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SUBSURFACE GEOLOGY AND HYDROTHERMAL ALTERATION OF WELL HE-53, HELLISHEIDI GEOTHERMAL FIELD, SW–ICELAND

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ABSTRACT

Well HE-53 is one of the exploration wells drilled in Hverahlíd 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 well is comprised of alternating basaltic lava sequences and hyaloclastite formations. The first one 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 in the lower part of the well. 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 wells drilled in the Hverahlíd area which is located south of Hellisheidi geothermal field. The well was drilled to investigate geothermal resources for the newly proposed Hverahlíd power plant (plans which have since been abandoned) and the drilling was completed in the middle of June 2009.

This subsurface study of well HE-53 was conducted by applying comprehensive skills and knowledge acquired during the UNU geothermal six-month training. All obtainable and available data were acquired and used to characterize and understand the geological conditions in the well. Important information from well logging during drilling and the drilling report were also evaluated for this work.

1.2 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) (Figure 1). 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). High temperature geothermal activity in Iceland is confined to the volcanic and tectonic rift zones. As indicated in Figure 1, 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

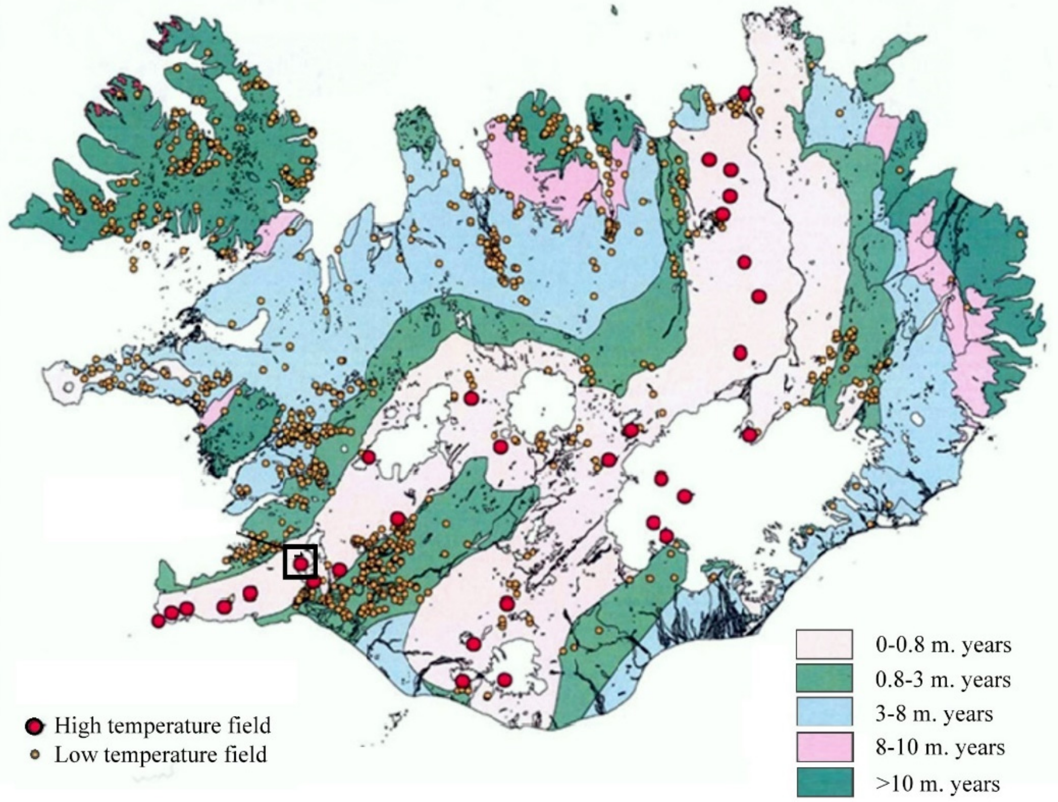

FIGURE 1: Simplified geological map of Iceland and distribution of low and high temperature geothermal fields, modified after Hersir et al. (2009)

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.

1.3 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 2), generating 120 MWe and 300 MWt and 303 MWe and 400 MWt, respectively (Hardarson 2014). Wells in Hverahlíd 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).

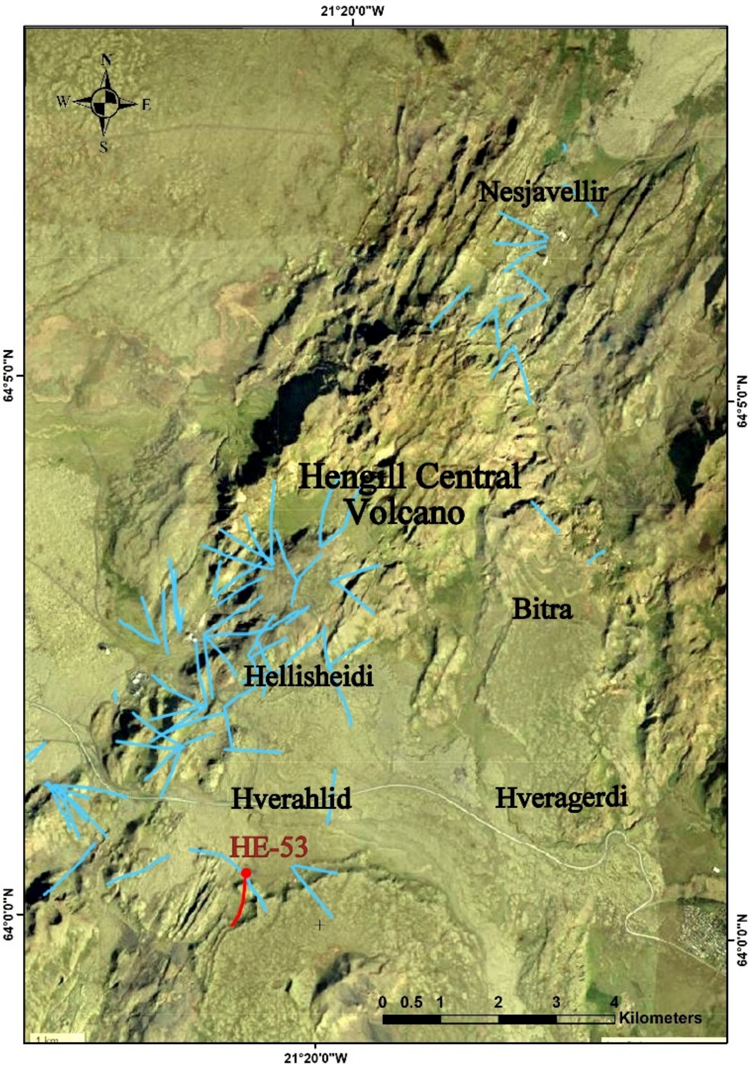

FIGURE 2: Location of geothermal fields around the Hengill central volcano. The blue lines show the well paths of directionally drilled wells, the red line shows well HE-53

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.

1.4 Previous studies

Multiple intensive studies have been conducted since the mid-1960s. These studies mainly focused on geothermal resource investigation and management in Hengill and the surrounding geothermal fields based on both surface and subsurface studies.

Numerous surface geological and geochemical studies of the volcanic system have been made (e.g. Saemundsson, 1967, 1995a, 1995b; 1995c; Árnason et al., 1987). Surface exploration studies were able to identify and map thermal expressions of both active and passive geothermal manifestations, permeability of the reservoir and surface hydrogeological controlling tectonic structures. Geochemical studies indicate that the fluid origin in Hellisheidi is local and that Nesjavellir to the north is isotopically and chemically more mature than Hellisheidi (Mutonga, 2007).

Geophysical methods are important as exploration methods for geothermal development. They are widely used to locate wells for exploration, production and reinjection. Different geophysical methods have been applied in the Hengill area since the early 1970s. An aero magnetic survey was conducted by Björnsson and Hersir in 1981, as well as passive seismic surveys (Pálmason, 1971; Foulger, 1984), a Bouguer gravity survey (Thorbergsson et al., 1984; Árnason et al., 1987), and a Schlumberger and dipole-dipole survey (Hersir, 1980, Björnsson and Hersir, 1981). MT surveys are one of the most important tools to map the resistivity structure of temperature dependent hydrothermal minerals down to 15 km depth. This method was first applied in the Hengill area in 1976 and then later more comprehensively conducted in INTAS, I-GET and ISOR projects (Hersir, 1980 and Árnason et al., 1987). The outcome of the MT surveys was later used in geothermal modelling along with available subsurface geological and geophysical data.

Drilling of exploration wells for district heating production first started in Nesjavellir in 1965 and drilling for power generation has since continued. Meanwhile, exploration and drilling activities continued in Hellisheidi, Bitra and Hverahlíd fields in the years 1986-1990 (Franzson et al., 2010) and drilling is ongoing in all fields except Bitra. Drilling provides information about the subsurface conditions, that is subsurface stratigraphy, depositional sequence of hydrothermal minerals, thermal history, current pressure and temperature condition, as well as other reservoir parameters such as permeability and distribution of feed zones. To this day, more than 60 geothermal wells have been drilled in Hellisheidi and Hverahlíd geothermal fields.

2. METHODOLOGY AND ANALYTICAL METHODS

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. Drill cuttings are samples typically collected from geothermal wells and are an independent and relatively inexpensive downhole data source essential for a successful subsurface investigation. Analytical methods and sampling procedures are discussed below.

