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Geology and Hydrothermal Alteration of Well HE-59, Hellisheidi Geothermal Field, SW- Iceland

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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 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 brine 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. Hengill geothermal area is within the SW rift zone ofIceland and has a size of 110 km2, with a capacity of about 5500 GWh/y for 50 years (Franzson et al.,2010). Surface thermal manifestations 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. Hellisheidi power plant is located in the southern part of Hengill volcanic complex, comprising a totalof 59 deep (1300 - 3300 m) exploration and production wells in the year 2016, which were producing about 303MWe, and 133 MWth (Hardarson et al., 2015).

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 and hydrothermal alteration of well HE-59. This paper is part of the six-month geothermal training program held in Reykjavik, Iceland 2016.

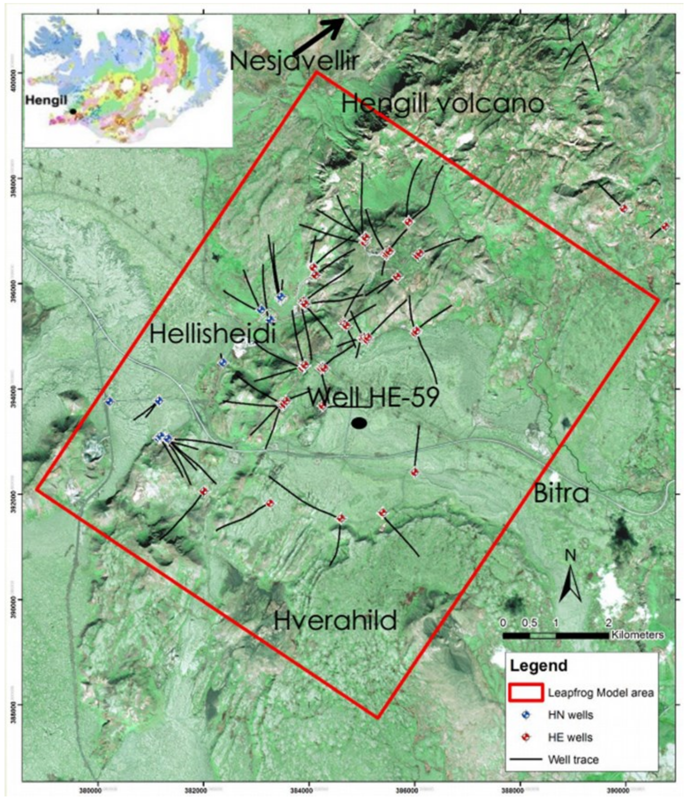


Figure 1: Map of Hengill area showing the four geothermal fields and location of well HE-59 (modified from Gunnarsdóttir, and Bastien, 2016).

2. GEOLOGY AND GEOTHERMAL SYSTEMS OF ICELAND

Geologically, Iceland is young and on the diverging MidAtlantic Ridge, which was created about 60 million years ago along the diverging American and the Eurasian plates, after the north westwardlymigration 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 peninsulain the southwest to the north through the country and divide into two parallel branches in southern Iceland. The rift zones are 40-50 km wide with 5-15 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.

Iceland is mainly made up of basaltic volcanic products of subglacial (hyaloclastites and pillow lavas), interglacial and postglacial (fissure eruptions) volcanic origins. 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 to 16 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 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).

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. 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 on 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 2). 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, haverevealed the existence of a large geothermal high-temperature potential in the Hengill area. Thegeophysical studies 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 km2 thermal anomaly at 850 m depth 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).Geochemical studies from fumarole samples showed that the concentration of gases in the area is inequilibrium with mineral buffers at different temperatures. Gas geothermometry studies also 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. Thedirectional 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 intrusive (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: utilized to analyse cutting samples which 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 the mini-graben, which is found in Mt. Reykjafell (Figure 2). 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 2). 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).

