Thór (9 m)	3. phase	8½"	2183	762-1130	7"

Pre-drilling
Well HE-59 was spudded on April 17th 2016 using the rig Nasi and pre-drilling was completed at a depth of 114.7 m on April 23rd. The well was cased with 18¼" surface casing to 113.7 m and cemented using 29 m^3 of slurry. No circulation losses were observed. Drilling fluid was mud.

Phase 1. After setting up the rig Thor on the well, phase 1 commenced on May 17th and was completed on May 19th at 317 m depth. Following a logging program (temperature, calliper, resistivity, NN and gamma) the well was cased with 13⅜" anchor casing to a depth of 314.2 m. The casing was set with 33 m^3 of cement slurry. No circulation losses were encountered during drilling of phase 1. Drill fluid was mud.

Phase 2. After WOC (weight on cement), welding a flans and testing the BOP (blowout preventer) unit, phase 2 started on May 25th, on Thor´s 9th working day. Drilling was achieved using a 12¼" bit, motor and MWD (Measure While Drilling). Drill fluid was mud. The drilling was completed at 800 m depth on May 28th and no circulation losses were observed. Gyro logging showed that the azimuth at 785 m depth was 254° and the inclination 34,5°, which is close to the targets. The 9⅝" production casing was RIH (Run In Hole) to a depth of 798,7 m and set with 42,5 m^3 of cement slurry.

Phase 3. Following preparations and BOP tests phase 3 commenced on June 2nd using water. This phase proved to be rather complicated and several problems were encountered. Early in the drilling phase circulation losses occurred and had to be plugged with cement. However, as drilling cement commenced, the well side-tracked. Total loss was encountered in the side-tracked well at 904 m depth and no cuttings were retrieved after this. Drilling continued and the string got stuck a few times but the crew managed to get it loose every time. Drilling was stopped at 2381 m depth when the string got stuck once again. After several attempts to loosen the string it was cut by explosives at 1130 m and a 7" slotted liner was RIH. Drilling of HE-59 was completed at July 11th, 2016. Circulation losses during phase 3 are shown in Table 2.

TABLE 2: Circulation losses during drilling phase 3 of HE-59 (Helgadóttir et al., 2016)

Depth (m)	Losses (l/s)
833	18
835	26
840	45
850	30
885	30
890	18
902	>45

4.3 Stratigraphy of well HE-59

The cutting samples from the well were only collected down to 902 m due to total circulation loss below that depth. From the upper 902 m of the well, different lithologies were identified with the help of binocular microscope. The lithology of well HE-59 falls into two groups; hyaloclastites and crystalline basaltic rocks. Hyaloclastites incorporates subglacial eruption products of basaltic tuff, basaltic breccia and pillow lava, while crystalline basalt encompasses lava flows. The detailed lithological description of each of these rock units is described below, and shown in Figure 5.

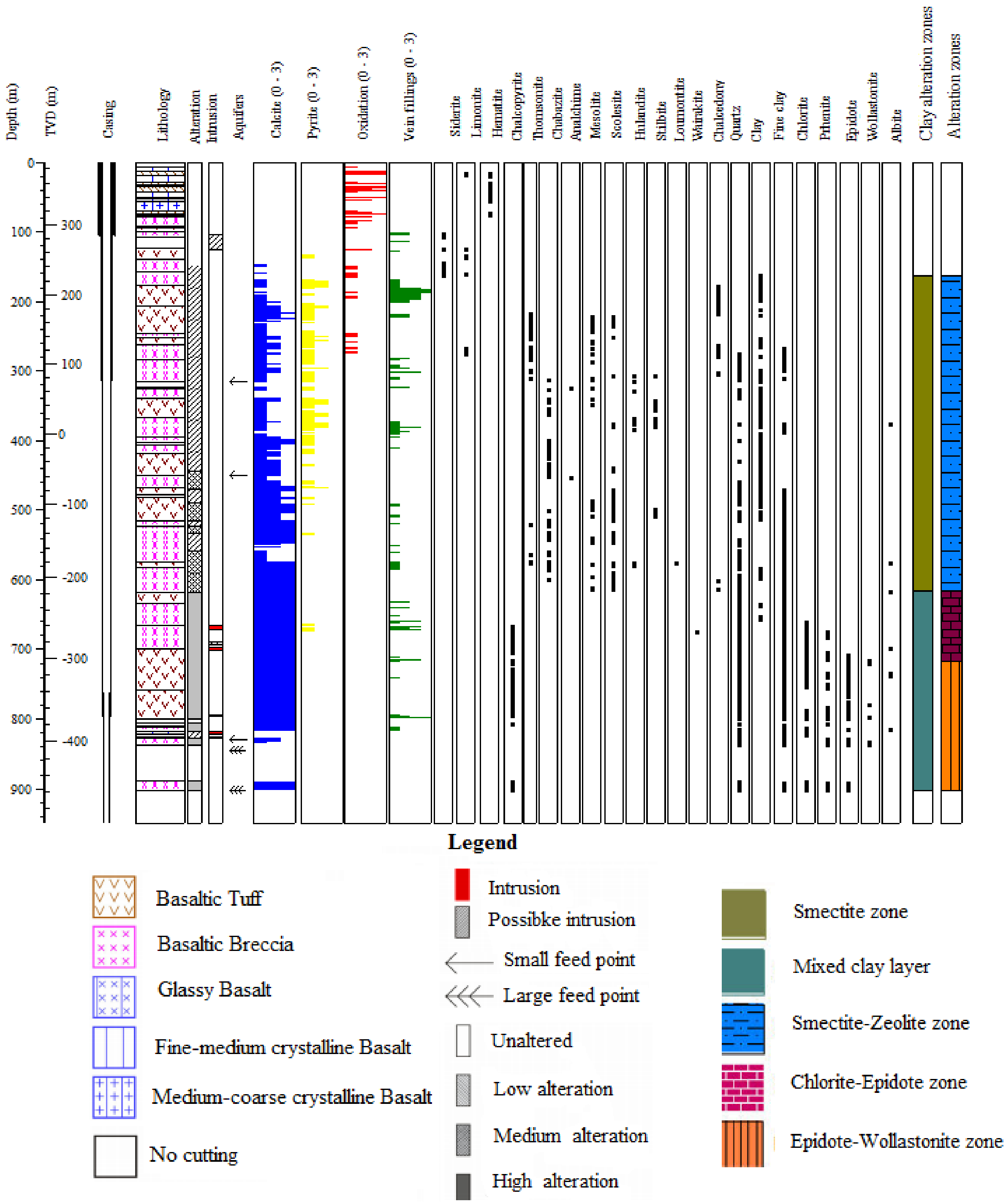


FIGURE 5: Lithology and hydrothermal minerals distribution in well HE-59. Feed zones are shown as arrows. Alteration zones are indicated far right

0-6 m: No cuttings

6-12 m: *Fine- to medium-grained crystalline basalt*
Fine- to medium-grained, greyish and partly porous unaltered basalt with very slight oxidation at 8 m. It has primary minerals like plagioclase, olivine and pyroxene.

12-18 m: *Scoria*
Reddish scoria with plagioclase phenocrysts and abundant hematite and limonite.

18-28 m: *Fine- to medium-grained crystalline basalt*
Fine- to medium-grained, greyish crystalline basalt with crystals of plagioclase, olivine and abundant pyroxene.

28–32 m: *Scoria*
Slight to highly oxidized reddish and few black scoria, having crystals of olivine and plagioclase phenocrysts, rich in hematite.

32-34 m: *Fine- to medium-grained crystalline basalt*
Fine- to medium-grained, greyish basalt with few olivine and plagioclase phenocrysts. The cuttings are slightly mixed with scoria from the upper sections.

34-42 m: *Scoria*
Oxidized reddish and a few black and brownish scoria. Plagioclase as a primary mineral and hematite are common.

42-50 m: *Fine- to medium-grained crystalline basalt*
Fine- to medium-grained, greyish basalt. Plagioclase is the dominant primary mineral, but some olivine and pyroxene are also occurring. The cuttings are slightly mixed with oxidized scoria.

50-52 m: *Scoria*
Highly oxidized reddish scoria with plagioclase phenocrysts.

52-56 m: *Fine- to medium-grained crystalline basalt*
Light greyish medium-grained basalt. At 56m, the cuttings are mixed with oxidized scoria from the upper section.