Binocular Microscope Analysis was used to analyse cuttings down to 1350 m depth. The instrument magnifies the samples for visual identification. By using this method, rock type, hydrothermal alteration minerals, intensity of alteration and indications of permeability and veins can be clearly identified. Visual analysis of drill cuttings can at times be difficult, due to high alteration, mixing and fine cuttings. This might lead to wrong interpretation, however, in such cases experience and understanding of the geology of the area is helpful. Examples are shown in Appendix I.

Petrographic microscope analysis: Optical microscopy of 22 thin sections from the drill cuttings was used to further examine details of the alteration mineralogy, hydrothermal mineral depositional sequence and paragenesis. Additionally, the thin section analysis was used to identify the rock type, porosity and vein fillings as well as alteration of primary minerals. The data is used to support and enhance the binocular observation. The thin section samples were selected from different rock formations with variable alteration intensity.

X-ray diffractometer analysis (XRD): The XRD analysis helps to identify types of clays present in the sample. For this purpose, 26 samples were analysed. Temperature dependent clay types can be traced using this method in order to estimate the temperature of the reservoir and depth of the clay cap. Sample preparation for XRD clay mineral identification is somewhat different from bulk compositional analysis because the method identifies clay types qualitatively. The mineral grains in the sample are not randomly oriented like in the bulk XRD analysis. Instead they show some degree of orientation when the dissolved clay is suspended and eventually dried in the sample holder. Interpretation of selected XRD graphs is presented in the Appendix II.

Fluid inclusion analysis: This method is applied to determine the temperature history of the reservoir. It can give important information about the temperature conditions during the entrapment of the inclusion. The outcome of the analysis can describe the thermal history of the well.

3. GEOLOGY OF THE WELL

3.1 Drilling of well HE-53

Well HE-53 is one of three exploration wells drilled in Hverahlíd intended to study the geothermal reservoir for the proposed Hverahlíd power plant. The well is located on the same drill pad as wells HE-36 and HE-60. The well is 2507 m deep (measured depth) and is deviated to the south to a maximum inclination of 33°. The initial well design of HE-53 is presented in Figure 3. The drilling program of HE-53 included pre-drilling and three phases and the whole well was drilled by Iceland Drilling's Ódinn drill rig.

Pre-drilling: Drilling commenced on April 9, 2009 after the mobilization of drilling equipment on April 5. Drilling to 69.5 m depth ended on April 16 and an 18⅝″ surface casing was run down to 68 m depth. Total circulation losses were encountered at 15, 30 and 46 m depth. Cement plugs were emplaced at 15 and 46 m depth.

Phase 1: The first phase started soon after the pre-drilling on April 21.

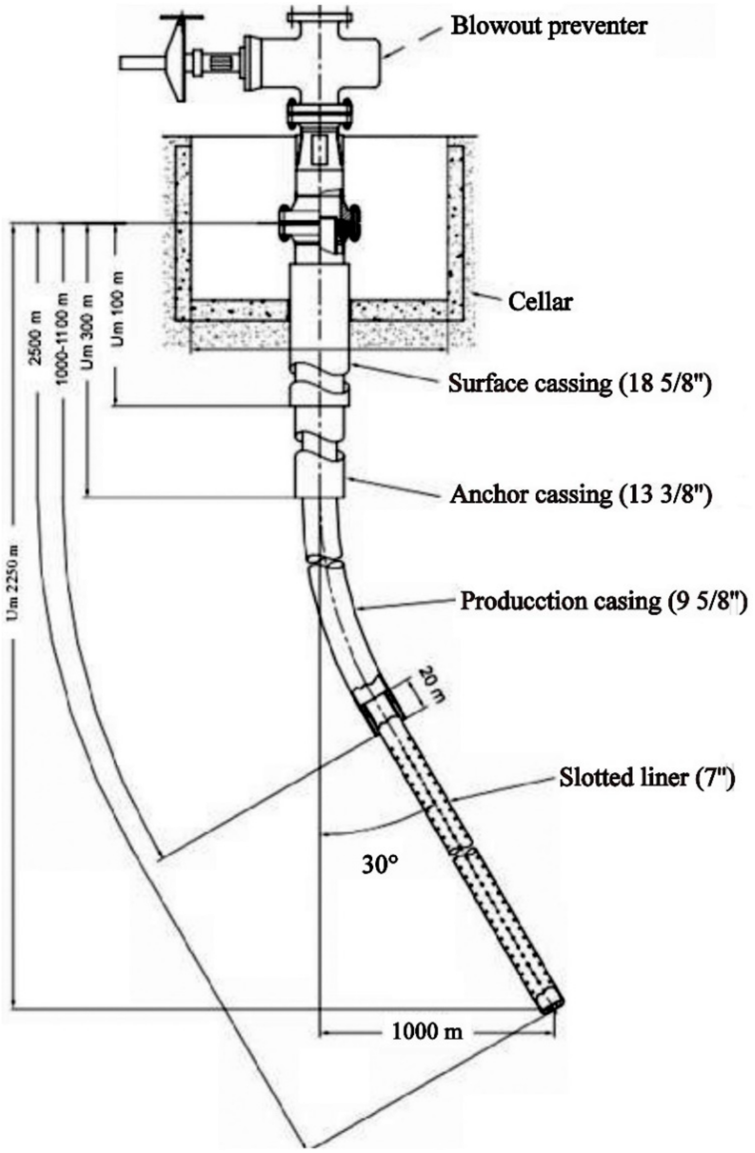

FIGURE 3: HE-53 well design

The drilling was smooth until it reached 132 m depth when a collapse occurred and the drill string got stuck. From 132 to 163 m depth multiple collapses and repeated losses were encountered. To overcome the problem cement plugs were emplaced to seal off the problematic formation. The final depth of 309.5 m was reached on May 2 after further encountering areas of partial loss. Temperature and caliper logs were performed the same day. Later, a 13⅜″ safety casing was installed down to 305.7 m depth.

Phase 2: Drilling of the second phase was performed from May 7 to 12. A mud motor was used to drill the 12¼″ well to a depth of 965.8 m. Afterwards a 9⅝" production casing was run down the well to 965.7 m depth. There were no considerable losses of circulation encountered during this phase.

Phase 3: The final phase started with installation and testing of the blowout preventers on May 17 and the drilling continued with an 8½″ bit to 2507.4 m depth. Water was used for circulation during the drilling of the production zone. Circulation loss was initially insignificant until around 1630 m when losses increased. At 1642 m, when a drill pipe was added to the string, the loss reached 17 l/s and at 1655 m the loss was more than 40 l/s, slowly increasing with depth. No drill cuttings were retrieved below 1878 m. On June 13, drilling to the final depth of 2507 m was completed and geophysical wireline logging was performed. Following the logging on June 15, a 7" slotted liner was cased from 919 to 2470 m depth. Details of the drilling of well HE-53 can be found in the original drilling reports (Níelsson and Tryggvason, 2011a; 2011b).

3.2 Borehole stratigraphy

The rock types encountered in well HE-53 down to 1350 m depth are described below. The cuttings were analysed with regards to hydrothermal alteration, physical condition and textural and mineralogical aspects. Observation of drill cuttings on a microscopic level allows us to understand and describe the bulk macroscopic textural features of the rock.

The subsurface stratigraphy of the well can broadly be categorized 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). A summary of the lithological log is presented below.

8-30 m: *Fine to medium-grained basalt*
Unaltered, porphyritic, vesicular, reddish brown basalt. The vesicles are not filled. Between 20-30 m the basalt is moderately oxidised and phenocrysts of plagioclase and olivine are visible.

30-44 m: *Fine- to medium-grained basalt*
Vesicular basalt with considerable amount of magnetic iron oxides. The rock is less oxidised than above. Oxidation and presence of vesicles increase between 38 and 44 m which might indicate a contact zone between lava sequences (scoria). Micro plagioclase phenocrysts are present.

44-60 m: *Fine- to medium-grained basal*t
Fresh, massive, fine-grained, dark gray basalt with few microphenocrysts of plagioclase.

60-64 m: *Fine- to medium-grained basalt*
Vesicular, slightly to moderately oxidised basalt, vesicles are more distinctive than in the unit above.

64-66 m: *No cuttings*

66-86 m: *Fine- to medium-grained basalt*
Crystal grains are relatively coarser than above and olivine phenocrysts are abundant. At the bottom of the lava layer vesicles are commonly observed. Palagonitized glass grains are admixed.

86-132 m: *Glassy basalt*
Unaltered glassy basalt, partly with a shiny black appearance as well as disseminated white spots, revealing the onset of fine crystal growth. Variable amount of fine-grained basalt is admixed. At 120-126 m some parts of the glass show palagonitization.

132-140 m: *Glassy basalt*
Both the glass and basalt grains seem reworked. They are well rounded and have medium to fine gravel size.

140-164 m: *Glassy basalt*
Within this depth the glass is somewhat palagonitized and mixed with considerable amount of medium-grained basalt. Cement fragments are present.

164-166 m: *Cement*

166-192 m: *Fine- to medium-grained basalt*
Slightly to moderately oxidized, dark gray, massive aphanitic basalt. At the bottom of the section banded light reddish mineral appears, probably limonite and reddish, globular, spherical siderite has been precipitated. This is a good indication for a low temperature ground water flow. The lower contact at 190-192 m is marked by a brecciated mixture of tuff as well as higher oxidation.

192-208 m: *Basaltic tuff*
Yellow brownish tuff. The uppermost part of the tuff is affected by the baking effect of the overlaying lava. The tuff contains basaltic glass and basalt fragments. Few calcite vein fillings were seen.