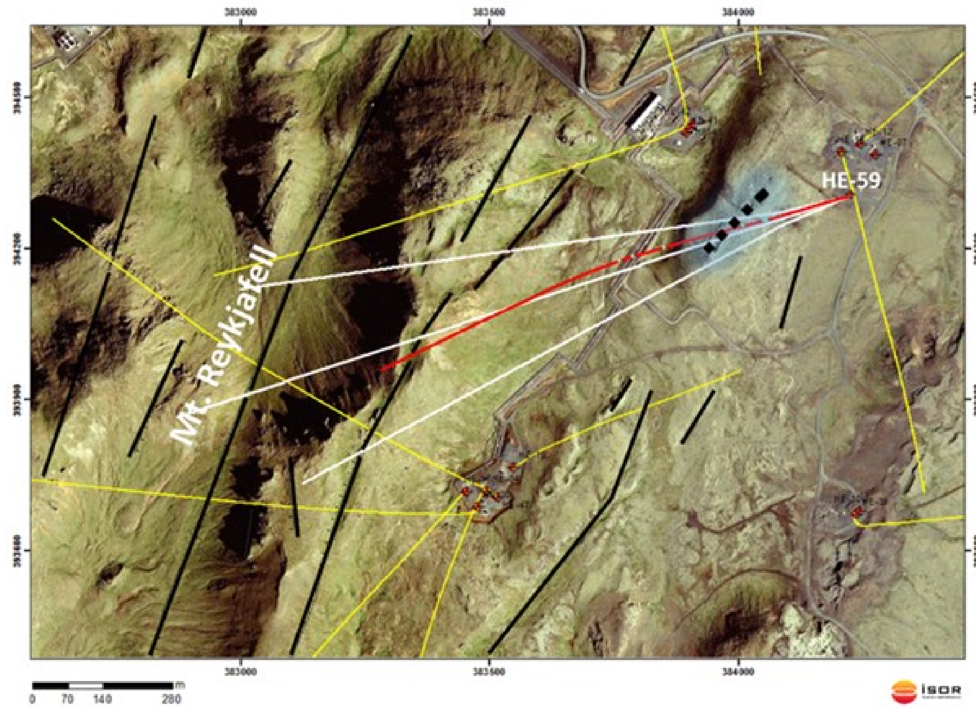


Figure 2: The well path of HE-59 extrapolated to the surface (red line). White lines show the planned track and allowed deviation. Yellow lines are nearby wells, black lines represent faults and fissures and black dotted line is the small fissure west of the wheel pad (Helgadóttir et al., 2016).

Table 1: Drilling information of well HE-59. Depths refer to the platform of Thor, 9 m above ground level.

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

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 major 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 3.

4.4 Intrusions

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 3). An intrusion is fresh or slightly altered compared to the surrounding rocks andsometimes it can be identified by the oxidation and increased precipitation of hydrothermalminerals (e.g. calcite and pyrite) at their margins, as at the depth of 104-124 m. The intrusions in this well are dominantly black and greyish, fine- to medium-grained crystalline basalt, while from the depth 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, where the plagioclase crystals are enclosed by pyroxene (augite) and olivine.