56-70m: *Medium-to coarse-grained crystalline basalt*
Light greyish pyroxene rich basalt with small olivine.

70-74 m: *Scoria*
Moderately oxidized scoria, has hematite in vesicles.

74-76m: *Basaltic tuff*
Oxidized, medium- to coarse-grained reddish brown tuff and fragments of glass.

76-78 m: *No cutting*s

78-92 m: *Basaltic breccia*
Medium-to coarse-grained reddish brown, light greyish and dark greyish oxidized moderate to highly welded tuff with slightly oxidized porous fine- to medium-grained basalt. The depth 84 to 92 m consists of a mixture of this rock unit with light yellowish sandstone. Plagioclase crystals and glass fragments are common.

92-94 m: *Glassy basalt*
Black, shiny holocrystalline basalt (pillow basalt).

94-100 m: *Basaltic tuff*
Fine- to medium-grained oxidized reddish brown, light greyish, and greyish strongly welded tuff with common glass and crystals of plagioclase and olivine.

100-107 m: *Basaltic breccia*
Light greyish very slightly altered tuff, abundant with glass together with yellow to light greyish and light reddish brown fine sand stone. Fine-grained black fresh basalt (probably intrusive) is also mixed

from 104 m with the cuttings. Glass and plagioclase crystals are common with secondary mineral siderite. At 106 and 107m, the cuttings are slightly oxidized.

107-124 m: No cuttings

124-140 m: *Basaltic tuff*
Light greyish and dark greyish moderately to highly welded tuff with plagioclase crystals and little glass. Pyrite emerges at 136 m as very fine and dispersed.

140- 158 m: *Basaltic breccia*
Light greyish and greyish moderately welded tuff and greyish partially porous fine basalt with plagioclase and glass. Siderite is a common secondary mineral. From 150 to 158 m the cuttings are slightly altered.

158-176 m: *Basaltic breccia*
Greenish and greyish tuff with greyish, fine-grained basalt consisting of black xenoliths in abundance (164-176 m). At 160 m the greenish tuff shows an increase in alteration. At 162 m, siderite, amorphous silica and at 172 m calcite is occurring. Other secondary minerals include sparse, very fine pyrite and greenish clay. Plagioclase and minor olivine are the primary minerals encountered.

176- 206 m*: Basaltic tuff*
Greyish, moderate to highly welded and slightly altered tuff, where the pore spaces and veins are extensively filled by chalcedony. Pyrite (at 188, 192 and 204 m) and calcite are also found. Plagioclase with some olivine present as primary crystals. Chalcedony is quite abundant from 180 to 190 m. Zeolites (thomsonite) emerge at 176 m.

206- 246 m: *Basaltic tuff*
Dominantly light greenish, grey and dark greyish, fine- to medium-grained, slightly altered tuff, with plagioclase crystals. At 222 m the tuff has vesicles are filled with green clay. There is an increased amount of calcite with dispersed fine pyrites. Chalcedony and zeolites (chabazite, thomsonite, mesolite and scolecite) are also increasing after 218 m.

246-252 m: *Basaltic breccia*
Fine to medium, light greenish grey tuff, with plagioclase crystal mixed with fine black basalt. Alteration minerals include green clay and zeolites. The cuttings are slightly altered.

252-262 m: *Basaltic tuff*
Fine- to medium, light greenish grey and dark greyish, slight to moderately welded tuff. The cuttings are faintly altered and consist of some pyrites, crystalline calcite, zeolites and clay.

262-284 m: *Tuff rich basaltic breccia*
Dominantly black, fragile tuff, with fine- to medium-grained light greenish and greyish, poorly to moderately welded tuff. Minor black fine-grained basalt is also occurring. The cuttings have zeolites, chalcedony and sparse limonite.

284-316 m: *Basaltic breccia*
Light greenish grey and dark greyish, fragile and moderately welded tuff, which is slightly to moderately altered, with black fine porphyritic, relatively unaltered basalt (has crystals of plagioclase and micro olivine). At 308-314 m, the basalt is partially porous and some are filled by zeolites at 314 m. The cuttings include calcite, pyrite, quartz, zeolites, clay and minor siderite.

316-324 m: No cuttings

324- 326 m: *Fine- to medium-grained crystalline basalt*
Dark greyish, fine- to medium-grained basalt, with micro olivine crystals. Zeolite (analcime) is found at this depth.

326-340 m: *Basaltic breccia*
Fine-grained, slightly porous, dark greyish basalt (some of the pore spaces are filled with zeolites) mixed with fine, greyish, slightly welded tuff and glass. Abundance of fragments of cement grout. Small amounts of calcite, pyrite, quartz, zeolites, clay and limonite are also present.

340-*366 m: Basaltic tuff*
Fine-grained, poorly welded black tuff, with partially altered glasses. Below 352 m, light greenish grey tuff is mixed in. At 342 m, the amount of calcite and alteration is increasing. There is also an increase in pyrite, but constant amount of zeolites (chabazite and mesolite) and quartz.

366- 402 m*: Tuff rich basaltic breccia*
Minor, fine- to medium-grained black basalt, mixed with greenish grey, very slightly to somewhat compacted tuff. At 394-402 m the tuff is moderately altered and more compacted, dominated by white secondary minerals like calcite.

402-406 m: *Basaltic tuff*
Poorly to moderately welded black and greyish tuff. The cuttings have zeolites (e.g. chabazite) and black clays with abundant calcite and rare pyrite.

406-418 m: *Tuff rich basaltic breccia*
Few, fine-grained black basalts with moderately welded black and greyish tuff. The cuttings are slightly altered and commonly have secondary minerals like calcite, pyrite and zeolites.

418-450 m: *Basaltic tuff*
Fine- to medium-grained and loose and moderately welded, some course grained, light greyish and greyish tuff. Moderately welded with the commonly partly altered dark brownish glass. Black medium-grained with high amount of zeolites (e.g. thomsonite) and remnant of altered glass. Moderately altered.

450-468 m: *Tuff rich basaltic breccia*
Fine-grained, light greenish grey, poorly and moderately welded, mixed with some greyish fine- to medium-grained basalt.

468-478 m: *Basaltic tuff*
Fine- to medium-grained, light greenish grey, greyish and black, slightly to moderately welded tuff. Quartz, zeolites, and clays are present as secondary minerals.

478- 482 m: *Basaltic breccia*
Fine-grained, light greenish grey, moderate to highly welded tuff, together with dark greyish fine porphyritic (with crystals of plagioclase and few olivine) basalt. Clays, zeolite, quartz with common pyrite and calcite are also occurring.

482-516 m: *Basaltic tuff*
Dominantly greenish grey, and slightly to moderate welded tuff with some black fragile tuff. Zeolites (scolecite and mesolite), quartz and clays are also found.

516-524 m: *Basaltic breccia*
Fine- to medium, mixed light greenish, greyish and black, moderate to highly compacted tuff, together with fine black basalt, which has plagioclase and minor olivine phenocrysts. Some glassy basalt at 520-522 m is also mixed in.

524- 574 m: *Tuff rich basaltic breccia*
Dominantly fine- to medium-grained, greenish grey and few black, slight to moderately welded tuff. The tuff is mixed with light brownish grey, partly porous tephra at 534-538 m. Some of the pores are filled with scolecite. Calcite and some pyrite are occur.

574-*582 m: Basaltic tuff*
Fine-grained, light greenish grey, slightly to moderately welded tuff. It is relatively altered and has some glass fragments. An increase in calcite with some clay, zeolites and quartz are observed.

582- 618 m: *Basaltic breccia*
Greenish and greyish slightly to moderately welded and moderately altered tuff, together with slightly altered light brownish grey, partly porous (filled with greenish clay and quartz) tephra. Well crystallized coarse pyroxene is observed in high amounts.

618-634 m: *Basaltic tuff*
Fine- to course grained, light greenish, moderate to strongly welded and highly altered tuff with few black tuffs. Green clay and quartz are common with high amount of calcite.

634-666 m: *Basaltic breccia (tuff rich)*
Light greenish and greenish grey, moderately to strongly welded and highly altered tuff, together with fine-grained, fresh and slightly altered black and greyish basalt.

666-700 m: *Basaltic breccia*
Fine- to medium-grained, greyish, light greyish and black basalt (intrusive) together with light greenish grey slight to moderately welded and heavily altered tuff.