208-216 m: *Fine- to medium-grained basalt*
Dark gray vesicular basalt containing some amount of siderite precipitations. Calcite veins are not observed.

216-228 m: *Basaltic tuff*
The tuff in the uppermost part is mixed with basalt and glassy basalt fragments and brecciated in contrast to the lower portion which is predominantly composed of tuff. Oxidation is higher and siderite is also present.

228-260 m: *Fine- to medium-grained basalt*
Medium-grained basalt which contains visible olivine and plagioclase phenocrysts. Oxidation is higher between 236 and 242 m and at 236 m yellow brownish clay is observed on the palagonite. Siderite is present over the whole depth and radiating unknown zeolite is seen in a single vein at 258 m.

260-262 m: *No cuttings*

262-278 m: *Basaltic tuff*
Slightly fragmented vesicular tuff and highly fragmented, fine-grained tuff admixed. The colour of the tuff shows slight oxidation. Some of the tuff itself has olivine phenocrysts and is slightly mixed with basalt grains. Fibrous unknown zeolite and calcite veins are seen at the top of the section.

278-326 m: Basaltic tuff
Less fragmented massive glassy vesicular unaltered tuff which has a distinctive dark brownish colour. Variably mixed basaltic rock fragments and plagioclase phenocrysts are found at around 290 and 302 m. Calcite veins are encountered at around 318 m depth.

326-402 m: Basaltic tuff
The tuff is more mixed with porphyritic basalt at around 328 m depth and it is also partly palagonitized. There are abundant plagioclase phenocrysts in both the glassy dark brownish tuff and the basalt. Mixture

of abundant basalt fragment is only present at specific depth horizons. Highly fragmented ash like tuff starts from 350 m. Calcite vesicle fillings are present throughout the depth interval.

402-416 m: *Fine- to medium-grained basalt*
The top part contains dark grey, fresh, massive, aphanitic basalt while the bottom is vesicular with porphyritic texture and coarse plagioclase phenocrysts. Vesicular glass is mixed in at the base and the vesicles are filled, predominantly with calcite and two types of unknown zeolites (transparent type and powdery zeolite).

416-470 m: *Basaltic tuff*
Dark brownish compacted vesicular tuff which at some depth intervals is mixed with light yellowish coloured tuff. Both contain plagioclase phenocrysts. Vesicular porphyritic basalt is also mixed in with the tuff at some depth intervals. Glass is altered to greenish clay and unknown zeolites fill the vesicles. Veins are filled with calcite, unknown zeolites and clay.

470-472 m: *No cuttings*

472-476 m: *Basaltic tuff*
Dark and light brownish tuff with scarce vesicles partly filled with calcite and zeolites.

476-490 m: *Basaltic breccia*
The basaltic breccia contains fragments of fine-grained, aphanitic basalt and light and dark brown tuff in different proportions. The basalt is less altered than the tuff. Veins are common and they are filled with calcite.

490-496 m: *Basaltic tuff*
Predominantly brown vesicular tuff and vesicular dark grayish tuff. Vesicles are filled with calcite, zeolites and smaller amounts of siderite.

496-518 m: *Fine- to medium-grained basalt*
Fine-grained, fresh, dark gray, aphanitic basalt which is brecciated at 502-506 m depth. At the bottom contact part, the basalt is altered to clay. Within the breccia the tuff vesicles are filled with calcite and zeolites.

518-594 m: *Basaltic tuff*
Vesicular brownish tuff which is highly altered to yellow brownish clay. Vesicular tuff grains are almost entirely altered to clay. Calcite and unknown zeolites in veins and vesicles are common. Fresh plagioclase phenocrysts are present.

594-596 m: *No cuttings*

596-604 m: *Basaltic tuff*
Porphyritic vesicular tuff, vesicles are filled.

604-606 m: *No cuttings*

606-656 m: *Fine- to medium-grained basalt*
Dark gray to black colour, less altered than before, fine-grained, aphanitic basalt. Fresh micro phenocrysts of olivine are found at 634 m and plagioclase phenocrysts at around 650 m. The rock is affected by calcite alteration and pyrite veining. This rock is easily identified in the Neutron-Neutron and resistivity logs in Figure 4.

656-698 m: *Basaltic tuff*
Considerably altered tuff containing relatively unaltered basalt grains. The clays have variable colours; light grey, greenish and dark brown. No cuttings were retrieved from 668 to 672 m.

698-710 m: *Fine- to medium-grained basalt*
Dark grey to black aphanitic basalt with multiple veins filled with pyrite and calcite. At the lower contact microphenocrysts (possibly plagioclase) and vein fillings are prominent. The more dense nature of this rock, compared to the surroundings, is noted in the Neutron-Neutron and resistivity logs in Figure 4.

710-764 m: *Basaltic tuff*
Brownish coloured fragmented ash tuff slightly mixed with medium-grained basalt, olivine and plagioclase. Phenocrysts of the basalt are not altered although the rock is affected by calcite and pyrite veining. Between 736 and 746 m depth alteration is higher and the presence of more calcite and pyrite might indicate the presence of a localized feed zone.

764-880 m: *Pillow basalt*
Partially crystallized brownish vesicular basalt partially altered to fine-grained greenish clay. Fresh porphyritic basalt and less altered brownish tuff occasionally occur. Alteration minerals are most often present in connection to greenish basalt and tuff grains. At 764 m depth quartz and laumontite are seen for the first time.

880-904 m: *Basaltic breccia*
The breccia consists of variable tuff and abundant basalt. Alteration intensity of the tuff is higher than the basalt grains. Veins and vesicles are filled with laumontite and pyrite.

904-920 m: *Fine- to medium-grained basalt*
Altered greenish vesicular basalt and some slightly altered brownish basalt. Quartz is abundant at the bottom contact.

920-948 m: *Basaltic breccia*
The breccia shows different alteration depending on the rock appearance. Some of the basalt itself is greenish with medium- to coarse-grained clay while the fine-grained, porphyritic basalt is still fresh. Similarly, the tuff shows alteration with colour variations.

948-950 m: *No cuttings*

950-964 m: *Fine- to medium-grained basalt*
Greenish, altered, fine-grained, aphanitic basalt. Alteration minerals are not common except for disseminated pyrite. Few slightly altered basalt and tuff grains are admixed. Prehnite is seen from 948 m together with small amounts of epidote. The upper limit of the crystalline rock is noted in the Neutron-Neutron log in Figure 4.

964-966 m: *No cuttings*

966-1020 m: *Fine- to medium-grained basalt*
Medium-grained, altered, greenish basalt. Vesicles are mostly filled with coarse-grained clay. Prehnite is common in this unit and small amounts of epidote started to appear from 948 m onwards.

1020-1048 m: *Medium- to coarse-grained basalt*
The coarse-grained crystals might indicate an intrusion. Magnetic iron oxide (most likely magnetite) is common in the crystalline basalt. There is also fine- to medium-grained more altered basalt mixed in. Epidote is occasionally identified by its distinctive colour.

1048-1050 m: *No cuttings*

1050-1198 m: *Medium- to coarse-grained basalt*
Dark gray, medium-grained crystalline basalt, sometimes with a glassy look. Magnetic iron oxide (most likely magnetite) abundantly occurs within the basalt and the oxide is not altered. The alteration of the rock at this depth interval is in general less than before, although high temperature minerals are found and some sections are more altered. Epidote was first clearly seen in crystal form at 1170 m and wollastonite at 1182 m. Near the top and the bottom contact alteration is higher.

1198-1222 m: *Fine- to medium-grained basalt*
Highly altered, fine- to medium-grained basalt mixed at the top with crystalline basalt and tuff grains. High temperature alteration minerals such as prehnite and epidote are commonly found.

1222-1258 m: *Basaltic breccia*
The breccia is composed of predominantly fine- to medium-grained crystalline basalt and whitish tuff. Hydrothermal alteration is anomalously high and alteration minerals coarsely grown. This could indicate a localized feed zone. Wollastonite is usually found clustered with prehnite.

1258-1286 m: *Fine- to medium-grained basalt.*
Highly altered, light greenish coloured basalt slightly mixed with highly altered tuff. Wollastonite is found within the tuff grains.

1286-1300 m: *Basaltic breccia*
Mixed basaltic breccia along with tuff fragments. Basalt grains are more dominant than the tuff. Very few alteration minerals are present.

1300-1350 m: *Fine- to medium-grained basalt*
Slightly to moderately altered greenish basalt. The grains within the basalt are visible but they are not coarse. Veins are filled with epidote and an unknown white mineral. The basalt is intruded twice by thin possible intrusions at 1328-1334 m and 1344-1348 m. The medium- to coarse-grained potential intrusive rock contains abundant magnetic oxides and they are relatively little altered.

3.3 Intrusive rocks

Intrusive rocks are commonly found below 1000 m depth intruding the crystalline basalt series. They were identified in the binocular and petrographic microscopes, 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 is the occurrence of magnetic iron oxides (magnetite) in addition to oxidation. Vein fillings may be noticeable at the margin. As is shown in Figure 4 the inferred possible intrusions are quite thick and located at 1046-1134 m and 1142-1168 m, while the most likely or confirmed intrusions are located at 1020-1026, 1028-1046, 1328-1334 and 1344-1348 m.

4. 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.

Understanding this process is one of the most important tasks of borehole studies to understand the geothermal system.

