Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Subsurface Geology and Hydrothermal Alteration of Well HE-53, Hellisheidi Geothermal Field, SW - Iceland

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Keywords: Hydrothermal alteration, Well HE-53 in Hverahlid geothermal field, Borehole logging

ABSTRACT

Well HE-53 is one of the exploration wells drilled in Hverahlid geothermal field south of Hellisheidi and Hengill central volcano. The well is drilled directionally to a depth of 2507 m, but the current study focuses on the first 1350 m. Methods used during the study included rock cuttings binocular analysis, thin sections, XRD analysis and fluid inclusions along with the use of drilling data and geophysical wireline logs. The well has two major and five minor feed points. The feed point at 1180 m depth appears to be the largest and most important indicated by alteration minerals as well as temperature profiles. The hydrothermal alteration mineral distribution with an unaltered zone close to the surface, a zeolite smectite zone at greater depth and finally a high temperature actinolite zone at the bottom of the well suggests a continuous temperature rise with depth. Depositional sequences of alteration minerals revealed only prograde alteration. The comparison of alteration minerals with the formation temperature of the well suggests that the well is currently heating. The downhole temperature of the well, as confirmed by temperature of homogenization of fluid inclusions, alteration minerals and direct measurements, reaches about 300°C (at 1350 m).

1. INTRODUCTION

1.1 General background

Well HE-53 is one of the three exploration wells drilled in the Hverahlid area which is located south of Hellisheidi geothermal field. The well was drilled to investigate geothermal resources for the newly proposed Hverahlid power plant (which has since been abandoned) and the drilling was completed in the middle of June 2009. The complete drilled depth reaches 2507 m (measured depth) and is deviated to the south to a maximum inclination of 33°.

1.2 Objective

The purpose of this study is aimed to characterize and determine the subsurface condition of the geothermal system around the well by considering important parameters of the well such as alteration intensity, hydrothermal mineral zonation, and hydrothermal depositional sequence.

1.3 Methodology

Different sampling and analytical methods have been used collaboratively with available data from geophysical loggings in order to identify, interpret and support geological characteristics of the well. The geological data analysis is based on drill cuttings sampled every 2 m during drilling and analysed using binocular microscope. Additionally 22 thin section and 26 XRD samples analysed for further identification of hydrothermal minerals and rocks. Micro fluid inclusion geothermometry, were used to determine temperature during entrapment.

2. OUTLINE OF GEOLOGY

2.1 Geology of Iceland

Iceland is an island located in the northern part of the North Atlantic Ocean. The land covers an area of about 103,125 km^2. The island was formed by intense volcanic activity related to the presence of the Icelandic mantle plume and its interaction with the accretionary spreading centre of the Mid-Atlantic ridge (Arnórsson, 1995). The presence of this relative eastwards moving mantle plume has produced complicated tectonic and volcanic features in Iceland (Zakharova and Spichak, 2012).

Iceland is geologically young, formed within the last 25 million years. The oldest rocks at the surface are 16 million years old tertiary basaltic lavas, located in the northwest and eastern part of the country (Hardarson et al., 1997). Icelandic rocks are mainly composed of basalt which covers about 80-85% of the land (Saemundsson, 1979). The remaining rocks comprise 10% acidic and intermediate rocks and 5-10% sedimentary rocks. The Quaternary rocks are composed of sequences of basalt lavas and hyaloclastites that are exposed in the central, southwest, and northeast sectors. Volcanic episodes during this period were strongly controlled by climatic conditions. The volcanism is divided into ice free volcanism and glacial time volcanism (Vargas, 1992). The ice free volcanism is categorized into inter- and post-glacial volcanism. The rock types erupted during post-glacial climatic conditions are subaerial eruptions forming lava flows, pyroclastic scorias, and welded lavas. The glacial volcanism is divided into sub- and supra-glacial volcanism, and eruptions beneath glaciers are characterised by phreato-magmatic deposits and the formation of hyaloclastites (Vargas, 1992). The high temperature geothermal fields are located on young quaternary central volcanoes. Rocks that are formed within the volcanic zones gradually drift away by accretionary processes which lead to the gradual cooling of central volcanoes and associated geothermal systems as they move further away from the heat source (Zakharova and Spichak, 2012). In time the systems become totally extinct.