700- 758 m: Tuff rich *basaltic breccia*
Moderately altered, black fine-grained basalts with dominant fine light greyish, strongly welded and highly altered tuff. Plagioclase is common. From 716 m, greyish basalt and greenish tuff become dominant. There is slight oxidation from 724 to 736 m which might be part of a fault breccia. An emergence of epidote is recorded at 708 m, prehnite at 676 m and wollastonite at 716 m. Well defined cubic pyrite crystals are occurring at 726 m. Primary crystals of pyroxene and plagioclases are common.

758-800 m: *Basaltic* tuff
Fine- grained, light greyish, strongly welded and highly altered tuff with common plagioclase crystals. For the upper parts, minor, fairly altered, black fine-grained basalt is mixed.

800-806 m: *Cement grout*
The cement is very lightly mixed with light greenish tuff, calcite and quartz at 806 m.

806-810 m: *Basaltic breccia*
Heavily altered greenish tuff and fine-grained greyish basalt with dominant white primary and secondary minerals (plagioclase, calcite and quartz).

810-812 m: *Basaltic tuff*
Dominated by white primary and secondary minerals (plagioclase, calcite and quartz), with very strongly altered light greenish tuff.

812-818 m: *Basaltic breccia*
Highly altered, greenish tuff and slightly altered fine-grained dark greyish and greyish basalt, with dominant white primary and secondary minerals

818-822 m: *Fine- to medium-grained crystalline basalt*
Fine- to medium-grained, black and grey basalt (intrusive) mixed with few tuffs.

822-826 m: *Basaltic breccia*
The cuttings contain highly altered, greenish tuff and fragments of the basalt from the intrusive.

826-828 m: *Fine- to medium-grained crystalline basalt*
Black and fresh, fine- to medium-grained basalt (intrusive).

828-838 m: *Basaltic breccia*
A mixture of black, fine- to medium-grained basalt and highly altered greenish tuff with common plagioclase, quartz, chlorite, prehnite, chalcopyrite, epidote and wollastonite.

838-888 m: *No cuttings*
At 843 m there is black shiny and fresh basalt with secondary minerals of chlorite and chalcopyrite. The depth 865 m has light greenish moderate to highly welded tuff.

888-902 m: *Basaltic breccia*
Dominated by highly altered, light greenish tuff, with some fine-grained shiny black basalt. Hydrothermal minerals include quartz, chlorite, and chalcopyrite.

4.4 Intrusions

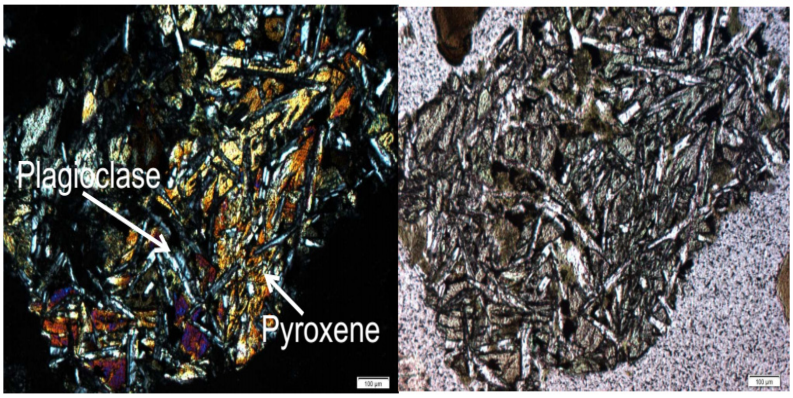


FIGURE 6: Crossed (to the left) and plane polarized (to the right) view of thin section picture showing poikilitic texture in the basaltic intrusion. The scale is 100

Several intrusive rocks were encountered in well HE-59. The depths 104-126, 690-694 and 794-796 m are marked by probable intrusions and 666-672, 698-702, 818-822 and 826-828 m are identified as intrusions (Figure 5). An intrusion is fresh or slightly altered compared to the surrounding rocks and sometimes it can be identified by the oxidation and increased precipitation of hydrothermal minerals (e.g. calcite and pyrite) at their margins, as at the depth of 104-124 m. The intrusions in well HE-59 are dominantly black and greyish, fine- to medium-grained crystalline basalt, while from 666 to 672 m it is characterized by medium- to coarse-grained, dark and fresh basalt. Petrographic analysis of the intrusions shows poikilitic texture from 822 m (Figure 6), where the plagioclase crystals are enclosed by pyroxene (augite) and olivine.

4.5 Hydrothermal alteration

4.5.1 Alteration of primary minerals

In high-temperature geothermal systems like Hengill, the replacement of primary minerals by secondary minerals (hydrothermally altered minerals), as a result of fluid-rock interaction, is a common process and one of the most important part of borehole studies.

Primary minerals, including olivine, pyroxene and plagioclase, are found in the form of phenocrysts and micro phenocrysts. Plagioclase is the most abundant primary mineral throughout this well, in the form of euhedral and subhedral crystals, and typically after 450 m, it is found as coarse-grained regularly

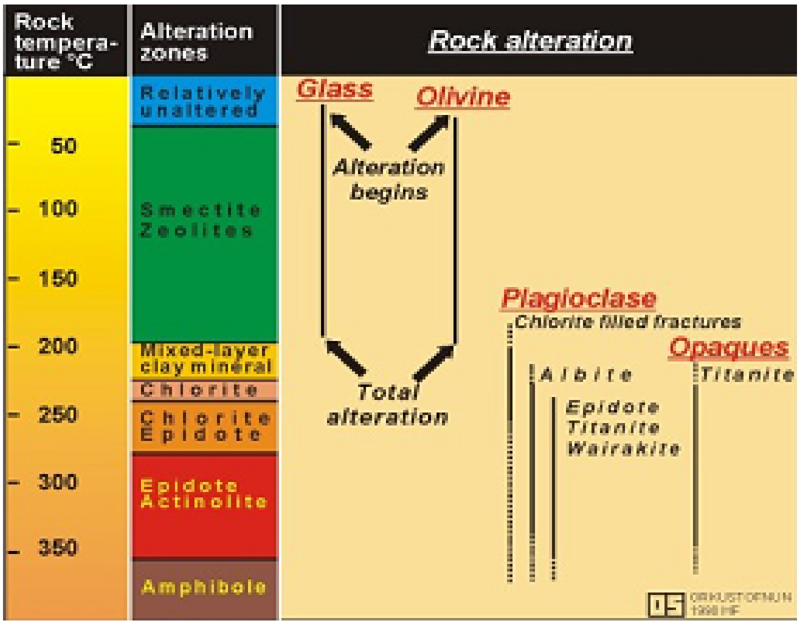


FIGURE 7: Zones of rock and mineral alteration in Iceland (Franzson, 1998)

crystallized grains. In the hydrothermal process it will be transformed to albite, calcite, epidote and wairakite. The second abundant mineral in the well, pyroxene, is very common with its well defined prismatic crystal shape and coarse grains, especially from 586 to 618 and 714 to 742 m. Olivine is mostly found as micro crystalline in the lava flows. The replacement mineral for pyroxene and olivine can be pyrite, chlorite, quartz, calcite and actinolite at high temperatures (> 280°C). Volcanic glasses are susceptible to hydrothermal alteration (Figure 7) at low-temperature and are easily changed to clay, chlorite, zeolites and calcite.

The replacement of these minerals, and some opaque minerals, by secondary minerals is dependent on temperature, composition of fluids, and permeability of the rocks. The hydrothermal minerals encountered in well HE-59 that have been identified, mainly by using binocular microscope as well as in thin sections and XRD, are described below.

Hematite: is a secondary mineral replacing magnetite in the shallow alteration environment. It is steel-black, shiny with metallic lustre and well-rounded spherical shape. It was seen at the very first depths of analysis and becomes dominant from 30 to 56 m, mostly hosted by scoria.

Limonite: is yellowish brown in colour and is the result of oxidation at shallow depths. In well HE-59, it appears at 14 m.

Siderite: is an iron carbonate mineral with a reddish brown colour and spherical appearance. Siderite mostly occurs at the edges of intrusions, as seen in this well. Siderite is appearing generally rarely but at shallower depths, it is fairly common. It is associated with pyrite.

Pyrite: is amongst the most common hydrothermal minerals. It is encountered throughout the well from 136 to 838 m. It is found as disseminated, small, micro cubic crystals, except at some depths, like 382 m and 602 m, where it is coarser with perfect regular cubic shape. The occurrence is mainly dispersed in the rock matrices and within fractures and vesicles. It is associated with calcite, quartz, and zeolite. Pyrite and Chalcopyrite may indicate permeability.