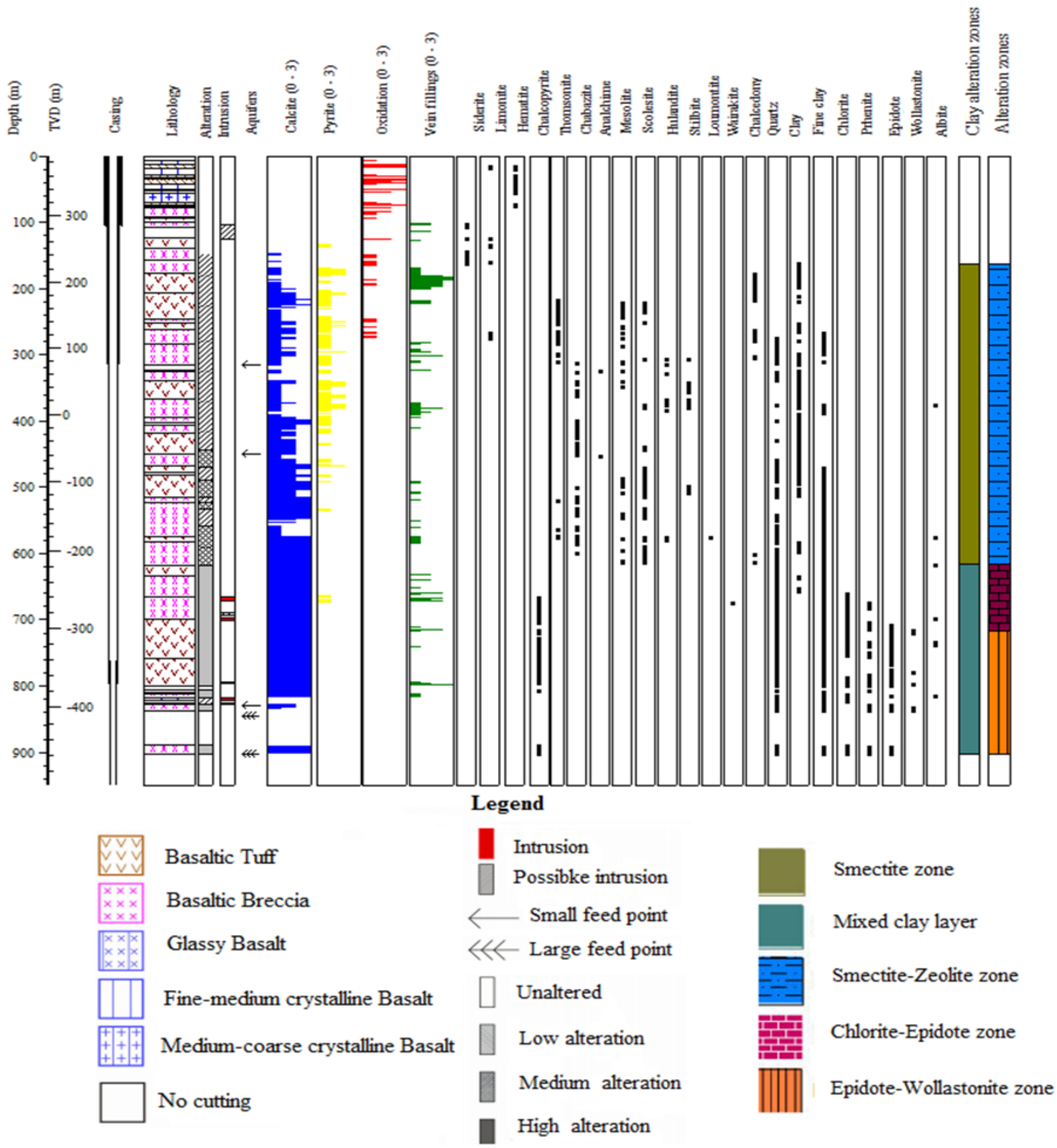


Figure 3: Lithology and hydrothermal minerals distribution in well HE-59. Feed zones are shown as arrows. Alteration zones are indicated far right.

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 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 commonwith its well defined prismatic crystal shape and coarse grains, especially from 586 to 618 and714 to 742 m. Olivine is mostly found as micro crystalline in the lava flows. The replacementmineral for pyroxene and olivine can be pyrite, chlorite, quartz, calcite and actinolite at hightemperatures (> 280°C). Volcanic glasses are susceptible to hydrothermal alteration at low-temperature and are easily changed to clay, chlorite, zeolites and calcite (Figure 4).

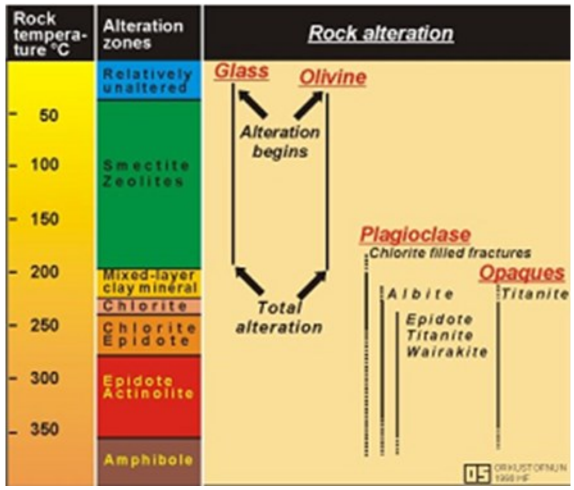


Figure 4: Zones of rock and mineral alteration in Iceland (Franzson, 1998).

The replacement of these minerals, and some opaque minerals, by secondary minerals is dependent ontemperature, composition of fluids, and permeability of the rocks. The hydrothermal mineralsencountered in well HE-59 that have been identified, mainly by using binocular microscope as well asin 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. Sideritemostly occurs at the edges of intrusions, as seen in this well. Siderite is appearing generally rarely butat 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 5).