2.2 Geological and tectonic settings of the Hengill area

Hengill central volcano hosts one of the most powerful geothermal fields in Iceland. Within Hengill there are traditionally believed to be four separate geothermal fields. Two of them are in production, namely Nesjavellir in the north and Hellisheidi in the southwest (Figure 1), generating 120 MWe and 300 MWt and 303 MWe and 400 MWt, respectively (Hardarson 2014). Wells in Hverahlid field to the south have been connected to the Hellisheidi power plant and the Bitra field to the east is currently under exploration. Additionally, the Hveragerdi geothermal field and volcanic system is not far from the Hengill central volcano and is currently used by the local community for district heating.

The Hengill volcanic system is located about 30 km east from the capital city within a structurally complex triple junction where the NE-SW trending Reykjanes peninsula, the Western Volcanic Zone and the ENE-WSW trending South Icelandic Seismic Zone meet (Hardarson 2014). Structurally, the dominant larger NE-SW faults and fissure swarms in the Hengill area form grabens while the northerly and easterly striking transverse structures play a role in the permeability of this seismically active field (Árnason and Magnússon, 2001).

The bottom of the Hengill volcano is believed to consist of ()lava flows from the nearby Hveragerdi extinct volcano. Dating of thick lava at around 900 m b.s.l suggests the age of the Hengill volcano could be around 0.4 m.y. (Franzson et al., 2005, Helgadóttir et al, 2010). Volcanism was intensive during the glacial period, particularly in central Hengill and Hellisheidi area. For this reason, thick hyaloclastite formations accumulated, intercalated by interglacial lava deposits (Franzson et al., 2005). The last eruptions took place after the glaciation period. Three different fissure eruptions have been identified in the Hengill area 9, 5, and 2 thousand years old (Saemundsson, 1995a; Franzson et al., 2005). The three eruptions are directly associated with 3-5 km wide and 40 km long vertical faults and fissure swarms and the last two are believed to act as major outflow zones for both Hellisheidi and Nesjavellir fields.

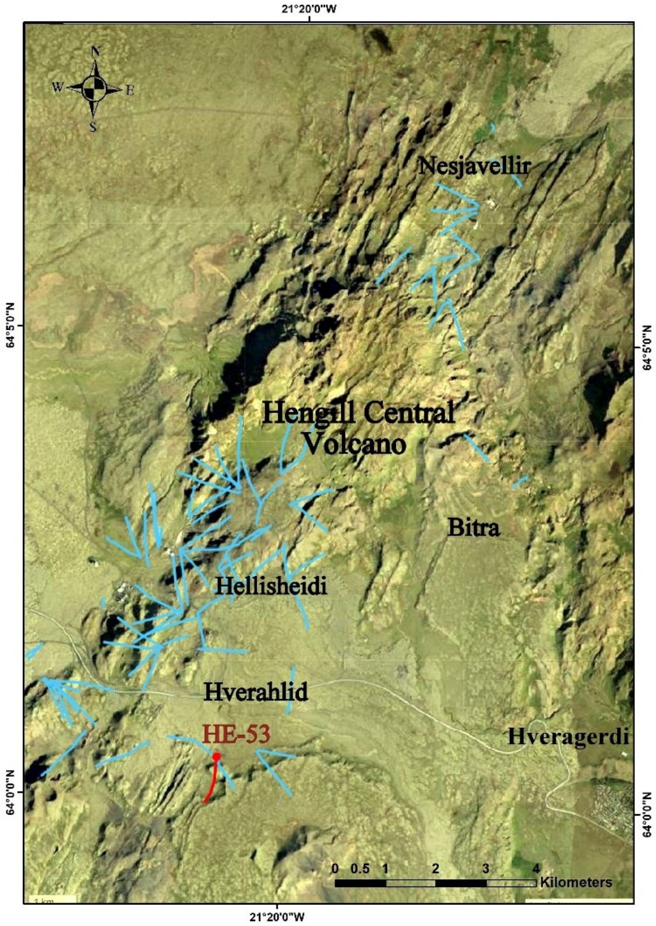

FIGURE 1: Location of geothermal fields around the Hengill central volcano. The blue lines show the well paths of directionally drilled wells, the red line shows well HE-53

2.3 Geology of well HE-53

Subsurface geology and stratigraphy of the well broadly be categorised into basaltic lava (fine to medium grained basalt), hyaloclastite formation (basaltic tuff and breccia), pillow lava formation (partially crystalline and crystalline rocks) and intrusive rock (medium to coarse grained, fresh crystalline basalt). The intrusive rocks are commonly found below 1000 m depth intruding the crystalline basalt series. They were identified mainly by their coarse grained texture and also by comparing the alteration intensity which is usually lower than in the host rock. One of the petrographical features that is most often associated with the intrusive rocks in the well

3. HYDROTHERMAL ALTERATION

Hydrothermal alteration is a process of change in the primary rock mineral assemblage as a result of water rock interaction which is controlled by the chemical composition of water and rock, temperature, pressure, time of exposure and permeability of the rock. The rock experiences a change in physical and chemical properties due to either depletion of components by leaching or deposition of hydrothermal minerals due to precipitation. In general, alteration intensity in the well gradually increased to depth, the first 400 m appear fresh.