Calcite: is the most common secondary mineral in the well, as it can be formed at a minimum temperature of 50°C and up to 300°C. It is found associated with clay, quartz, and zeolites. It emerges at shallow depths, 150 m in the basaltic tuff unit, and found as veins and vesicle fillings. At some depths, like 222 m, 252-258, 326, 416, 472, 482, 488, 512, 574-576 and 590 m, it is platy and transparent. Platy calcite may indicate boiling conditions in the formation. From 784 to 796 m it shows an increase in amount.

Chalcedony: is an amorphous form of quartz, with milky white to light bluish colour as it appeared in well HE-59. Its first appearance is recorded at 178 m and it extensively appeared down to 202 m in the form of veins and vesicle fillings, and it shows strong association with zeolites.

Zeolites: are low-temperature, hydrous, hydrothermal minerals that are common at shallow depths in geothermal systems. Different varieties of zeolites appeared in the well according to their specific temperature of formation. These can be identified by their definite shape of tabular, fibrous and granular (Saemundsson and Gunnlaugsson, 2014).

Zeolites from the well HE-59 were identified by binocular microscope and thin section, first found at 214 m and last observed at 614 m, but wairakite was seen at 676 m. Their occurrence is in the form of vesicle fills and rarely as veins within the basaltic tuff and breccia rock units. The distribution of different kinds of zeolites in this well is described below.

Chabazite: appeared as a granular cubic shape and as a bunch of small and compacted cubic crystals together forming rounded shapes. It is found as a cavity filling. Chabazite represent the lowest temperature, 50-70°C (Saemundsson and Gunnlaugsson, 2014) and is the first zeolite to emerge at 214 m. It mostly appears with thomsonite.

Thomsonite: is a flattened and fibrous radiating zeolite. It is dominant and occurs as vesicle and vein fillings. Thomsonite first appeared at 218 m, and was lastly seen at 614 m. Its occurrence shows the association with chabazite and scolecite/mesolite. Based on Saemundsson and Gunnlaugsson (2014), 50-120°C is the temperature where thomsonite occurs.

Analcime: is a granular type of zeolite group, found as white, multi-faced shaped, trapezohedron crystal, white in colour. It is stable at wide range of temperatures (50-160°C) but is rare in this well. The first appearance of analcime is recorded at 326 m.

Scolecite/mesolite: form aggregates of fibrous and elongated slender crystals. Scolecite is thicker and has flattened surfaces, while mesolite is thinner and spiky. They are white and occurred as vesicle and vein fills from 222 to 614 m associated with different zeolites. Scolecite/mesolite represent the temperature range 70-120°C (Saemundsson and Gunnlaugsson, 2014).

Stilbite: prismatic group of zeolites. It resembles quartz with its milky-white appearance. It is formed at temperatures of 70-140°C. Stilbite was first seen at 368 m and thin section analysis revealed its presence at 308 m.

Heulandite: appeared as a colourless, transparent, tabular crystal with a perfect cleavage. It is formed in a temperature range of 60-150°C and first found at 330 m, but under thin section it appeared at 308 m (Figure 8).

Laumontite: is tabular and white in the cuttings. It is rare in this well and it appeared only at 576 m representing the wide temperature range of 110-230°C.

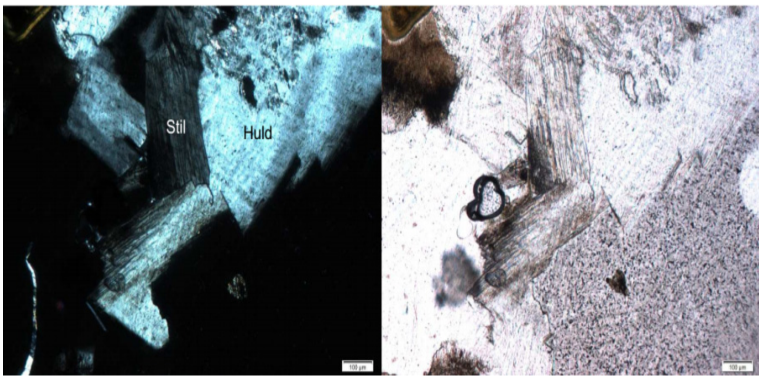


FIGURE 8: Crossed (to the left) and plane polarized (to the right) view of stilbite and heulandite from 376 m. The scale is 100 µm

Wairakite: is a high-temperature, granular zeolite with trapezohedron crystal shape, resembles analcime, since it is Ca-substitute of the analcime. It is associated with quartz and found only at 676 m, indicating a temperature of at least 200°C (Table 3).

Clays: are among the most abundant and most common alteration minerals in geothermal systems.

Clay formation is mostly the result of the alteration of glass, in a wide range of temperatures ranges from below 200 to above 300°C (Table 3). The temperature range results in different types of clays. In this well, three different clay varieties have been studied, namely smectite, mixed layer clay and chlorite, as described below. Clays were found as both vein and vesicle fillings. The analysis was achieved by using binocular microscope, thin section and XRD analysis.

TABLE 3: Common alteration minerals and respective temperature ranges in high-temperature geothermal systems (Kristmannsdóttir, 1979; Franzson, 1998)

Minerals	Min. temp. °C	Max. temp. °C
zeolites	40	120
*laumontite	120	180
quartz	180	>300
*wairakite	200	
smectite		<200
**MLC	200	230
chlorite	230	>300
calcite	50-100	280-300
prehnite	240	>300
epidote	230-250	>300
wollastonite	260	>300
actinolite	280	>300

*Belong to the zeolite group.

**Mixed layer clay.

Smectite: is light greenish in colour and fragile, a common clay mineral at shallow depths. In well HE-59, smectite was seen first at 220 m from the XRD analysis and from the binocular analysis, it is identified first at 164 m.

Mixed layer clay: represents the presence of different clay minerals that can form at a temperature range of 200 to 230°C (Table 3). It is seen from 616 m and is confirmed by the XRD analysis to extend continuously all the way down to the end of the cutting analysis at 902 m. As the name implies, it consists of varied colour clays, but commonly smectite is black and greenish.

Chlorite: is a high-temperature clay mineral (Table 3). From the binocular analysis, it starts to occur at 662 m and frequently occurs throughout down to the 902 m. Generally, it is deep greenish in colour with its flaky appearance, mainly found as vesicle fill.

Quartz: appeared as colourless to white, and under thin section both subhedral and euhedral crystals are present from 276 m to 902 m. Apart from these, prismatic hexagonal amygdales of quartz are also encountered (e.g. 544, 578, 594, 604, 638 and 654 m). Quartz is normally formed at a minimum temperature of 180°C, and stable even after 300°C.

Albite: identified from the petrographic study at 376 m. It is the replacement of plagioclase by a process called albitization. As can be seen in Figure 9, it has a dirty white to greyish colour, with the absence of twinning. The presence of albite indicates the temperature to be above 220°C (Kristmannsdóttir, 1979).

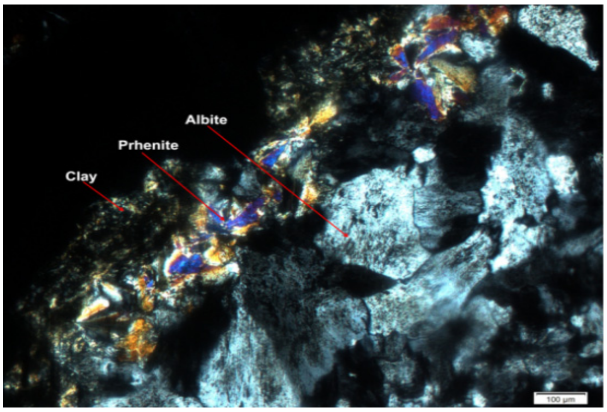


FIGURE 9: Showing depositional sequence filling the vesicle at 738 m. The scale is 100 µm

Prehnite: appears in this well at 676 m. It is white colour forming clusters of perfect spherical shapes. It is formed at a minimum temperature of 240°C.

Epidote: emerges at 708 m indicating that the minimum temperature of alteration is 230-250°C. It has yellow, greenish colour, with tiny prismatic elongated appearance in this well. Epidote was found as vein fill and as individual crystals frequently growing on quartz grains. It is associated with quartz and chlorite.