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.

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.

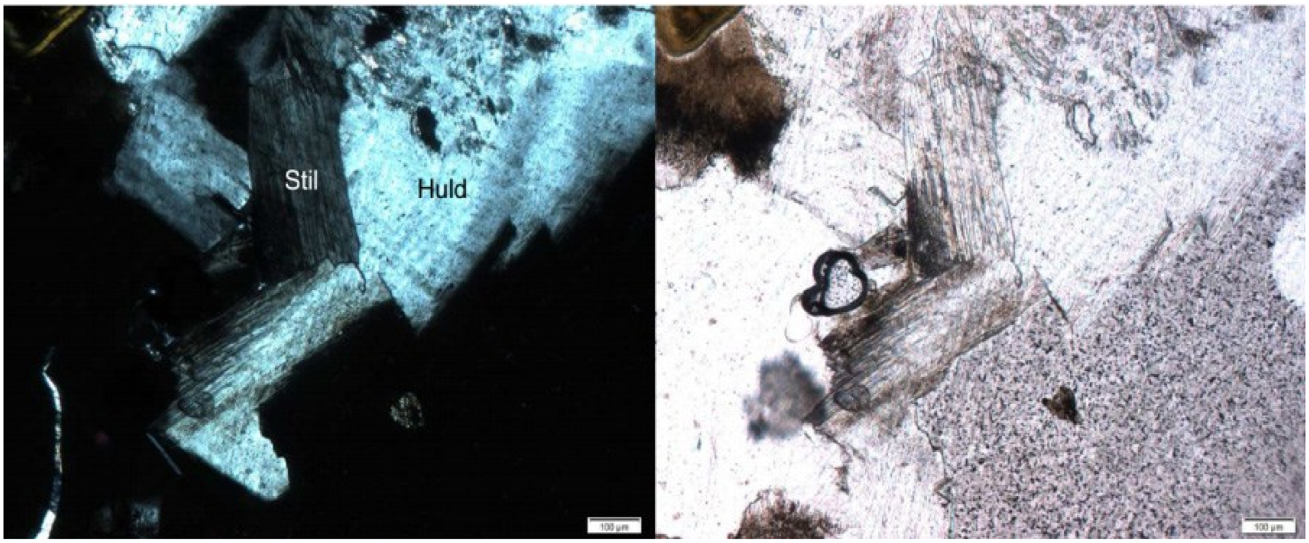


Figure 5: Picture showing a thin section under crossed polarized (to the left) and plane polarized (to the right) view of stilbite and heulandite from 308 m depth. The scale is 100 µm.

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. 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.

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. 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. 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.

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 3) (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 and petrographic analysis, three clay alteration zones were identified. These include unaltered zone (0-220 m), smectite zone (220-616) and 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.

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 3), 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 2 below, the deposition sequences of different minerals at different depths in the well are presented.

The dominant fill encountered is calcite, followed by quartz and clay, hosted mainly by basaltic breccia and basaltic tuff. In the upper portion of the well (Table 2), 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

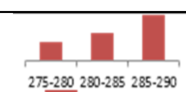
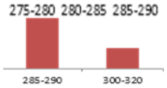
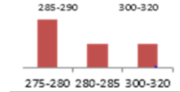
Formation and alteration temperature comparison is one way of estimating the conditions in a geothermal system, whether it is heating up, cooling down or in equilibrium. A fluid inclusion study in the geothermal context is a method of finding temperature from the fluids that had been trapped during crystallization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

For the study of well HE-59, 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 3 shows histograms of fluid inclusions with depth and homogenization temperatures. The comparison between fluid inclusion homogenization temperatures and alteration and formation temperature will be deliberated later in the discussion section.

Table 2: Sequences of hydrothermal minerals in well HE- 59

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

Table 3: 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	

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 6) 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 6). 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.