3.1 Primary rock forming minerals and their alteration

Minerals and volcanic glass are the primary constituents of volcanic rocks. They are primarily formed from magmatic melt at specific pressure and temperature conditions. When crystallized rocks are subjected to a new environment, they may become unstable. Therefore, understanding the rock's response to a hydrothermal environment will help us learn about the geological conditions of the geothermal system. The rock forming minerals and their alteration are discussed below. Based on the crystallinity of the minerals, rock formations in the well can be categorized into coarse to medium grained crystalline basalt, fine grained crystalline basalt, partially crystallized basalt (glassy basalt) and glass.

The medium and coarse grained basalt is composed of olivine, pyroxene, plagioclase and opaque minerals (magnetite and ilmenite). It is mostly found at the lower parts of the well in possible intrusions. They remain unaltered except the most unstable ones (or older intrusions). The fine grained basalt occurs throughout the well in the post glacial upper lava section and as interbedding within hyaloclastite formations. Most of the fine grained rocks are composed of abundant plagioclase, some olivine and pyroxenes as well as minor amounts of opaque minerals. Some of the fine grained basalt shows two phases of crystal growth, coarser phenocrysts and finer ground mass. Alteration is typically higher in the ground mass. Partially crystalline glass and highly fragmented glass are the main components of hyaloclastite rocks (tuff, breccia and pillow lava (glassy basalt) and glassy lava layers. They are easily altered even in lower temperatures although commonly there is fresh glass in the upper part of the well.

Volcanic glass is compositionally the same as crystalline rock but due to sudden cooling of the magma at the surface there is no time to form and grow crystals. Glass in this well often contains micro phenocrysts of plagioclase in both the glassy basalt and the volcanic tuff. The glass has a black shiny appearance. Under the petrographic microscope the glass appears yellowish brown or light brown and translucent in plane polarized light (PPL) while it is black (isotropic) in cross polarized light (XPL). Glass is the most unstable constituent of primary rock and alters quickly to palagonite, clay (smectite), zeolites, quartz and calcite.

Olivine is the first mineral to crystallize during crystallization of basalt. Unaltered olivine can easily be *Olivine* distinguished both under the petrographic and the binocular microscope by their second order interference colour in XPL and its lack of cleavage. Olivine is a commonly found mineral in the well although it is highly susceptible to alteration. The olivine was fresh down to 350 m but at around 400 m the grain boundaries were starting to alter. At around 980 m the olivine was totally altered to mixed layer clay (MLC) and chlorite.

Plagioclase is the most abundant primary mineral in the well occurring in all partially crystalline and crystalline rocks. The mineral is moderately alteration resistant. Plagioclase started to alter at around 650 m depth. Alteration then continually increased to the end of the logging depth (1350 m). Alteration started in the grain boundaries and fractures in the crystals forming fine grained clay (smectite). Dissolution from a large plagioclase crystal was seen at 700 m but most of the crystals were altered to calcite, MLC and quartz. Plagioclase is easily identified in thin sections and characterized by its multiple albite twinning.

Pyroxene is usually the next mineral to form in basalt, following plagioclase. Contrary to olivine it is highly resistant to hydrothermal alteration. Abundant pyroxene was found in the medium to coarse grained crystalline basalt, all of them were clinopyroxene (augite). Pyroxene can be identified by its dominating lower second order birefringence (resembling olivine colours) and nearly 90° cleavage. The clinopyroxene shows extinction around 20° to 30°. Pyroxene crystals in the well started to show indications of alteration on grain boundaries at around 1050 m. In thin sections from 1184 m and 1250 m actinolite (uralite) is suspected on the crystal margins where alteration was higher.

Opaque minerals (iron oxides) appear black in both XPL and PPL. When using reflective light in this study (without oils) the opaque minerals could be distinguished from pyrite which has a golden colour instead of the grayish one of most of the opaque minerals in this well. In the cuttings analysis they show magnetic properties (magnetite specifically, ilmenite is only weakly magnetic) and mostly occur within the crystalline basalt. Opaque minerals are the most alteration resistant, they only show an indication of alteration at around 1250 m.