Wollastonite: is one of the high-temperature hydrothermal minerals formed at a minimum temperature of 270°C and can be found above 300°C. The first appearance of wollastonite in well HE-59 is at 716 m. Generally, it is white in colour and has fibrous radiating pattern growing above the quartz grains. The depths 716, 718, 798, 832, 834 and 838 m are marked by the presence of wollastonite.

4.5.2 Alteration mineral zonation

Secondary minerals have their own range of temperatures at which they form. The temperature range allows us to distinguish different zones of minerals at different and specific depths.

Volcanic glass, dominant in Icelandic hyaloclastites, is partly responsible for the alteration zones to occur depending on temperature and depth (Figure 5) (Franzson, 1998).

Glass is susceptible to alteration and starts changing to clay at low-temperatures resulting in smectite. Based on clay analysis, different alteration zones can be outlined. The top most part of the wells is usually unaltered. Then as the down-hole temperature increases, smectite forms followed by mixed layer clay and then chlorite at the highest temperature (Franzson, 1998). According to the results of XRD (see the appendix) and petrographic analysis of well HE-59, three clay alteration zones were identified. These include unaltered zone (0-220 m), smectite zone (220-616) and lastly mixed layer clay zone (616-902 m). The XRD analysis did not recognize chlorite in this well. However, the combined study of XRD clay analysis, the general hydrothermal minerals distribution and petrography studies outlined four main alteration zones in well HE-59, as described below.

Unaltered zone (0-150 m): unaltered zone, where there is no alteration of rocks, except oxidation and precipitation of oxidation products.

Smectite-zeolite zone (150-616 m): marked by the abundance of smectite and different types of zeolites. The first appearance of smectite, identified by the binocular and also petrographic analysis, was at shallow depth. Smectite covers a wide range of depths, down to 616 m indicating the temperature of formation is < 200°C (Franzson, 1998) and the upper temperature limit for zeolites is also 200°C.

Chlorite-epidote zone (616-716 m): defined by the appearance of chlorite and epidote. Although the XRD analysis failed to detect the existence of chlorite, which might be caused by sampling error, petrographic analysis revealed the existence of chlorite in the well. The zone is defined by the temperature range of more than 230 to over 300°C (Table 3).

Epidote-wollastonite zone (716-902 m): represented by temperatures of 230-250 to over 300°C and the existence of epidote, wollastonite and also minor chlorite and prehnite. Within this zone, from 784-796 m (Figure 5), the amount of calcite is significantly increased. This implies the high-temperature (boiling) condition of the zone in the past hydrothermal history of the area.

4.5.3 Depositional sequences of hydrothermal minerals

Secondary minerals are deposited in the pre-existing fractures and pore spaces and as a result, vein and vesicle fillings will be formed. The replacement of a mineral into another form of mineral and precipitate is dependent on the different conditions of the geothermal system, mainly temperature, parent rock/mineral and composition of fluids. During precipitation, the former mineral sometimes leaves its traces so that one can trace it back to tell what the parent mineral was. The other important and common phenomenon is, that the low-temperature hydrothermal minerals deposited, are followed by the high-temperature ones as we go deeper into the high-temperature geothermal system. Veins and vesicle fillings are the prominent way to access the minerals depositional sequence. Studying the minerals depositional sequence will provide prevalent information on the past and present condition of the geothermal system.

The deposition sequence from well HE-59 shows the dominant fill, identified mainly through binocular studies as well as petrographic analysis. The fills occurred dominantly in the hyaloclastite successions (tuff and breccia) rather than in the lava flows. In Table 4 below, the deposition sequences of different minerals at different depths in the well are presented.

TABLE 4: Sequences of hydrothermal minerals in well HE- 59

Depth (m)	Minerals sequences (younger….older)	Host rock (formation)
284	Siderite.…Calcite….Zeolite	Basaltic breccia
314	Pyrite…. Quartz …. Calcite…. Pyrite	Basaltic breccia
326	Pyrite…. Calcite Pyrite…. Zeolite	Fine- to medium-grained crystalline basalt
330	Quartz…. Zeolite	Tuff rich basaltic breccia
390	Pyrite…Calcite…. Pyrite	Tuff rich basaltic breccia
532	Zeolite (chabazite)…. Zeolite (scolecite)	Tuff rich basaltic breccia
586	Calcite…. Zeolite	Basaltic breccia
624	Pyrite…. Calcite	Basaltic tuff
628	Clay…. Quartz…. Clay	Basaltic tuff
630	Clay…. Quartz…. Clay	Basaltic tuff
640	Clay…. Calcite…. Zeolite	Basaltic breccia
662	Clay…. Calcite…. Clay	Basaltic breccia
664	Clay… Pyrite… Calcite… Pyrite… Calcite … Clay Clay…. Calcite…. Quartz	Basaltic breccia
672	Clay…. Chalcopyrite	Basaltic breccia
674	Pyrite…. Quartz	Basaltic breccia
708	Clay….Epidote	Tuff rich basaltic breccia
738	Clay….Prehnite….Albite	Tuff rich basaltic breccia
740	Pyrite…. Calcite	Tuff rich basaltic breccia
772	Clay…. Pyrite…. Calcite	Basaltic tuff
796	Quartz…. Epidote Clay…. Quartz…. Epidote Quartz….Chlorite	Basaltic tuff
800	Quartz…. Epidote Quartz…. Chlorite…. Quartz	Basaltic breccia

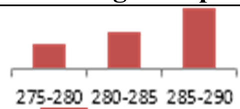
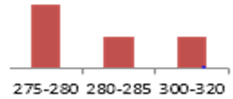
The dominant fill encountered in this well is calcite, followed by quartz and clay, hosted mainly by basaltic breccia and basaltic tuff. In the upper portion of the well (Table 4), one can tell that the system has been experiencing fluctuation in the geothermal environment, where the high-temperature minerals overlain by the low ones and vice versa. While the bottom portion of the well shows high-temperature minerals precipitate on top of the low-temperature minerals, implying heating up of the system.

4.6 Fluid inclusions

Formation and alteration temperature comparison is one way of estimating the conditions in a geothermal system, whether it is heating up, cooling down or in equilibrium. A fluid inclusion study in the geothermal context is a method of finding temperature from the fluids that had been trapped during crystallization of the secondary minerals.

For the well HE-59 study, two quartzes and one calcite grains were selected from suitable and appropriate depths at 700-726 m, 760-800 m and 812 m. Below these depths, the crystals were too fine grained and total circulation loss occurred below 902 m. From a total of 21 fluid inclusions, which were examined under micro thermometry, the homogenization temperatures range between 275 - 320°C. The homogenization temperature for the first depth, 700-726 m, ranges between 275-290°C. From the second depth (760-798 m) the homogenization temperatures range is between 285-320°C. The deepest inclusions (812 m) have a range of 275-320°C. Table 5 shows histograms of fluid inclusions with depth and homogenization temperatures.

TABLE 5: Homogenization temperature of fluid inclusions in well HE-59

Depth (m)	**Mineral**	**No of inclusions**	**Histogram = homog. Temperature (°C)**
700-726	Calcite	10	
760-798	Quartz	4	
812	Quartz	7	

The comparison between fluid inclusion homogenization temperatures and alteration and formation temperature will be deliberated later in the discussion section.

4.7 Aquifers (feed-points)

Temperature logs, circulation losses and gains, penetration rate, alteration and standpipe pressure, are the main parameters to identify the permeable water bearing rock and aquifers/feed-points. In well HE-59, four minor and five major feed zones are identified mainly from the upper 902 m. Interpretation of temperature logs, the temperature measured during and after drilling (Figure 10) and circulation losses, supported by the cutting analysis (alteration extent, lithological boundaries and the presence of intrusions), and geophysical logs like neutron-neutron and gamma logs were used to identify feed-points. The minor feed-points are found from 316 and 830 m, while at about 450, 845, 902, 1100, 1050 and 1140 m, larger feed-points are believed to be present. The description of each feed-point is given below.

Feed-point 1: is a minor feed-point found at 316 m. It is identified from the temperature logs and circulation loss, as well as the presence of lithological contact between basaltic breccia and fine- to medium-grained crystalline basalt. The neutron- neutron and gamma loge also shows an elevated peak at this depth.

Feed-point 2: a major feed-point, located at 450 m, showing a sharp curve on the temperature logs (Figure 5). The depth is marked by an increase in intensity of alteration and also the stratigraphic contact between basaltic tuff and tuff rich basaltic breccia.