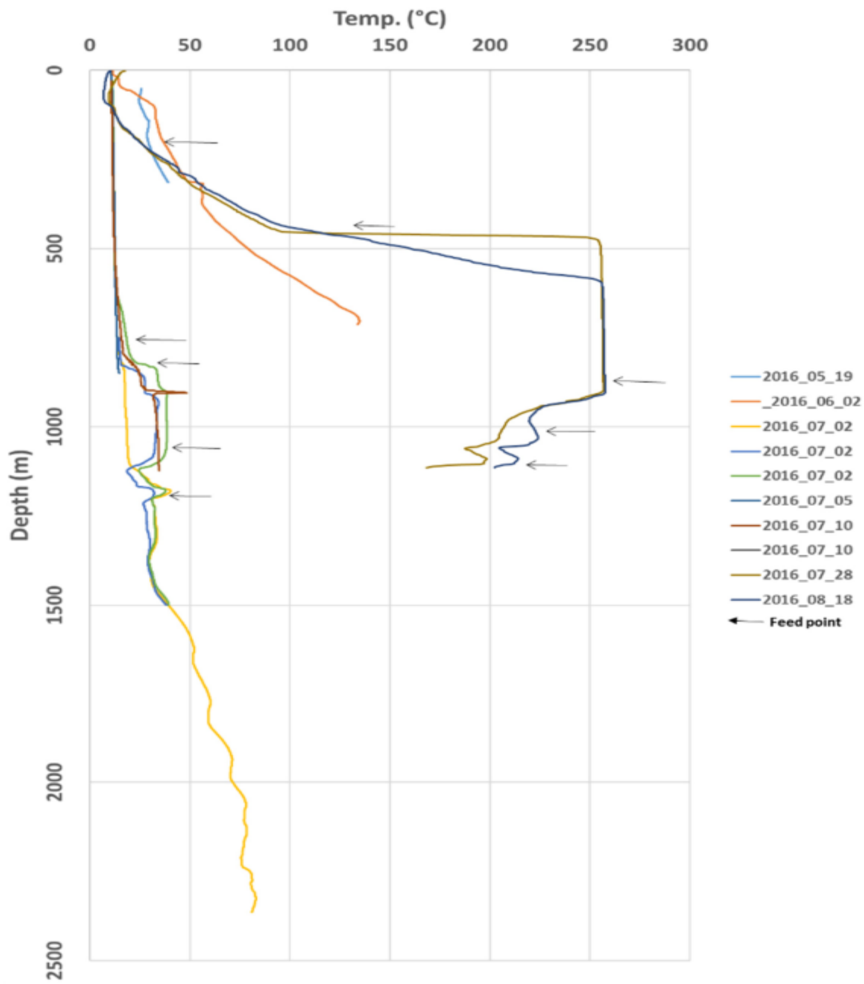


Figure 6: Temperature logs and feed-points

6. DISCUSSION AND CONCLUSION

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 depth, the feed-points are controlled both by structures and stratigraphic boundaries. Alteration of the rocks and secondary mineral precipitation starts below 150 m, followed by precipitation of low-temperature minerals (zeolites). 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.

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 6 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.

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 6). From this comparison, one can 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 be 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 7).

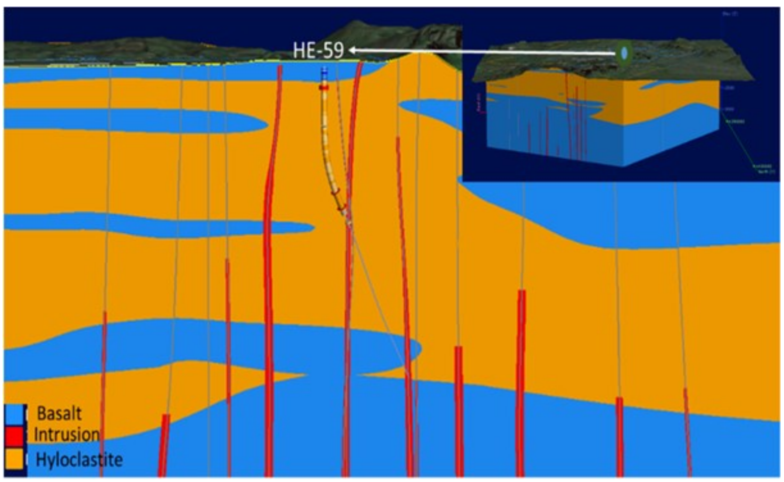


Figure 7: 3D model showing subsurface track of well HE-59 and its relation with the structures, lithology and intrusions.

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