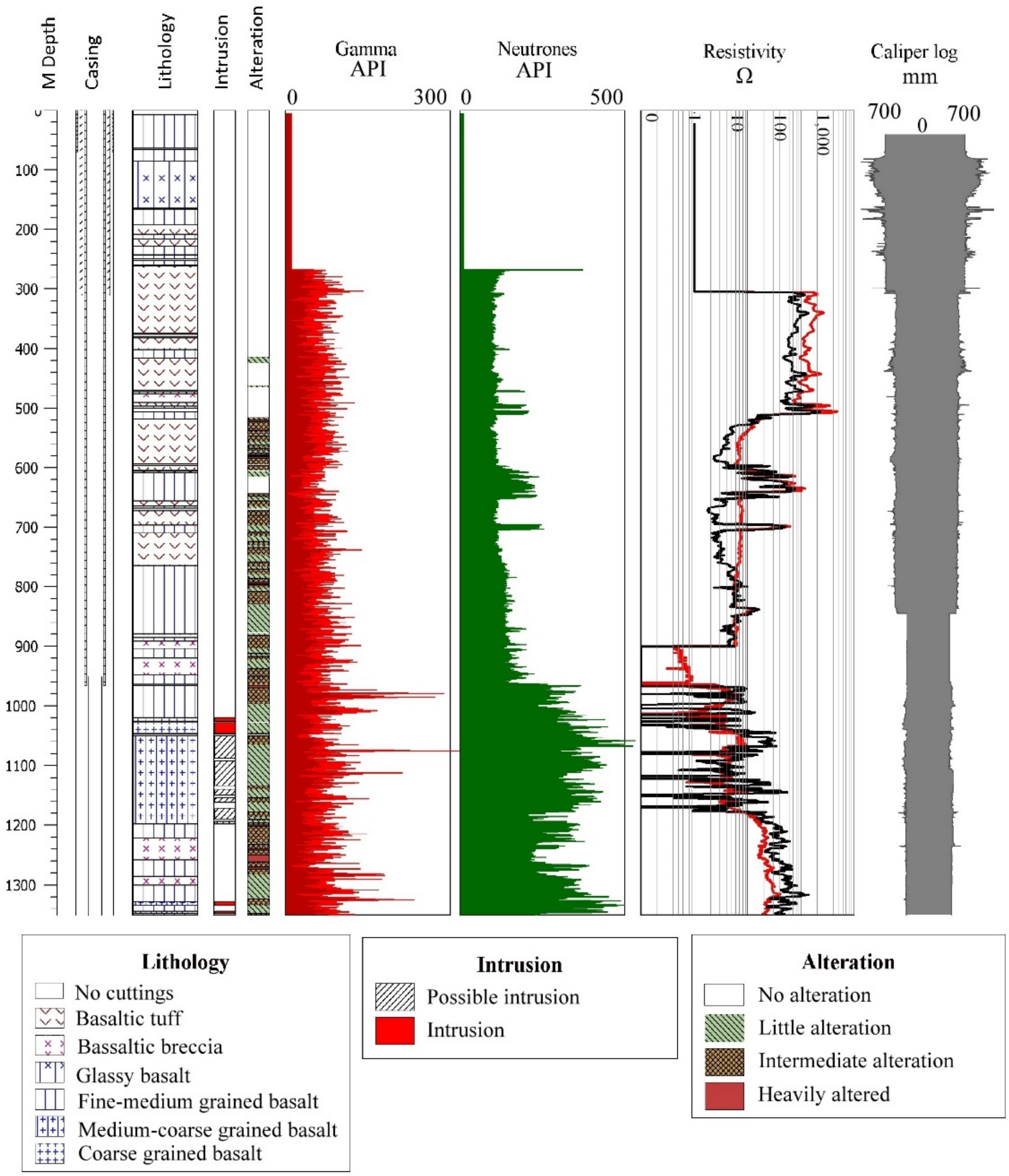

FIGURE 4: Stratigraphy and wireline logs in well HE-53 at 0-1350 m depth

4.1 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 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 greyish 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.

4.2 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 described below and shown in Figure 5.

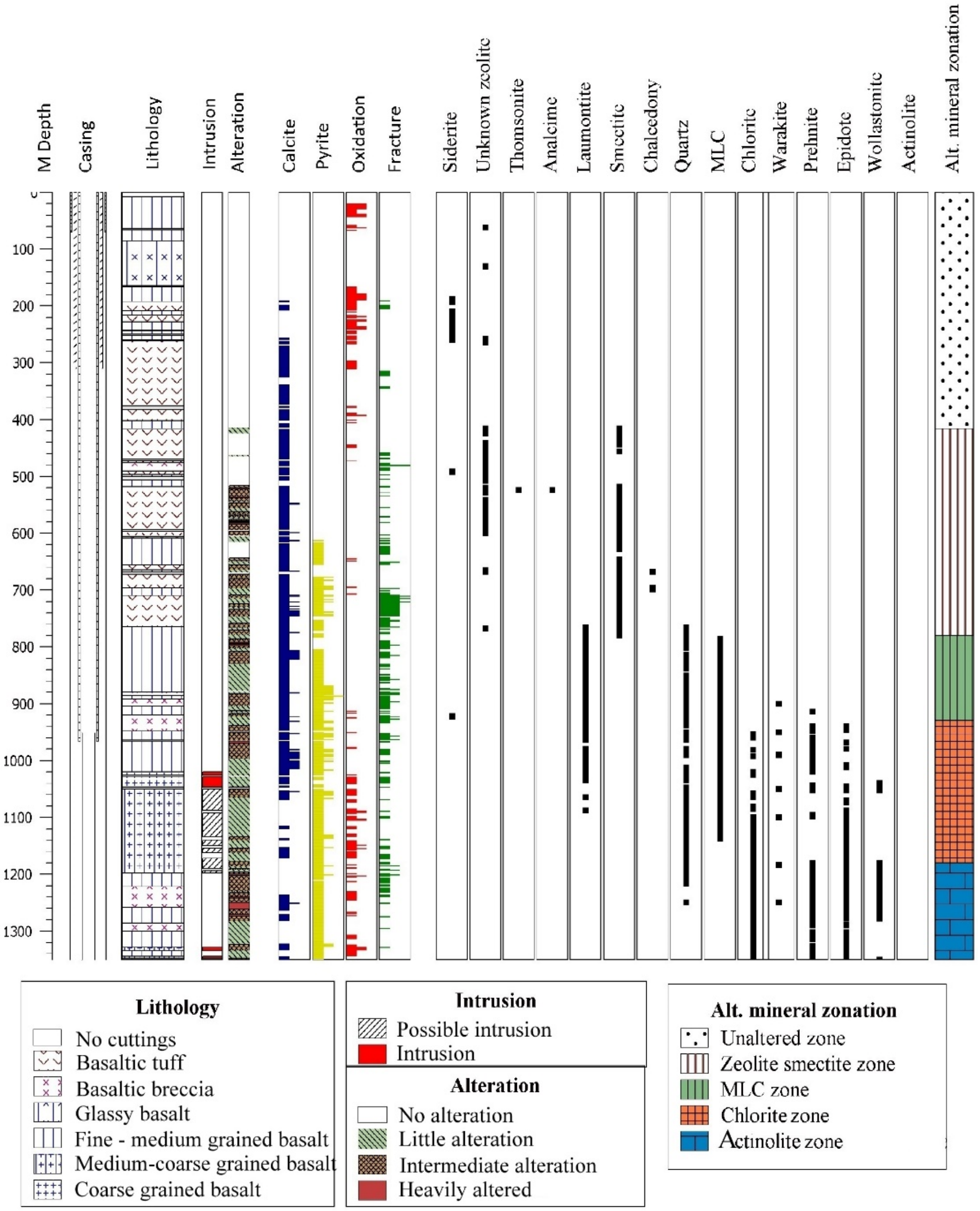

FIGURE 5: Distribution of hydrothermal minerals and alteration mineral zonation in well HE-53

Calcite is the most widely distributed alteration mineral in the well. The occurrence temperature of the mineral from 50 to 300°C allows them to form in a wide depth range. The first calcite crystal was seen associated with siderite at 192 m depth. Most of them were precipitated in veins and vesicles in the upper part of the well. Calcite can easily be identified in both thin sections (extremely high birefringence and variable relief) and under the binocular microscope using dilute hydrochloric acid. Calcite is abundant in less altered fracture-dominated basalt and in coarsely crystalized basalt. The occurrence gradually becomes less below 1070 m. According to Kristmannsdóttir (1979), calcite disappears when the temperature exceeds 290°C.

Siderite and Limonite are low temperature alteration minerals which first appear together at 190 m and limonite is only seen around this depth. It is found as finely laminated, banded, sometimes spherical layers. Siderite is commonly found in the upper part of the well from 190 to 260 m. The occurrence is associated with oxidized basaltic horizons. It is identified by its distinctive red to reddish brown globular form and in thin sections it looks like spherical carbonate minerals (Figure 6). Both siderite and limonite are good indicators of cold ground water.

FIGURE 6: Spherical radiating siderite precipitated on fine-grained basalt at 226 m

Zeolites are a group of hydrated aluminium silicate minerals that form in low temperature zones. The temperature of formation commonly ranges from 30°C to about 200°C (Kristmannsdóttir and Tómasson, 1978). It was not possible to identify many members of this group using the methods applied except for analcime and laumontite. Other occurrences are referred to as unknown zeolite or described by their habit and crystal form, like blocky (heulandite, chabazite or stilbite) at around 480 m and fibrous or radial (scolesite or mesolite) around the same depth. The lowest temperature zeolites are absent below 668 m.