Feed-point3: indicated by the elevated temperature log at 830 m and circulation loss of about 26 l/s. It is within the basaltic breccia unit and marked by the presence of a high-temperature mineral zone, chlorite-epidote-wollastonite.

Feed-point 4: located at 845 m and has similar conditions as feed-point 3, except feed-point 4 has much higher (45 l/s) loss of circulation.

Feed-point 5: is the major feed-point at 902 m where the loss of circulation was > 45 l/s and cutting returns were not encountered below this depth.

Feed-point 6, 7 and 8: are major and minor feed-points, represent the depth at 1100, 1050 and 1140 m, based on the temperature logs.

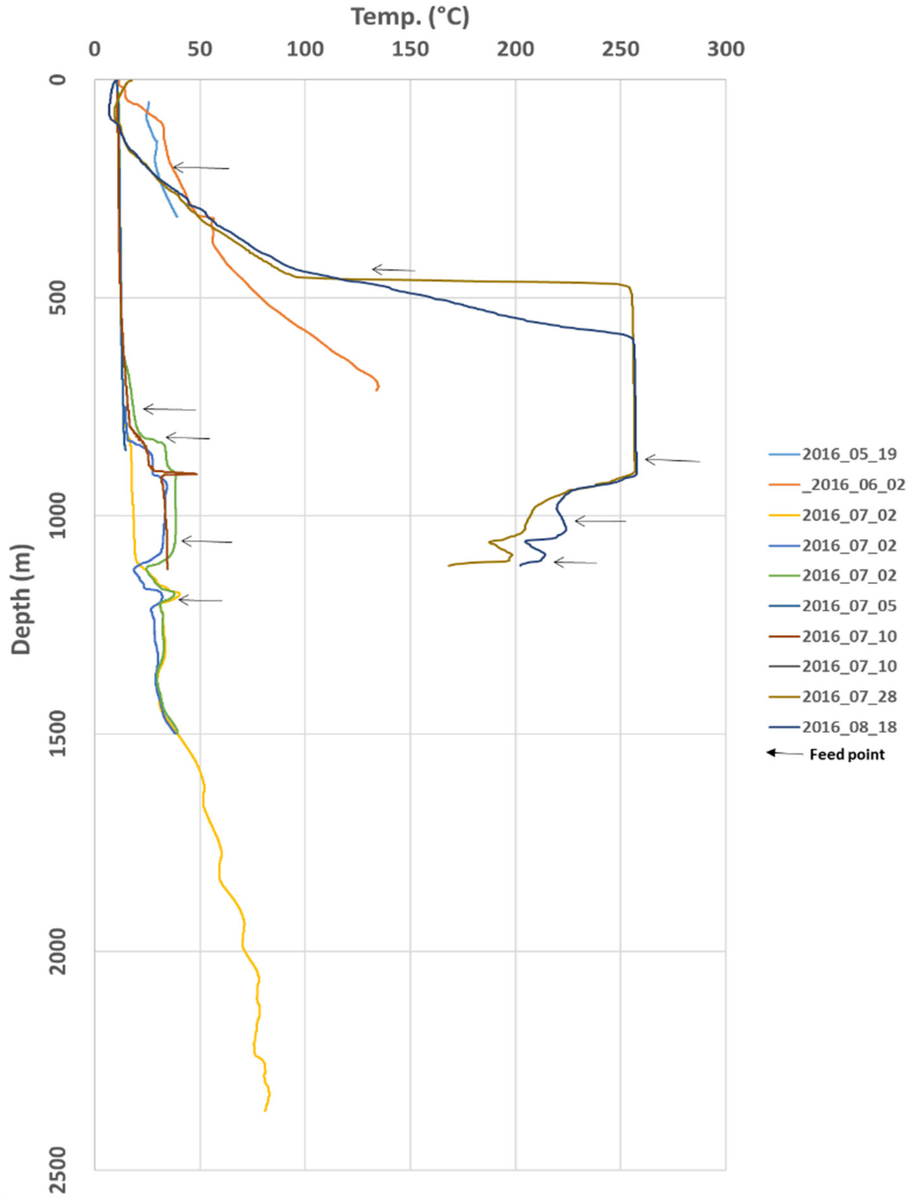


FIGURE 10: Temperature logs and feed-points in well HE-59

5. SURFACE AND SUBSURFACE STRUCTURAL RELATIONSHIPS

The aim of directional drilling of HE-59 in the Hellisheidi geothermal area, was to cross cut the major faults and the mini-graben that is situated within the major graben, locally called Reykjafell mini-graben (Figure 11). The graben is found at the western part of the area consisting of a number of localized faults and 2000, 5000, 8000 and 10,000-year-old fissures (Saemundsson, 1995; Hardarson et al., 2015).

During a surface structural study in the vicinity of well HE-59, a narrow and localized minor volcanic fissure was identified (Figure 11). This fissure lies between the well HE-59 (west) and the Reykjafell mini-graben (east) about 250 m and 760 m away from each respectively (Figure 11). It is believed to be about 8000 year old (Saemundsson, 1995).

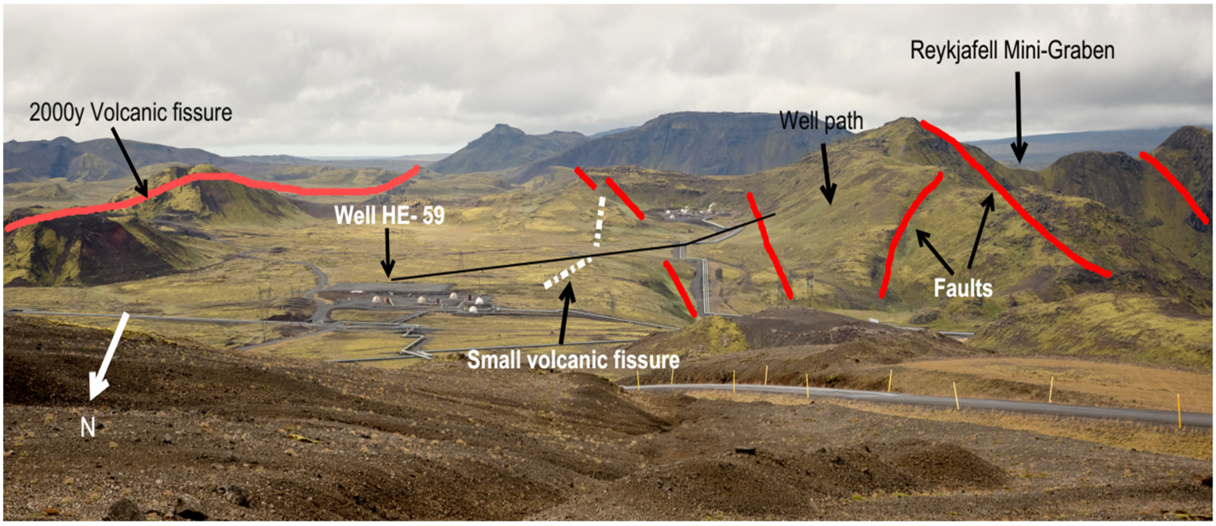


FIGURE 11: Surface structures and volcanic fissures around well HE-59

The gyro survey of well HE-59 shows that at 900 m the well is deviated 255.70° to the SW, having an inclination of 33.7° (Helgadóttir et al., 2016) and the extrapolation of this distance to the surface reaches 220 m, which is related to the small fissure that is about 250 m away from the wellhead. This can be evidenced from the circulation loss at 902 m (Table 1) and from the cutting analysis, which revealed the presence of a fine- to medium-grained crystalline basalt intrusion from 796 to 828 m (Figure 5). On the surface, the volcanic fissure was found as an oxidized scoraceous lava flow, being about 220 m long and 25-35 m wide, running NE-SW following the trend of the main fault system.

