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BOREHOLE GEOLOGY AND ALTERATION MINERALOGY OF WELL HE-52, HELLISHEIDI GEOTHERMAL FIELD, SW-ICELAND

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ABSTRACT

Well HE-52 is located in the northwestern part of Hellisheidi, which in turn is situated in the southern sector of the Hengill high-temperature field. It is drilled to a depth of 2516 m as a directional well and deviated northwards (N) to reach the high-temperature reservoir situated at the root of the Skardsmýrarfjall Mountain. The lithology of this well comprises alternating successions of hyaloclastite formations and lava flows of basaltic composition, as well as minor successions of sedimentary basaltic tuff. The hyaloclastite formations make up about 80% of the stratigraphy, and include breccia, pillow lava and tuff. The permeability in the well is related to lithological contacts, intrusions, faults and fractures. Four hydrothermal alteration zones were identified below the unaltered zone: a smectite-zeolite zone (120-386 m), a mixed-layer clay zone (386-586 m), a chlorite zone (586-634 m) and a chlorite-epidote zone (634-1190 m). Based on the intensity of alteration, the abundance of veins and vesicles and stratigraphical boundaries, seven feed zones were recognized in the uppermost 1000 m and categorized as weak aquifers. Based on a study of the mineral assemblage and the mineral sequence, the hydrothermal system in well HE-52 is increasing from low- to high-temperature sequence with increasing depth. This condition is followed by cooling evidence envisaged by precipitation of calcite at a later stage. Fluid inclusions studied have shown a wide range of homogenization temperatures which range from 180 to 285°C and, after comparing it with the formation temperature, indicate large temperature variation in the geothermal system at 874 m.

1. INTRODUCTION

1.1 General information

Well HE-52 is located in Hellisheidi which is a part of the Hengill high-temperature field. It is situated in the southern sector of the Hengill central volcano south of the Nesjavellir high-temperature field. The Hengill active volcanic system lies about 30 km east of Reykjavik. This volcanic system includes a 40-60 km long north-northeast trending fissure swarm with normal faults, fissures, frequent intrusions of magma and a central volcano. The geothermal system is currently supplying 213 MWe from the Hellisheidi field and 120 MWe and 290 MWt from the Nesjavellir field. Reykjavik Energy started exploration of the Hengill geothermal resource some 50 years ago. An early assessment in 1986 predicted the size of the geothermal area in Hengill to be around 110 km^2 with a capacity of about 5500 GWH/y or 690 MWe for 50 years (Franzson et al., 2010).

1.2 Purpose of the study

In order to study subsurface geology and explore a geothermal field, drilling is of utmost importance. Borehole geologists study the subsurface formation through cuttings and cores in order to identify the lithology, hydrothermal alteration and aquifers. This evaluates the resource and helps in developing a plan for geothermal utilization of the system. The main aim of this study was to determine the geothermal conditions in the system through understanding of the lithology, hydrothermal mineralisation, the sequence of mineral deposition in veins and vesicles, location of aquifers, and the temperature of the reservoir in this well. This geological research is mostly based on available data from the time of drilling.

1.3 Methodology

Five hundred cutting samples were collected at 2 m intervals and eleven thin sections made from the uppermost 1000 m of well HE-52 with respect to describing the geology and hydrothermal alteration. The methods used for analyses included a binocular microscopy (Olympus SZ12 with a magnification of 7× to 90×) followed by detailed thin section petrography, X-ray diffraction analysis (XRD), fluid inclusion geothermometry, interpretation of circulation losses and geophysical logs, in order to get a comprehensive view of the subsurface and the geothermal system surrounding the well. This report is the result of a study that was done during the six-month training course at the United Nations University Geothermal Training Programme (UNU-GTP) in 2010.

2. OUTLINE OF GEOLOGY

2.1 Regional geology of Iceland

Iceland is located at the Mid-Atlantic Ridge, where spreading occurs between the North-American and Eurasian plates. The direction of spreading is WNW-ESE (Figure 1). The velocity of spreading is estimated to be about 1 cm/yr in each direction (Talwani and Eldholm, 1977). The rocks in Iceland are predominantly of basaltic composition, or ~80% of Icelandic succession, while ~10% are intermediate and acid rocks, and ~5% are sediments, mainly of volcanic origin. The age of the exposed volcanic succession ranges back in age to about 16 m.y. The oldest rocks are exposed in the extreme northwest and east. The stratigraphy of Icelandic rocks is divided into four groups with regard to age (Fridleifsson, 1983):

1. Tertiary (Mio-Pliocene), older than 3.1 m.y.
2. Plio-Pleistocene, 3.1-0.7 m.y.
3. Upper-Pleistocene, 700,000-11,000 y.
4. Postglacial, 11,000 y. and younger.