> *Analcime* occurs at 524 m and is distinctively identified by its trapezohedron crystal shape under the binocular microscope. It is stable at temperatures between 40°C and about 200°C.
>
> *Laumontite* is the most commonly found higher temperature zeolite in the well. It first appears at 766 m together with a quartz crystal. Laumontite forms in the range of 120 to 230°C (Kristmannsdóttir, 1979). It is easily identified in the binocular microscope by randomly oriented clustered platy appearance and breaks easily into fine fragments. It was also identified in an XRD analysis. Laumontite is found with prehnite down to 1034 m depth.

Clay is the most significant alteration mineral due to its quick response to temperature changes in the system. For that reason, it is very useful for the interpretation of thermal history (Kristmannsdóttir, 1979). In binocular microscope analysis, clays were identified by their colour, grain size and by their association with other temperature dependent hydrothermal minerals. The clay types were also identified in XRD analysis. In this study, combining binocular and petrographic microscope analyses could identify the clay type even if XRD would not yield any results.

Smectite is a low temperature mineral and mostly occurs associated with zeolites as is the case in this well. Smectite is stable below 200°C (Kristmannsdóttir, 1979). In HE-53 it was found between 416 and 780 m.

Mixed layer clay (MLC) is an alternating layer of smectite and chlorite. According to Kristmannsdóttir (1979), it is dominant in the 200-240°C temperature range. MLC was identified at 780 m depth using thin sections and at 800 m using XRD analysis. It is present in abundance down to 1140 m depth. We can identify MLC in thin sections by its feathery texture and orange and bluish interference colours (Figure 7).

Chlorite is a high temperature clay mineral, abundant below 1150 m. It coexists with MLC and other high temperature minerals in the well. Chlorite alone could rarely exist below 240°C (Kristmannsdóttir, 1979). The mineral is identified in XRD analysis presented in the Appendix II. In PPL in the petrographic microscope chlorite has a light greenish colour and in XPL it is identified due to first order birefringence (gray colours).

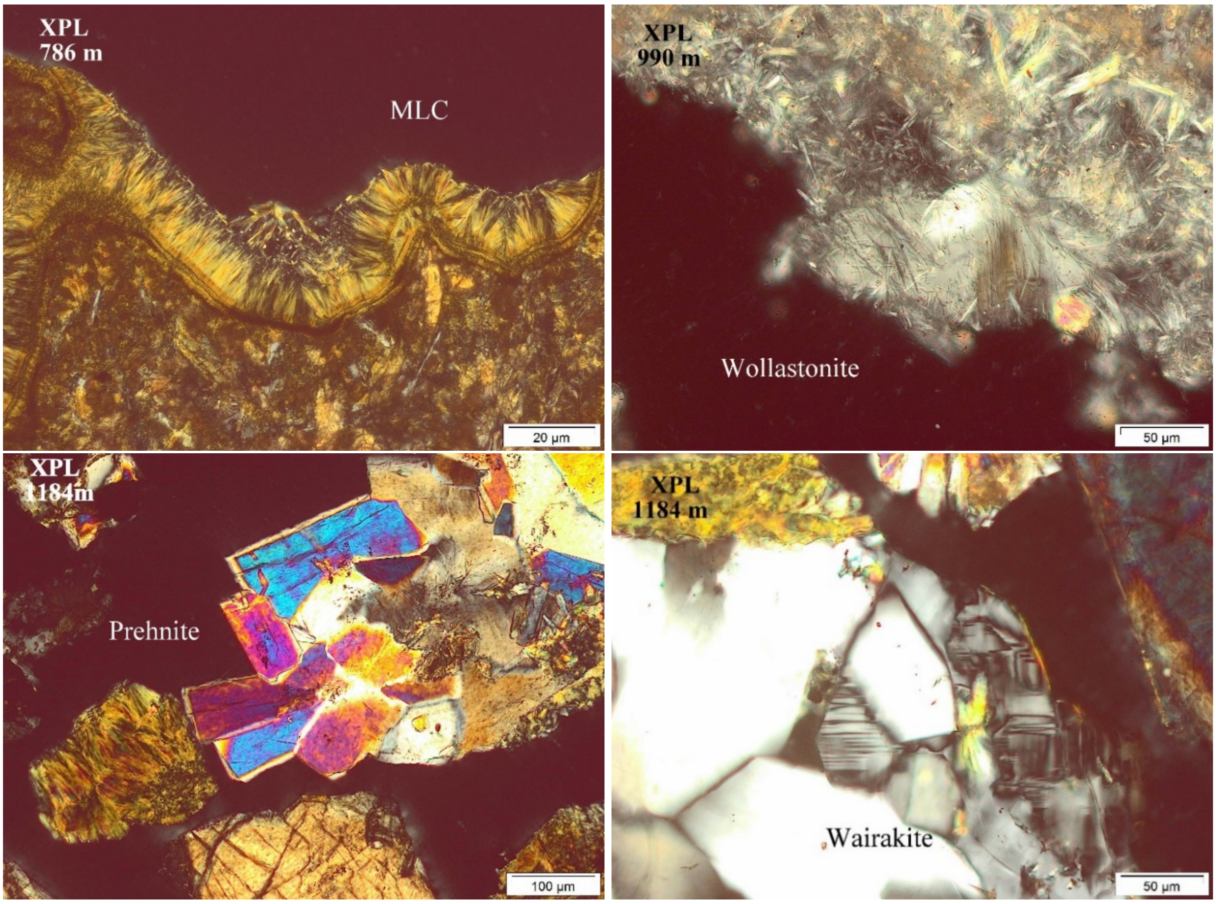

FIGURE 7: Selected high temperature hydrothermal minerals in well HE-53

Pyrite and chalcopyrite are the second most widely occurring secondary minerals in the well following calcite. Pyrite was first noted between 36 and 56 m depth and then at 614 m depth. The occurrence of pyrite does not provide any information about the temperature of the system but is a good indicator of permeable zones. Along with pyrite, reddish yellow chalcopyrite is commonly found in the basalt that contains abundant magnetite or ilmenite at 1080 to 1130 m.

Quartz crystals are first found with laumontite at 766 m depth. The first appearance of quartz indicates a minimum temperature of 180°C which is close to the minimum temperature of a high temperature reservoir. Quartz is stable at high temperatures and important for the fluid inclusion analysis carried out in this study. Most of the time quartz was found as pore and vein fillings. Amorphous silica (chalcedony) was seen at 668 and 698 m depth before quartz was identified.

Prehnite is the first high temperature mineral to occur starting from 900 m depth together with wairakite. It requires a minimum temperature of 240°C to form. Most commonly it is formed and found together with epidote which is not common in this well (down to 1350 m). Prehnite is identified in the binocular microscope by its spherical growing, clustered, cubic sugary texture and in the petrographic microscope it can be easily identified by their second order colourful birefringence and its radiating crystals (Figure 7).

Wairakite is not abundant in the well and was only identified in the petrographic microscope. In petrographic analysis wairakite shows tartan like cross hatch twinning in XPL (Figure 7) and dark low order birefringence. It is the only member of the zeolite group formed at a minimum temperature of 200°C. It is first seen with prehnite at 900 m.

Epidote is a good indicator of a high reservoir temperature. Epidote starts to form at around 230-250°C and can be easily identified by its yellowish green distinctive colour (epidote colour) both under the binocular and the petrographic (PPL) microscope. Well-developed crystals of epidote have the appearance of thin prismatic needles dispersing from a common centre. Epidote becomes abundant and forms euhedral crystals when the temperature exceeds 260°C (Kristmannsdóttir, 1979). The colour of epidote was found in samples from 950 m. However, well developed crystals were first found at 1170 m.

Wollastonite is a high temperature alteration mineral that forms at temperature above 260°C. In HE-53 wollastonite is first seen at 990 m (rarely) but it becomes abundant below 1180 m. They occur in two forms, as a single crystal and clustered along with quartz or prehnite. In the single form the fibers of the crystal are not randomly growing.

Actinolite was not clearly identified in either the petrographic or the binocular analysis except for a hint of uralite on an altering margin of pyroxene and a hint of actinolite at 1230 to 1250 m depth. However, in XRD analysis amphibole was identified starting from 1220 m depth. Actinolite requires a minimum temperature of 280°C to grow.

4.3 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.

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.

4.4 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 as shown in Figure 8. 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.

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.

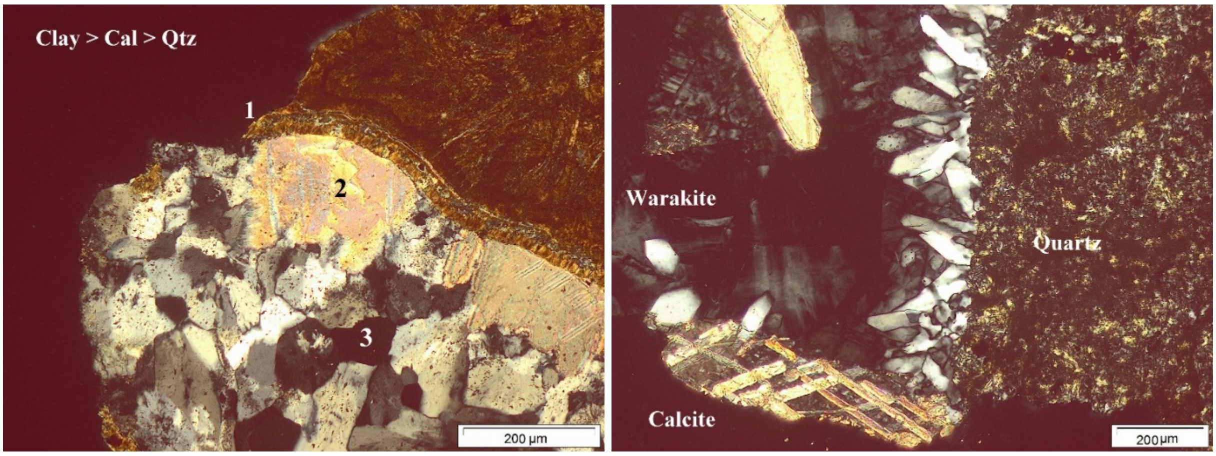

FIGURE 8: Depositional sequences of clay, calcite and quartz in a vesicle at 786 m depth (to the left). Wairakite is precipitated at a later stage after platy calcite and quartz crystals have been formed in the vein at 950 m (to the right)

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

4.5 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. The results are presented in the graphs in Figure 9.