6. SUMMARY AND DISCUSSION

Well HE-59 is characterized by postglacial basaltic lava flows on the surface, followed by dominant hyaloclastite formations (basaltic tuff, basaltic breccia and glassy/ pillow lava) and interglacial lavas, based on cutting analyses from the upper 902 m. The deeper formations are intruded by fine- to medium-grained and medium- to coarse-grained basaltic intrusions. The stratigraphic relationship between the intrusions and the host rock, and also within the boundaries of the rock units, reveals permeability, resulting in aquifers/feed-points to be formed. In addition to this, the structural setting of the area, NE-SW running faults and transform faults, are the main cause of permeability. In the upper portion the well, above 900 m, the feed-points are controlled both by structure and stratigraphic boundaries (Figure 5). Alteration of the rocks and secondary mineral precipitation starts below 150 m, followed by precipitation of low-temperature minerals (zeolites). High-temperature minerals include prehnite, chlorite, epidote and wollastonite. Below 150 to 616 m, the zone is identified as a smectite-zeolite zone, as it is dominated by the presence of smectite clay and different types of zeolites with their respective temperatures reaching up to 200°C. The chlorite-epidote zone is the zone which covers 616-716 m and the last alteration mineral zone is the epidote-wollastonite zone (716-902 m), which is marked by high intensity of alteration. The clay analysis shows the absence of chlorite in this well and the presence of smectite zone from 220 to 616 m, and mixed clay below 616 m to 902 m. For this contradiction the reason could be the sampling error, but it requires further analysis.

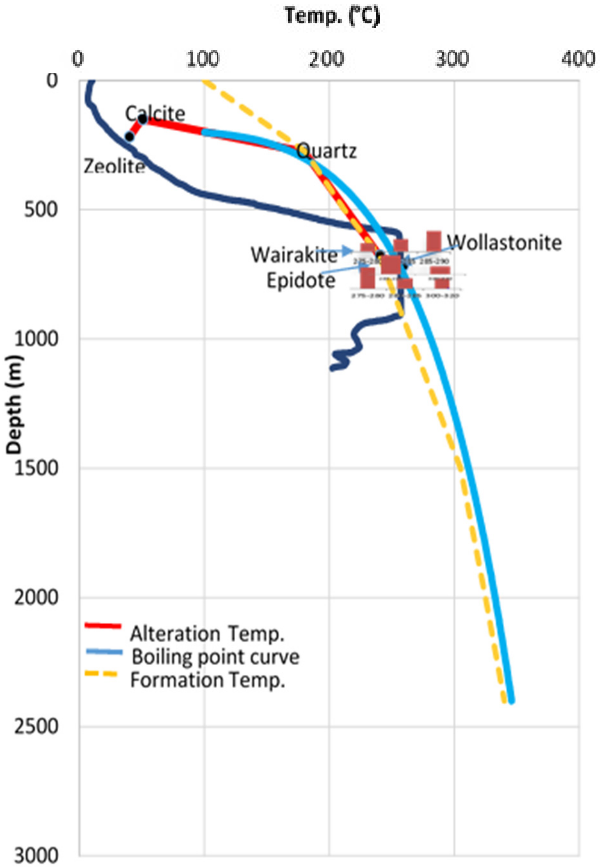


FIGURE 12: comparison between formation temperature, alteration temperature, fluid inclusions and boiling point curve

Understanding the thermal conditions of a well, i.e. whether it is cooling, heating or in equilibrium, is one of the main purposes of studying borehole geology. In this respect, studying the depositional sequence of hydrothermal minerals, alteration temperature, formation temperature and fluid inclusion plays an important role. The depositional sequences taken from 284-800 m of well HE-59 show that the system has experienced fluctuations in the geothermal environment, where apparent over growths of high and low-temperature minerals seems irregular. However, the lower section of the well shows high-temperature minerals growing on low-temperature minerals, implying a heat up of the system, or at least equilibrium conditions. Figure 12 shows the comparison between alteration temperature, formation temperature and fluid inclusion with respect to the boiling point curve. Alteration temperature (a temperature curve found from the first appearance of the alteration minerals and their specific formation temperature) and formation temperature, the present temperature in the well, shows equilibrium condition above 700 m, while below this depth the alteration temperature exceeds formation temperature implying cooling. However, it is very likely that the true formation temperature has not been revealed by the latest temperature logs, as the well had not recovered, implying that there is probably no cooling present.

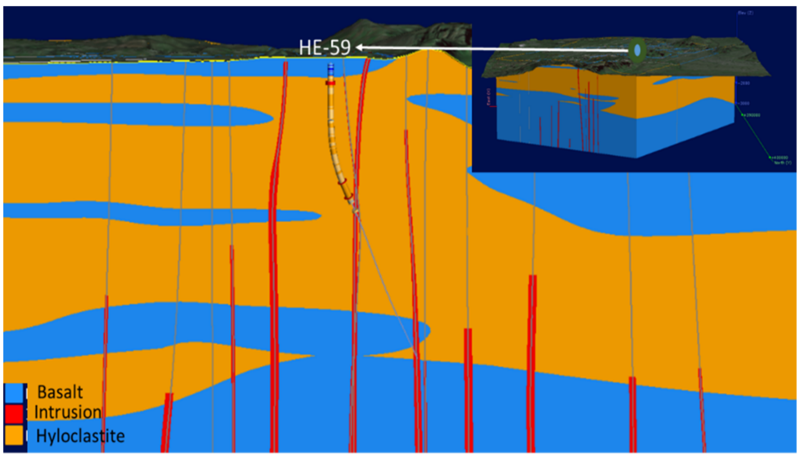


FIGURE 13: 3D model of Hellisheidi area showing subsurface track of well HE-59 related to structures, lithology and intrusions

The application of the fluid inclusions analysis method on samples taken from depths of 700-812 m, consists of homogenization temperatures between 275 and 317°C, and thus shows temperature conditions which exceed both the formation temperature and alteration temperature, as well as the boiling point curve (Figure 12). From this comparison, one could conclude that the system in this well is cooling. Nevertheless, since the well is new and the formation temperature curves are based on temperature logs measured during and soon after drilling, this is probably not reliable. Further temperature measurements after recovery of the well are, therefore, crucial to understand the thermodynamic conditions. On the other hand, the high-temperature records from the alteration temperature and fluid inclusions might represent past condition of the system and the young postglacial volcanic fissure triggered fresh input to the heat source (Figure 13).

7. CONCLUSIONS

- Well HE-59 was directionally drilled on May 17 2016 to a total depth of 2400 m into the Reykjafell mini graben, but total circulation loss was encountered below 902 m.
- The uppermost 902 m of well HE-59 is characterized by dominant hyaloclastite and basaltic lava flows, together with basaltic intrusives. The hyaloclastites consist of basaltic breccia, basaltic tuff and glassy basalt (pillow basalt), while the lava flows are dominantly fine- to medium-grained, crystalline basalt.
- About six intrusions have been identified from the stratigraphy of the well, where three of them are probable intrusions. The intrusions are fine- to medium-grained and medium- to coarse-grained crystalline basalt.
- The alteration zones in this well are challenging, where the hydrothermal mineral distribution and clay analysis shows different outlines of alteration zones. However, the combination of the two approaches infers the presence of four alteration zones. These include an unaltered zone (0-150 m), smectite-zeolite zone (150-616 m), chlorite-epidote zone (616-716 m) and epidote-wollastonite zone (716-902 m).
- Nine aquifers were identified which relate to the geological boundaries and structures. Five of them are major feed points and four are minor feed points.
- The combined result of formation temperature, fluid inclusions study and alteration temperature may indicate some cooling of the well, but the temperature logs after recovery of the well could indeed amend this conclusion.
- The structural relationship, based on gyro surveys, circulation losses and geological findings from well HE-59 shows a clear relationship between surface faults, fissures and the well path.

ACKNOWLEDGEMENTS

I would like to express my gratitude to the United Nations University, Geothermal Training Programme (UNU-GTP) and the government of Iceland for funding this project. I would also like to thank Mr. Lúdvík S. Georgsson, director of United Nations University, Geothermal Training Programme and the deputy director Mr. Ingimar Gudni Haraldsson, for giving me this opportunity. The UNU-GTP staff Ms. Thórhildur Ísberg, Ms. Málfrídur Ómarsdóttir and Mr. Markús A. G. Wilde are also thanked for their support and guidance throughout my stay in the programme.

My special thanks go to my supervisor Dr. Björn S. Hardarson for his excellent guidance, patience and kindness. Dr. Hjalti Franzson and Ms. Helga Helgadóttir are thanked for the guidance during fluid inclusion analysis. Mr. Sigurdur S. Jónsson is acknowledged for his support on the XRD preparation and analysis. I would also like to thank Dr. Tobias Weisenberger for his guidance during petrographic analysis. Bastien Poux is also thanked for his guidance and patience during field study and introducing Leapfrog software. Ms. Saeunn Halldórsdóttir is thanked for her assistance on the study of reservoir temperatures.