3.2 Distribution and description of hydrothermal minerals

Hydrothermal alteration minerals in the well have been identified using the methods discussed before. The list of secondary minerals includes calcite, siderite, zeolites, smectite, chlorite, mixed layer clay (MLC), pyrite, prehnite, epidote, quartz, wollastonite and wairakite. Distribution and occurrence of hydrothermal minerals vary greatly with depth while alteration intensity is noticeably higher in fractured zones with multiple veins. Alteration also appears to be higher at lithological contacts and originally permeable rocks containing abundant glass, such as tuff (hyaloclastite formations). The distribution of alteration minerals in well HE-53 is shown in Figure 2.

3.3 Alteration mineral zonation

Alteration mineral zonation is the representation of hydrothermal facies based on dominant index hydrothermal minerals. This dominant hydrothermal mineral should be a temperature dependent hydrothermal mineral in order to mark out a specific range of temperatures. This provides us with information about the temperature a reservoir has reached in the past. For that purpose, there is a list of alteration minerals most often used along with clay minerals. Clays are very important to classify alteration zones because, according to Kristmannsdóttir (1979), they respond quickly to temperature change. It is possible to accurately identify the clay type using XRD analysis.

Based on the above reasoning and the first appearance of selected temperature dependent alteration minerals five alteration zones have been classified in well HE-53 down to 1350 m.

I *Unaltered zone (0-416 m):* The zone is mainly comprised of a few low temperature minerals and indications of cold temperature subsurface processes. These indications are the presence of siderite, oxidation of basaltic lava, sparsely distributed vague palagonitization and very rare calcite precipitation. The remaining rock has not been altered. The temperature for this section is estimated to be below 40°C.

II *Zeolite smectite zone (416-780 m):* The zone is clearly marked by the existence of zeolites and smectite first appearing together at the same depth. There are no other alteration minerals within the range except calcite and a few indications of chalcedony at around 660 m. The intensity of alteration is variable across the depth depending on the primary rock properties and fracture conditions. The estimated temperature ranges from 40°C to about 200°C at the bottom of the section.