As the graph shows, 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.

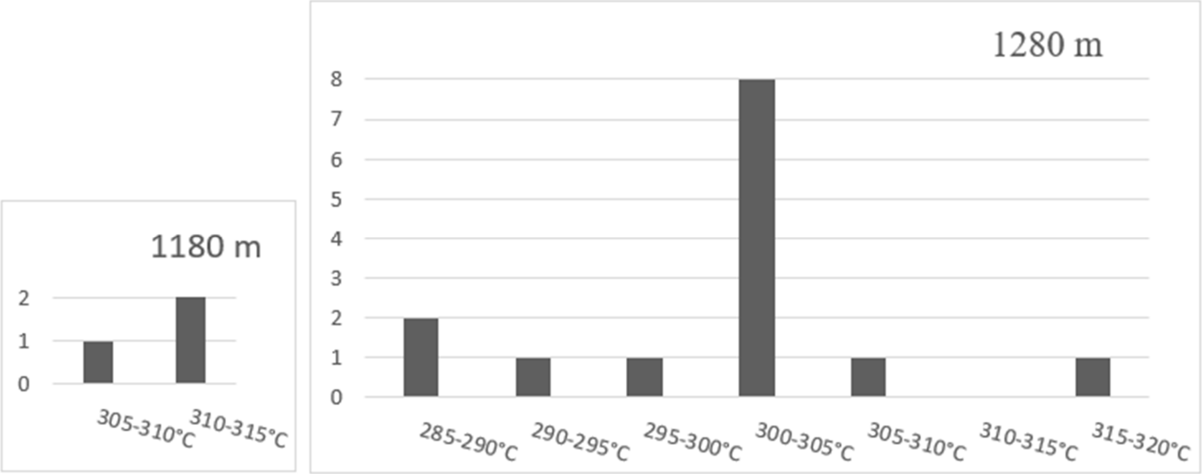

FIGURE 9: Temperature of homogenization in fluid inclusions in quartz at 1180 m and 1280 m depth

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 10, 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.

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 10 (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 10) 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 10 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.

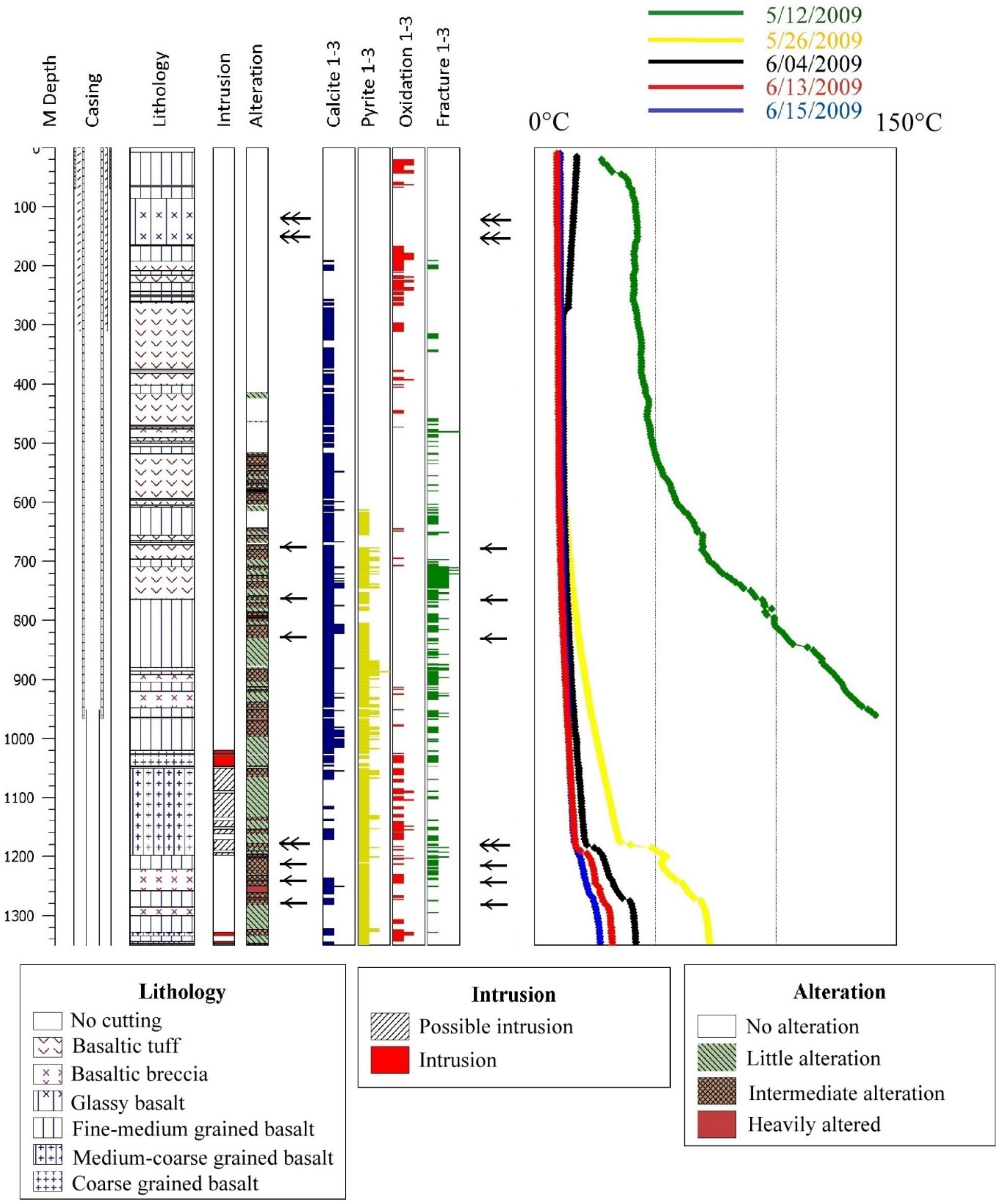

FIGURE 10: Feed points (black arrows) in relation to temperature profiles during injection, lithology, intrusive rocks and alteration intensity

6. DISCUSSION

The stratigraphy of well HE-53 in the Hverahlíd 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 11, 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.

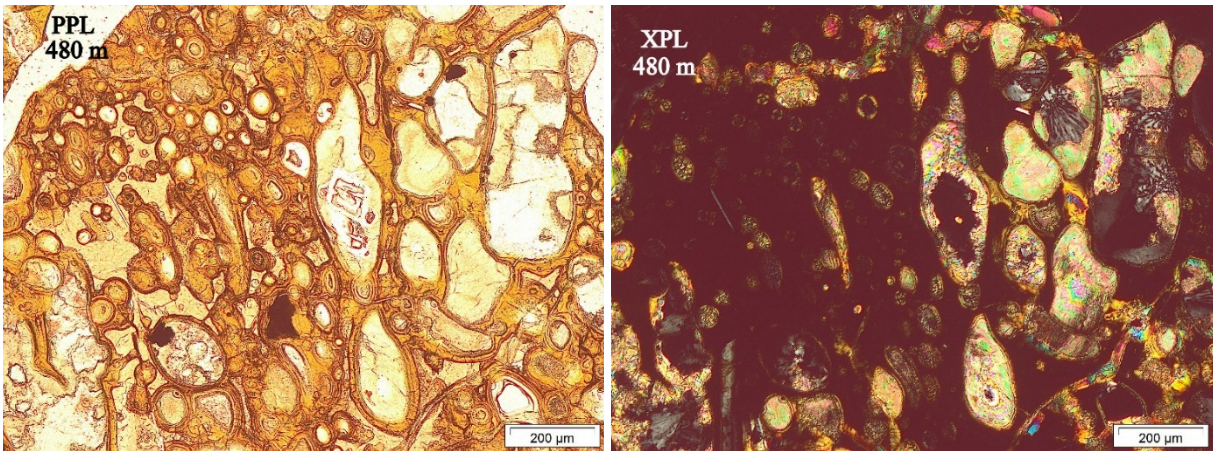

FIGURE 11: Vesicles of tuff glass are completely filled with precipitations of calcite and zeolites. The glass is still quite fresh

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 12). 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.