Reykjavik Energy is sincerely acknowledged for allowing generous access to data regarding well HE-59 in the Hellisheidi geothermal field. I am grateful to my company, Geological Survey of Ethiopia (GSE), for my participation in the six-month training program.

I would like to thank all the UNU-GTP 2016 fellows for their unforgettable friendship throughout my time. Special thanks for my course mates, Erios Naiga and Andrei Lup for their cooperation and the idea sharing.

Finally, my sincere gratitude goes to my beloved family. I am sincerely thankful to the lord of all who will make everything possible, Jesus Christ.

REFERENCES

Árnason, K., 2007:*TEM survey in Hengill area 2006 and suggested well sites at Eldborg*. ÍSOR – Iceland GeoSurvey, Reykjavík, report 2007/005, 34 pp.

Arnórsson, S., Axelsson, G., and Saemundsson, K., 2008: Geothermal systems in Iceland. *Jökull, 58,* 269-302.

Franzson, H., 1998: Reservoir geology of the Nesjavellir high-temperature field in SW-Iceland. *Proceedings of the 19th Annual PNOC-EDC Geothermal Conference, Manila*, 13-20.

Franzson, H., Árnason, K., Saemundsson, K. and Gunnlaugsson E., 2010a: The Hengill geothermal system, *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia*, 9 pp.

Franzson, H., Gunnlaugsson E., Árnason, K., Saemundsson, K., Steingrímsson, B., and Hardarson, B.S., 2010b: The Hengillgeothermal system, conceptual model and thermal evolution. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia,* 19pp.

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,* 7 pp.

Gasperikova, E., Rosenkjaer, K.G., Árnason, K., Newman, A.G., and Lindsey, I.N., 2015: Resistivity characterization of Krafla and Hengill geothermal fields through 3D MT inversion modelling. *Geothermics 57,* 246-257.

Gunnlaugsson, E. and Gíslason, G., 2005. Preparation for a new power plant in the Hengill geothermal area, Iceland. *Proceedings of the World Geothermal Congress*, *Antalya, Turkey*, 24-29.

Gunnarsdóttir, S.H. and Bastien, P., 2016:*3D modelling of Hellisheidi geothermal field using leapfrog: data, workflow and preliminary models.* ÍSOR – Iceland GeoSurvey, Reykjavík, report 2016/039, 22 pp.

Haraldsdóttir, S., Franzson, H., and Árnason, K., 2015: Comparison of down hole data and surface resistivity data from S-Hengill, a high-temperature geothermal field in SW-Iceland. *Proceedings of World Geothermal Congress 2015 Melbourne, Australia*, 12pp.

Hardarson B.S., Einarsson, G.M., Franzson, H., and Gunnlaugsson, E., 2009: Volcano-tectonicgeothermal interaction at the Hengill triple junction, SW Iceland. *Geothermal Resources 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 palaeo rift in northwest Iceland. *Earth Planet. Sci. Lett., 153,* 181-196.

Hardarson B.S., Kristinsson , S.G., Karlsdóttir, R., and Einarsson, G.M., 2015: Geothermal implications of rift zone mini-grabens. Geological and geophysical structure of the Reykjafell mini-graben, Hengill geothermal field, SW-Iceland. *Proceedings of World Geothermal Congress 2015*, *Melbourne Australia,* 11pp.

Helgadóttir, H.M., Snaebjörnsdóttir, S.,Nielsson S., Gunnarsdóttir, S.H., Matthíasdóttir, T., Hardarson, B.S., Einarsson, G.E., and Franzson, H., 2010: Geology and hydrothermal alteration in the reservoir of the Hellisheidi high temperature system, SW-Iceland. *Proceedings of World Geothermal Congress 2015*, Bali Indonesia, 10 pp.

Helgadóttir, H.M., Sveinborg, H.G., Tryggvason, H.,Sigurgeirsson, M.A., and Weisenberger, T., 2016:*Hellisheidi, well HE-59. Pre-drilling, and 1., 2. and 3. phase: Drilling for surface casing down to 115 m, safety casing to 317 m, production casing down to 800 m depth and perforated liner to 1130 m (depth of well 2381 m*). ÍSOR – Iceland GeoSurvey, Reykjavík, report 2016/46 (in Icelandic) 101 pp.

Hjartarson Á. and Saemundsson K., 2014: *Bedrock map of Iceland, 1:600 000.* ÍSOR – Iceland GeoSurvey, Reykjavík.

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.

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

Saemundsson, K., 1995: Hengill geological map (bedrock) 1:50000. Orkustofnun, Reykjavík, Reykjavík Energy and Iceland Geodetic Survey.

Saemundsson, K., and Gunnlaugsson, E., 2014: *Icelandic rocks and minerals* (2^{nd}ed.). Forlagid ehf., Reykjavík, 223 pp.

Sigmundsson, F., 2006: *Iceland geodynamics crustal deformation and divergent plate tectonics.* Praxis Publishing, Ltd., Chichester, UK, 231 pp.

APPENDIX I: XRD analyses

518 m - No clay

220 m - Smectite

308 m - Smectite

378 m - Smectite

500 m - Smectite

616 m - Smectite

672 m - Mixed layer clay

708 m - Mixed layer clay

744 m - Mixed layer clay

798 m - Mixed layer clay

822 - Mixed layer clay

832 m - Mixed layer clay

898 m - Mixed layer clay

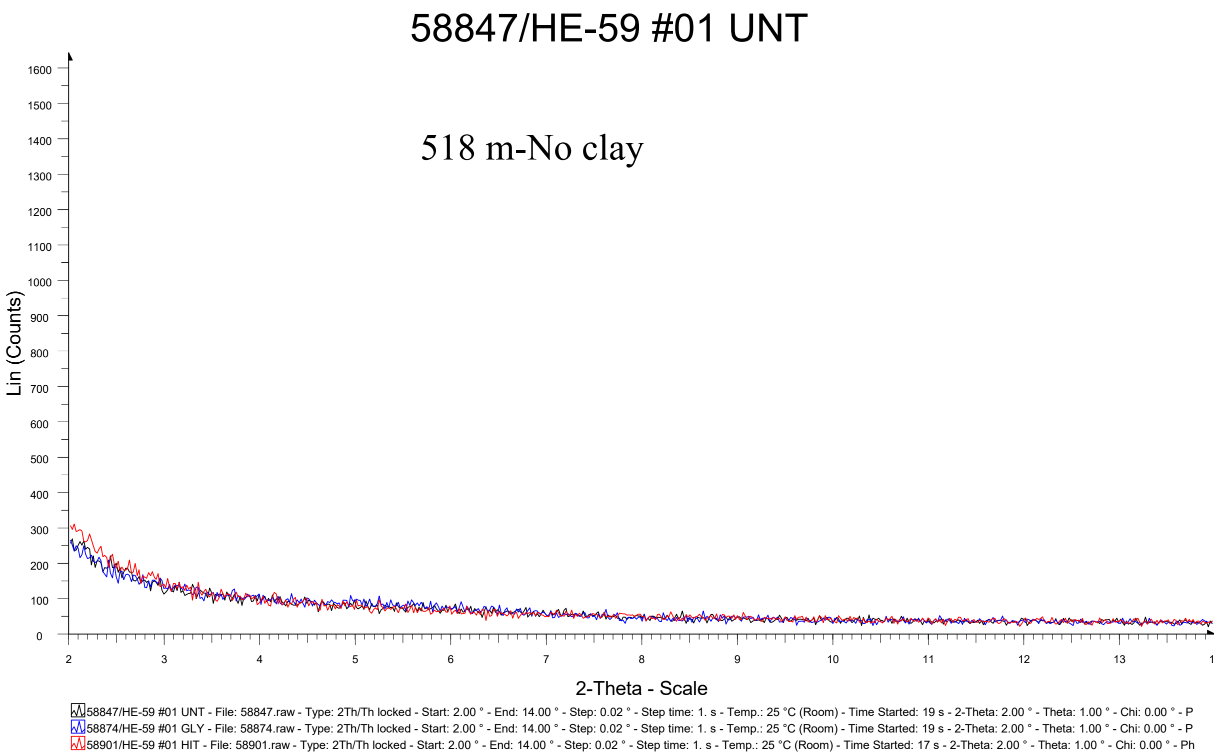


FIGURE 14: XRD-clay analysis of well HE-59