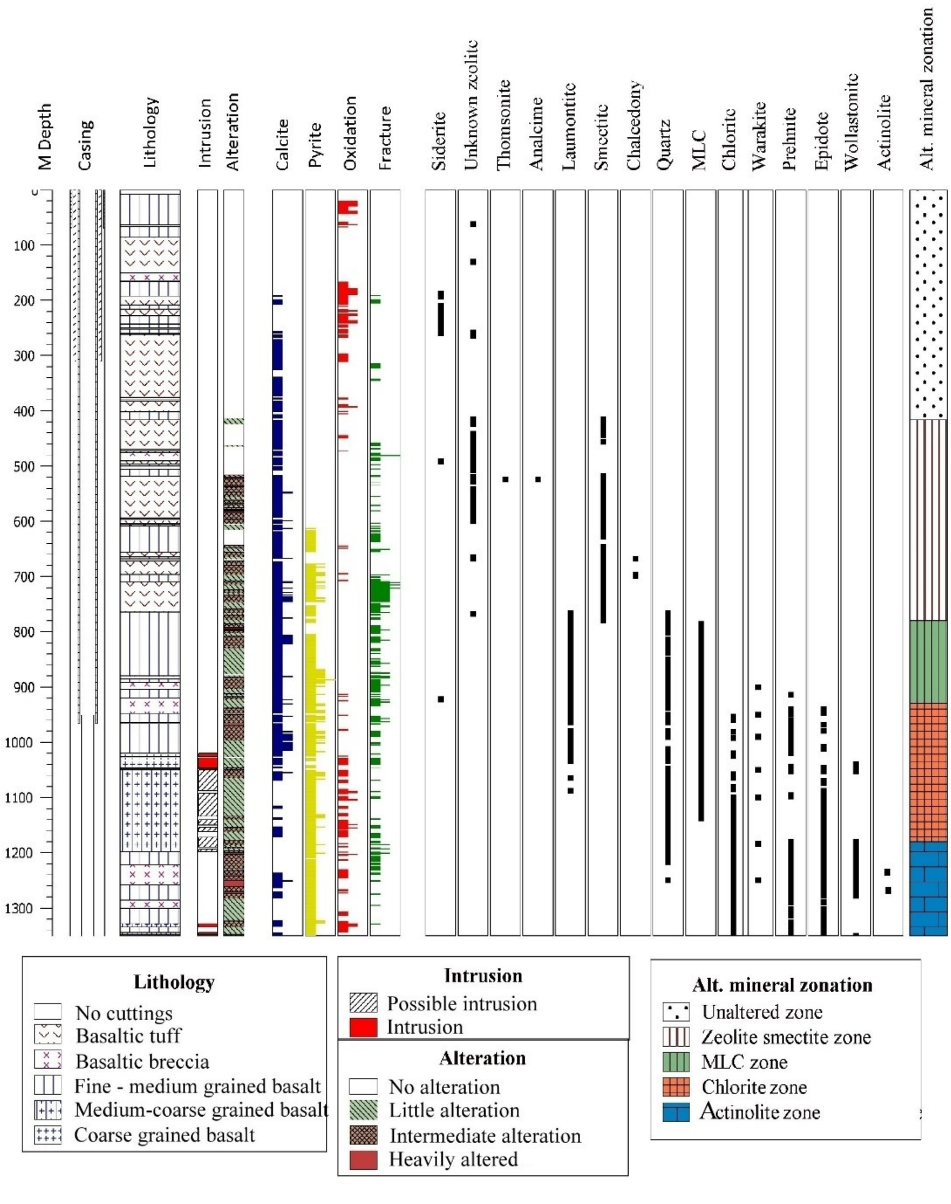

FIGURE 2: Distribution of hydrothermal minerals and alteration mineral zonation in well HE-53

III *Mixed layer clay zone (780-930 m):* The upper boundary of the MLC zone lies at 780 m depth based on the first appearance of quartz at 766 m and the results of the XRD analysis. The result of the XRD analysis shows the presence of smectite at 750 m and MLC at 800 m. The combination of these information indicates the upper boundary of the zone. The temperature of the MLC zone ranges from 200°C to 230-240°C.

IV Chlorite zone (930-1180 m): The temperature of the chlorite zone in well HE-53 is expected to be 230-240°C to 280°C. A change in clay type is seen between two consecutive XRD samples at 920 m and 952 m depth. The sample from 920 m shows MLC whereas at 952 m chlorite was a dominant phase in the XRD analysis. Prehnite is also a good indicator of this zone as it forms at a minimum temperature of 240°C. It was first seen at 900 m, then becomes abundant at 940 m. Within this zone chlorite, prehnite, pyrite, quartz, calcite, wairakite and epidote were present although epidote was not clearly identified as a well crystallized form until below 1170 m. Laumontite was found within the range but was not expected in this zone. The upper limit for laumontite is below 230°C and it was not possible to find an explanation for the discrepancy in this study. However, it is possible that minerals with lower temperature indications may be locked within rock formations that have become impermeable after the alteration mineral formed.

V Amphibole zone (1180-1350 m): Temperatures higher than 280°C are expected based on the available evidence which is the presence of uralite alteration of pyroxene at 1182 m seen in thin sections and amphibole at around 1220 m found in XRD analysis. Fluid inclusions from 1280 m depth indicate a temperature of homogenization of above 295-300°C and calcite seems to disappear in this zone below approximately 1300 m which also indicates that the temperature is at least close to 300°C.

3.4 Depositional sequence of hydrothermal minerals

Geothermal processes are dynamic geological processes that can vary greatly over a short period of time compared to other geological processes. Some properties like permeability of the system can quickly change. This change may have a considerable effect on the productivity of the system. Understanding of change in key parameters of the system is the main task for the borehole geologist and the depositional sequence study of hydrothermal minerals is an essential part of the study.

Subsurface change in the system is expressed through hydrothermal alteration minerals. Understanding of the occurrence and genesis of each mineral provides us with information about the environmental conditions in which they are formed. By applying this knowledge and by defining the sequence of alteration we can reconstruct the thermal history of the well.

Hydrothermal alteration minerals most commonly precipitate in fractures and in void spaces in the rock mass, such as vesicles, and the sequence is found imprinted as a vein or vesicle fill. The sequence is formed by the consecutive deposition of a younger phase on an older phase, from the outer layer (the vesicle/vein wall) to the inner core. Each layer consists of similar or different alteration minerals from the same or different facies. Depositional sequences were reconstructed from petrography and cuttings analysis and are presented in Table 1.