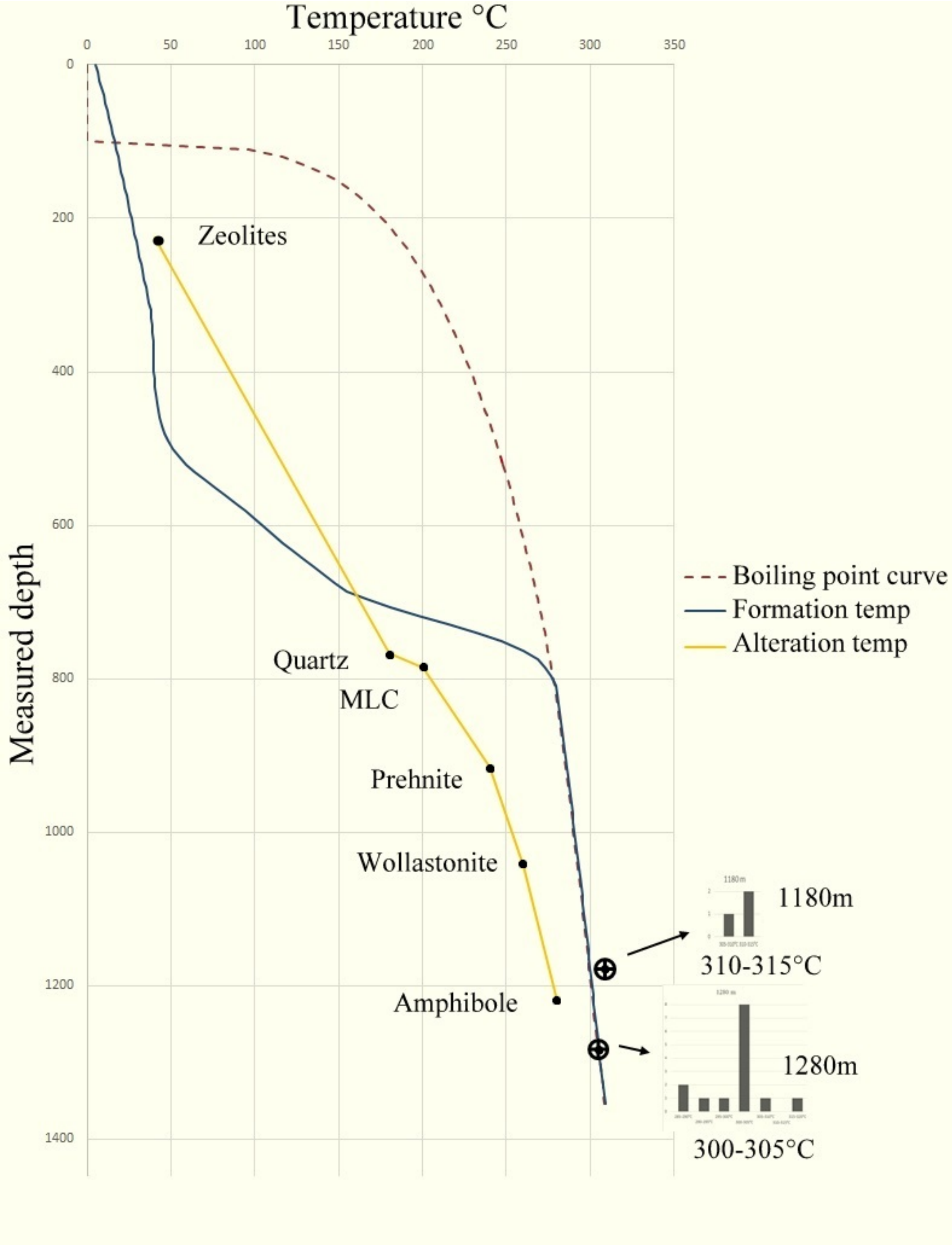

FIGURE 12: Comparison of formation temperature, fluid inclusion homogenization temperature and alteration temperature

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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APPENDIX I: Hydrothermal alteration minerals of well HE-53 highlight from thin section and binocular cutting analysis

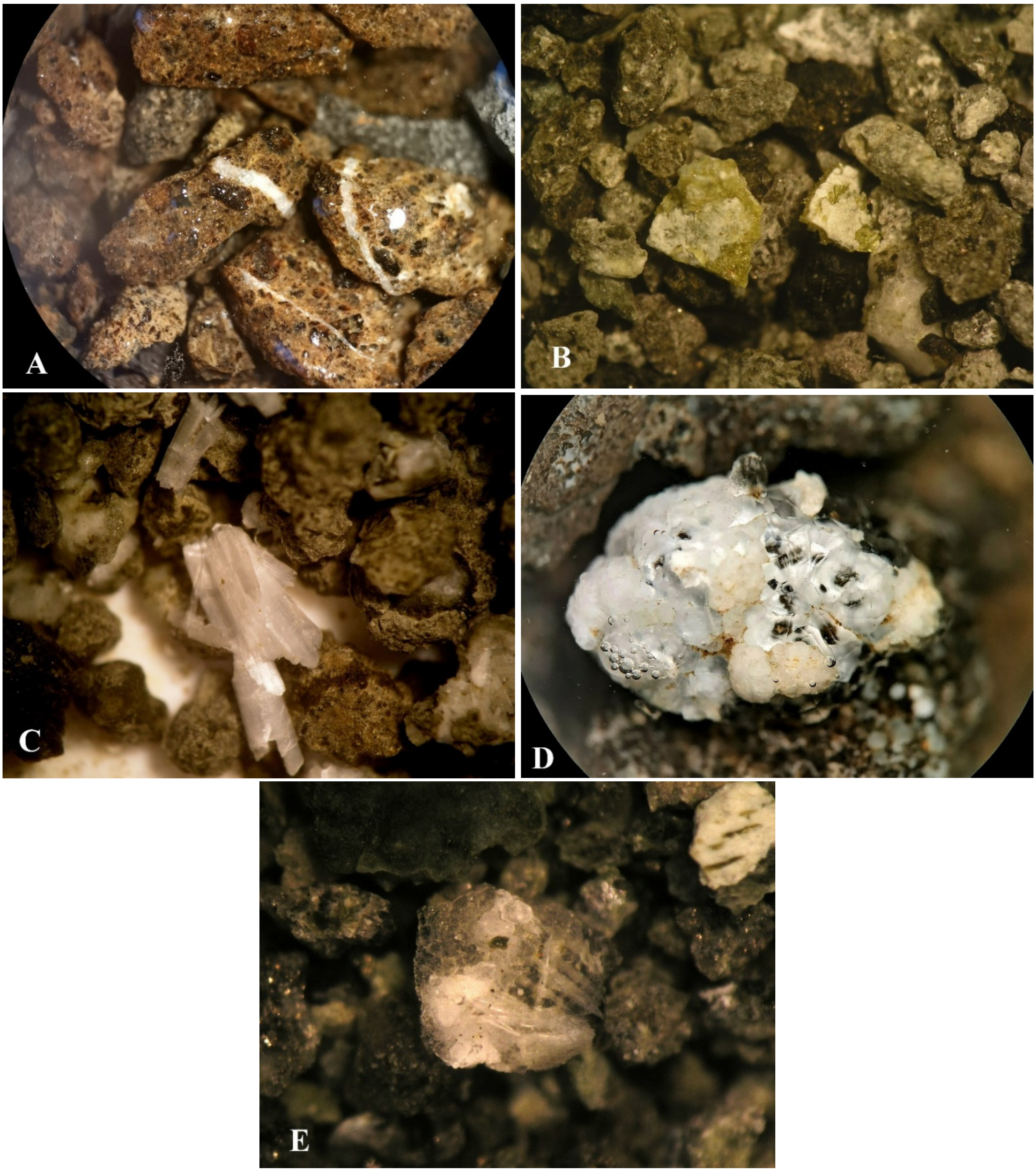

FIGURE 1: Image of hydrothermal mineral from binocular analysis. A: calcite filled micro veins usually counted to identify permeable zones. B: epidote in crystal form in veins at 1186 m. C: laumontite is an abundant mineral in the well and is preferentially identified by the binocular microscope rather than by other methods. D: trapezohedron crystal of analcime with unknown powdery zeolite at 524 m. E: transparent clustered sugary grains associated with fine fibrous wollastonite

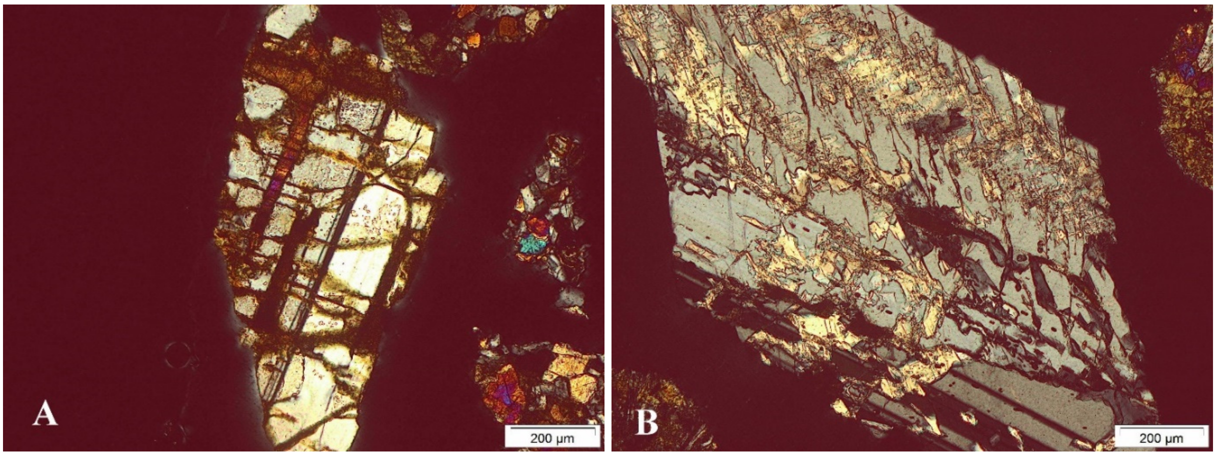

FIGURE 2: A and B show alteration of plagioclase phenocryst to fine-grained clay and calcite minerals, respectively