TABLE 1: Sequences of hydrothermal minerals in well HE-53

Sequences defined from binocular analysis		
Depth (m)	Order from older > younger	Host rock
628	Pyrite > Smectite	Fine to medium grained basalt
766	Smectite > Quartz	Fine to medium grained basalt
814	Laumontite > Quartz	Fine to medium grained basalt
946	Laumontite > Prehnite	Basaltic breccia
1250	Calcite > Prehnite	Basaltic breccia?
Sequences defined from thin section analysis		
650	Smectite > Calcite > Zeolite	Fine to medium grained basalt
786	Smectite > Calcite > Quartz	Fine to medium grained basalt
900	Chalcedony? > Quartz	Basaltic breccia
950	Calcite > Quartz > Wairakite	Fine to medium grained basalt
990	MLC > Prehnite, Sample 1 Calcite > Wairakite, Sample 2	Fine to medium grained basalt
1050	MLC > Chlorite, Calcite & Quartz	Medium to coarse grained basalt
1184	MLC > Quartz	Medium to coarse grained basalt

The hydrothermal alteration sequence in well HE-53 shows in general the prograde alteration of the system. Some sequences, however, do not show temperature change in the system, especially at the top 600 m of the well.

4. MICRO FLUID INCLUSION GEOTHERMOMETRY

Fluid inclusion samples were analysed to define the temperature of homogenization (Th) in order to characterize and estimate the temperature of secondary mineral formation in the reservoir. For this analysis two quartz crystals were selected from separate depths of 1180 and 1280 m, below the cap rock close to feed zones. The Th measured from the fluid inclusions revealed a close temperature range, but the number of inclusions analysed in the sample from 1180 m depth was not sufficient to provide a reliable result, more than half of the fourteen fluid inclusions measured at 1280 m settled at a temperature between 300-305°C and the remaining were closely distributed. However, the homogenization temperature at 1280 m seems a bit lower than at 1180 m. This needs additional data to confirm since there are only three measurements available from 1180 m.

5. AQUIFER AND FEED ZONES

In order to determine casing depth and to identify permeable structures and drilling targets for future wells it is very important to locate feed points and feed zones in the well. A combination of alteration mineralogy and alteration intensity, loss of circulation data from drilling reports, temperature measurements and fracture intensity was used to locate feed points. As shown in Figure 3, eight major and minor feed points above and below the production zone were identified. The feed points above the production zone are permeable zones with lower temperatures above the clay cap and were completely sealed by non-perforated casing.

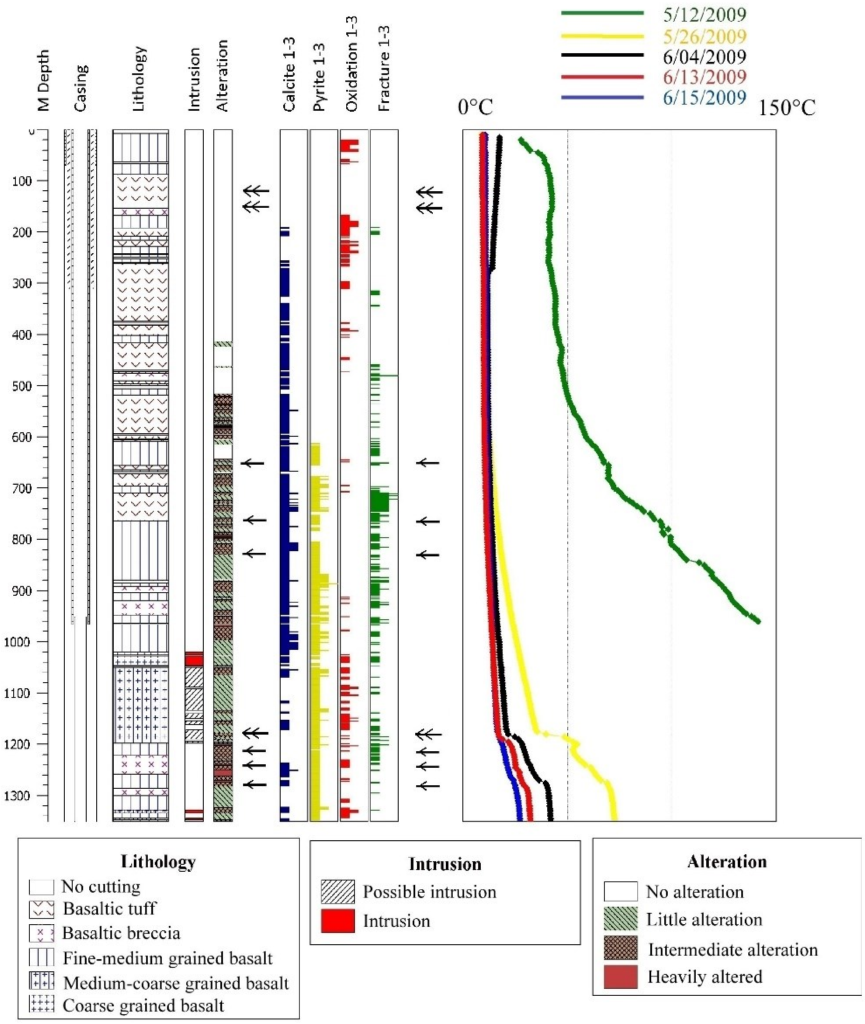

FIGURE 3: Feed points (black arrows) in relation to temperature profiles during injection, lithology, intrusive rocks and alteration intensity

Feed point 1: This is a highly permeable zone found between 136 and 166 m. Total circulation losses frequently occurred during drilling. There is neither indication of the feed zone in the alteration mineralogy nor the temperature logs in Figure 3 (the zone was sealed off by casings during logging). The formation in the loss zone consists of glassy basalt.

Feed point 2 and 3: Feed point 2 is a small feed point within crystalline basalt situated at 650 m depth. Alteration of the rock was locally higher and abundant calcite veins fillings imply fracture permeability. The temperature log (green line in Figure 3) also shows a slight change in temperature. Feed point 3 is located at 760 m. Similarly, a slight temperature change was seen in the same temperature log and higher temperature minerals quartz and laumontite were first observed at this depth. It is observed where a change from basaltic tuff to crystalline basalt occurs.

Feed point 4: The feed point is identified from a considerable change in the same temperature log. Hydrothermal alteration and fracture distribution were not anomalously high. The feed point is within a crystalline basalt unit.

Feed point 5: This is the major and most important feed zone in the well down to 1350 m. It is located at 1180 m depth in the production zone. The feed zone is evident from a prominent temperature change in all of the deeper temperature logs in Figure 3 and high temperature minerals such as epidote, prehnite and wollastonite in a localized zone.

Feed points 6, 7 and 8: These small feed points are located close to each other at 1220, 1240 and 1280 m. There was no loss of circulation below the production casing shoe to the end of the relevant depth except for 2 l/s loss at 1300 m. The loss might be related to those closely spaced feed points. The feed points were identified from small changes in the slopes of the temperature logs.

6. DISCUSSION

The stratigraphy of well HE-53 in the Hverahlid area is predominantly composed of hyaloclastite formations and less prominent basaltic lavas. They can be summarized as follows: the top 100 m are comprised of aphanitic and porphyritic lava overlain by post glacial basaltic lava deposits. Below that is a thick hyaloclastite formation which consists of glassy basalt (pillow basalt), basaltic tuff, breccia and minor fine grained basalt. Underlying this formation, there is fine and medium to coarse grained crystalline basalt interbedded with basalt breccia down to the bottom of the lithology log. This unit consist of inter glacial lavas and intrusions. The well can be classified into an upper and lower zone based on the general characteristics and origin of its permeability. Permeability in the upper part is caused by the combination of primary rock permeability and lithological contacts permeability as indicated by alteration and loss of circulation. As shown in Figure 4, pores in primary rock as well as contacts and fractures can be easily filled with precipitations of hydrothermal minerals in a relatively short period of time, especially when the rock contains abundance of glass. Feed zones in the lower part of the well show that permeability might in part be associated with intrusions and increased fracture intensity (based on vein fillings). Acoustic borehole scanners (e.g. televiewer) could be useful to identify intrusions, fracture distribution and aquifer properties.