APPENDIX II: XRD methods and graphs used to discriminate clay types and other alteration minerals

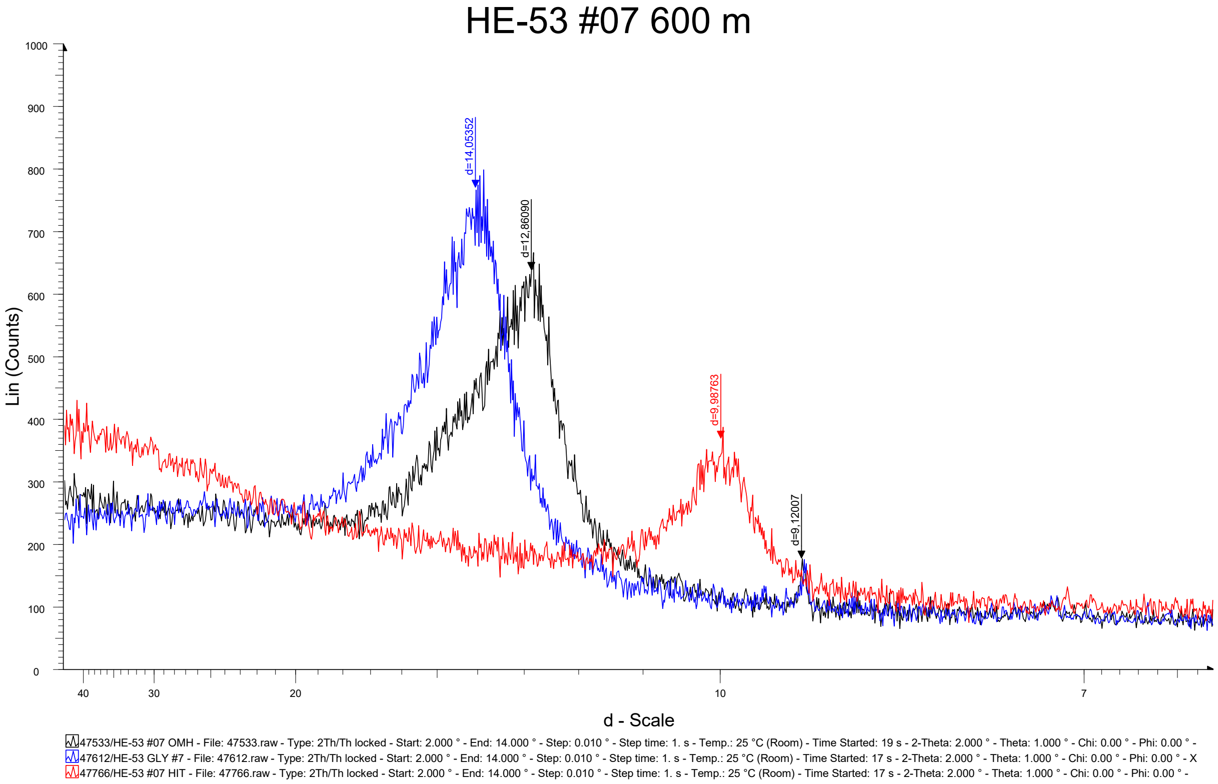

FIGURE 1: XRD analysis graph showing peaks at d= 14.05, d=12.86 and d=9.98 for the glycolated, untreated and heated samples are typical for smectite clay. A small peak at d=9.12 indicates zeolites which distinctively collapses for the heated sample

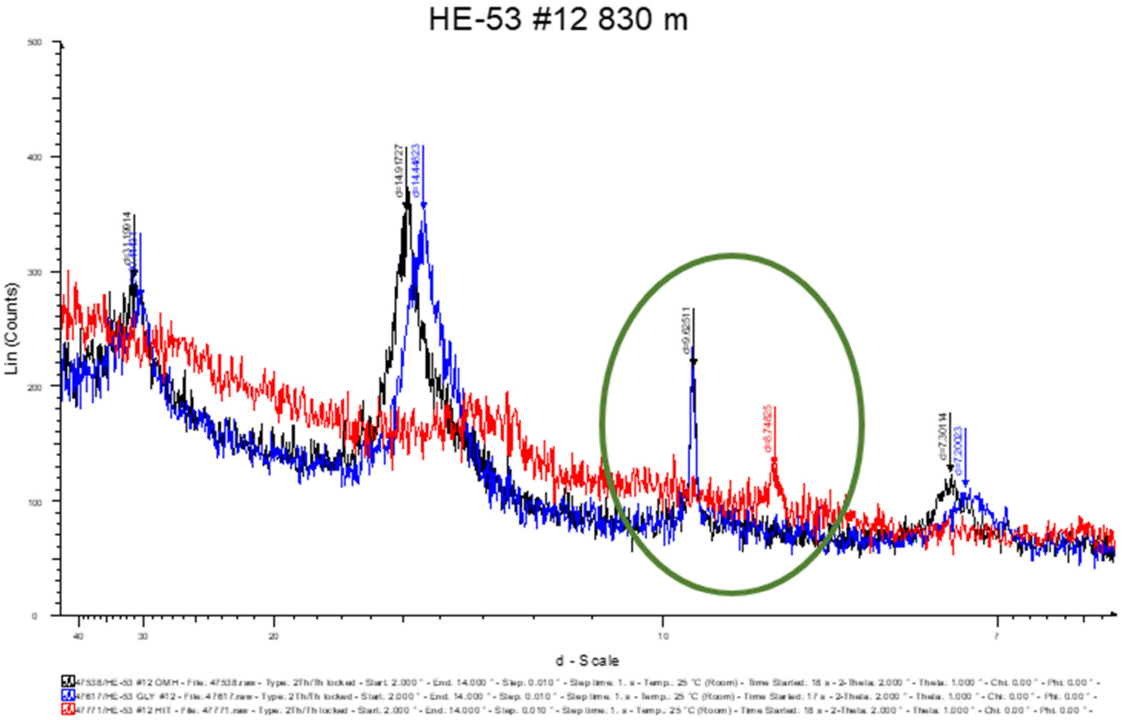

FIGURE 2: XRD clay analysis showing the MLC heated, glycolated and untreated samples has a main peak at around d=14 to 12 and smaller peaks at d=31 and d=7.2. The circled part of the graph shows the pattern for laumontite which is a peak at d=9.62 for the untreated and the glycolated sample and a small shift on the heated sample at d=8.74

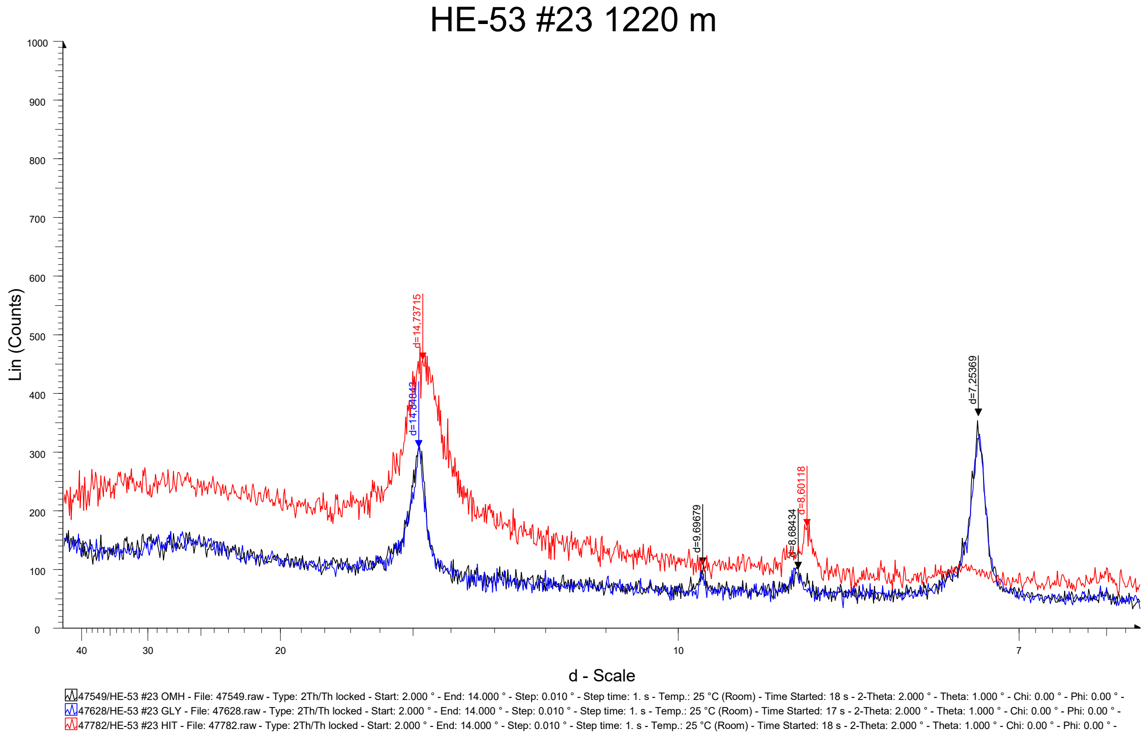

FIGURE 3: Chlorite peaks for all three samples are located at d=14.8 and second order peaks are at d=7.25 for the glycolated and untreated samples while the heated sample of the unstable chlorite shows no peak. Small peaks in the three samples at d=8.68 indicate an amphibole, most probably actinolite