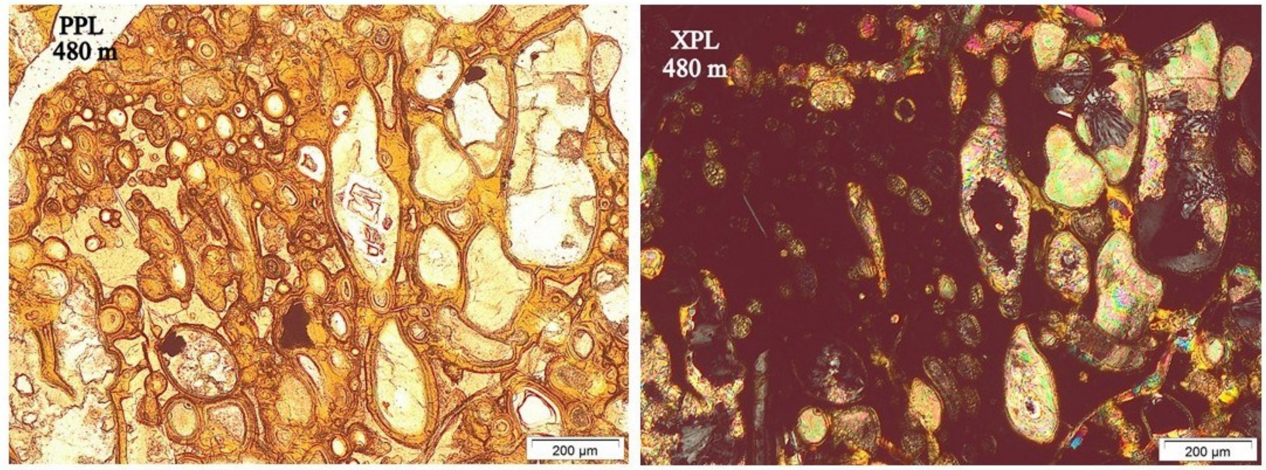

FIGURE 4: Vesicles of tuff glass are completely filled with precipitations of calcite and zeolites. The glass is still quite fresh

The distribution of hydrothermal alteration minerals in the well shows that the temperature increases with depth. The minimum formation temperature of alteration minerals shows that the well was quite cold down to roughly 400 m. Below temperatures become much higher within a short depth range (Figure 5). Based on the first occurrence of key temperature index minerals, five alteration zones could be identified in the upper 1350 m of the well. The well reached the highest alteration zone at around 1200 m depth. The distribution of hydrothermal zonation in the well is partly controlled by the feed zones and the presence of intrusions.

Paragenesis of the alteration minerals shows that the hydrothermal system has evolved from lower temperature to higher temperature conditions. Show case for this transition is seen in the well at 814 m depth where laumontite is followed by quartz and at 950 m depth wairakite is precipitated after calcite and quartz. In addition to the sequences, a comparison between the alteration temperature and the temperature of homogenization with the current formation temperature reveals that alteration temperature is lower than the formation temperature. This implies that the well is currently heating while the Th of fluid inclusions at 1280 m shows that the well is at equilibrium conditions.

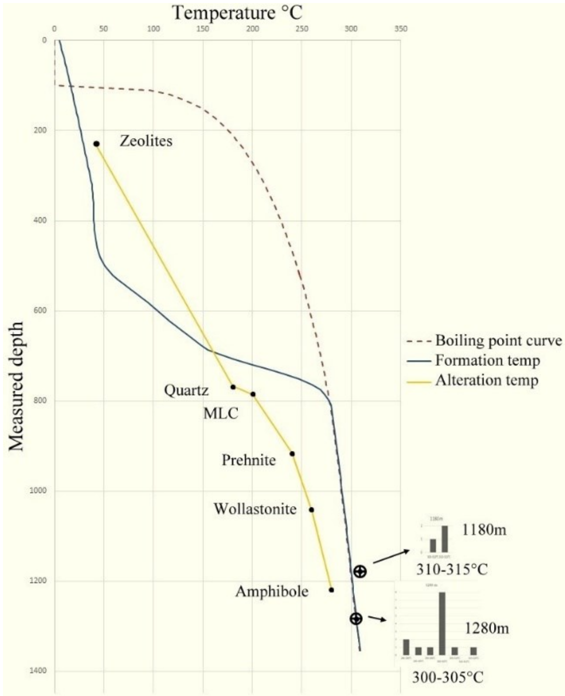

FIGURE 5: Comparison of formation temperature, fluid inclusion homogenization temperature and alteration temperature

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7. CONCLUSION

From this study the following can be concluded:

- The well is comprised of alternating basaltic lava sequences and hyaloclastite formations. The first is a postglacial basaltic lava sequence in the upper 100 m followed by a thick hyaloclastite formation containing basaltic tuff, glassy basalt, and basaltic breccia down to approximately 760 m. Variably thick basaltic lavas occur as well as possible intrusions at 760-1350 m.

- Comparing the boiling point curve to the formation temperature indicates that there is a two phase fluid in the well below 800 m.

- The casing depth of the next well should consider a feed zone situated at around 840 m.

- The comparison between the current formation temperature and alteration mineralogy shows that the well is heating below the smectite zone. The alteration temperature is higher than the formation temperature above 650 m which shows that the depth range above the reservoir is cooling.

- From eight identified feed points down to 1350 m depth, the bottom five are located within the high temperature reservoir. Out of those five the feed point at 1180 m appears to be the largest, based on the temperature profile and alteration minerals.

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