Geothermal systems in Iceland are commonly classified as high-temperature and low-temperature systems. Within the high-temperature fields the temperature is typically above 200°C at 1 km depth. These areas are usually located within central volcanoes or their fissure swarms. The activity is due to intrusions at shallow depth in the upper crust. Low-temperature areas are mainly found outside the volcanic rift zone. The temperature is lower than 150°C within the low-temperature areas which are usually fracture dominated systems (Bödvarsson, 1982; Björnsson et al., 1990). The volcanic systems in SW-Iceland strike southwest to northeast. Hellisheidi is located in one of the volcanic zones. These volcanic zones are characterised by active volcanoes, fissure swarms, numerous normal faults and high-temperature geothermal fields. The uppermost 1000 m in these zones is made of highly porous and permeable basaltic lavas and hyaloclastites with a heavy flow of groundwater (Pálmason and Saemundsson, 1979).

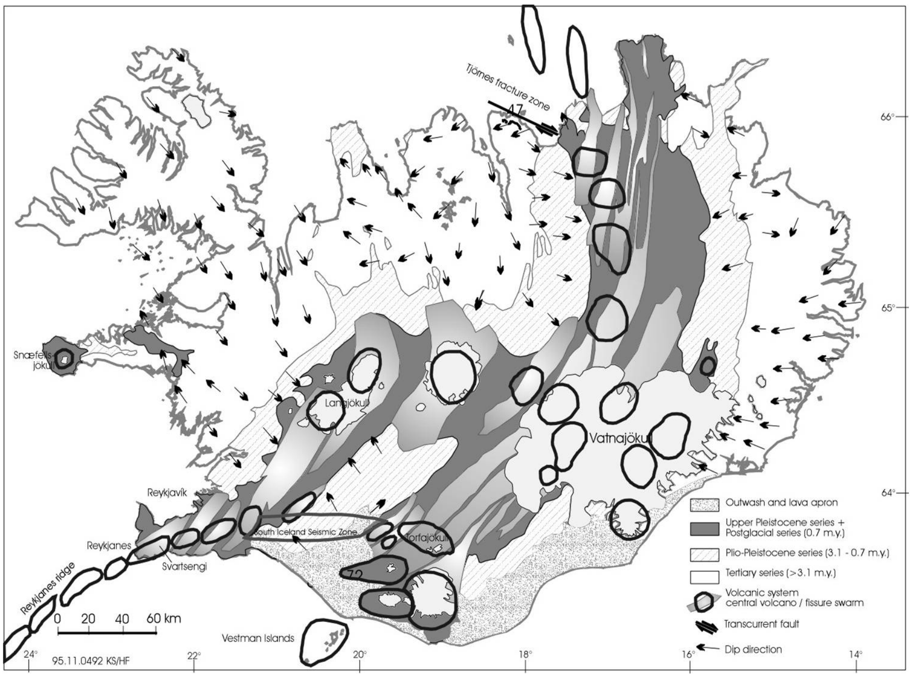

FIGURE 1: A simplified geological map of Iceland showing the volcanic zones, fissure swarms and central volcanoes (Saemundsson, 1979)

2.2 The Hengill high-temperature area

Nesjavellir and Hellisheidi are two production fields located 20-30 km southeast of Reykjavik within the Hengill geothermal region, one of the largest high-temperature geothermal areas in the country; these, along with two other fields, have proven to be suitable for energy production. In 1990, large scale utilisation of geothermal resources started when Reykjavík Energy commissioned a 100 MWt hot water plant at Nesjavellir, north of Mount Hengill, for space heating for the city of Reykjavík and surrounding communities. In 1998, a power plant of 60 MWe opened at Nesjavellir. Gradually, by the end of 2009, the production was expanded to a capacity of 120 MWe. In 2006, the first phase of the Hellisheidi power plant was built and operated with an installed capacity of 90 MWe. An expansion of the Hellisheidi plant occurred during 2007 (33 MWe) and 2008 (90 MWe) and the plant is now generating a total of 213 MWe. Currently, the total installed power production capacity in the Hengill geothermal area is 333 MWe (Árnason et. al., 2010). Fifty seven production and exploration wells have been drilled to date as well as sixteen reinjection wells. All of the wells were drilled by Jardboranir, Ltd, the main drilling company in Iceland. The wells at Hellisheidi are predominantly directional and range in measured depth from around 800 m to more than 3000 m (Figure 2). HE-52, the well explored in this study, is directional and is located near Kolvidarhóll in the western part of the Hellisheidi field (Helgadóttir, et al., 2010).

2.3 Geological and tectonic setting of Hengill area

The Hengill central volcano is located in the middle of the southwestern volcanic zone about 25 km east of Reykjavik city. The area consists of a triple junction where two active rift zones (the Reykjanes Peninsula volcanic zone and the Western volcanic zone) meet a seismically active transform zone (the South Iceland seismic zone). This volcano consists mainly of hyaloclastite formations (sub-glacial) which mostly accumulate in the surrounding lowlands, interrupted by interglacial lava successions. The Hellisheidi high-temperature field is part of the 110 km^2 low

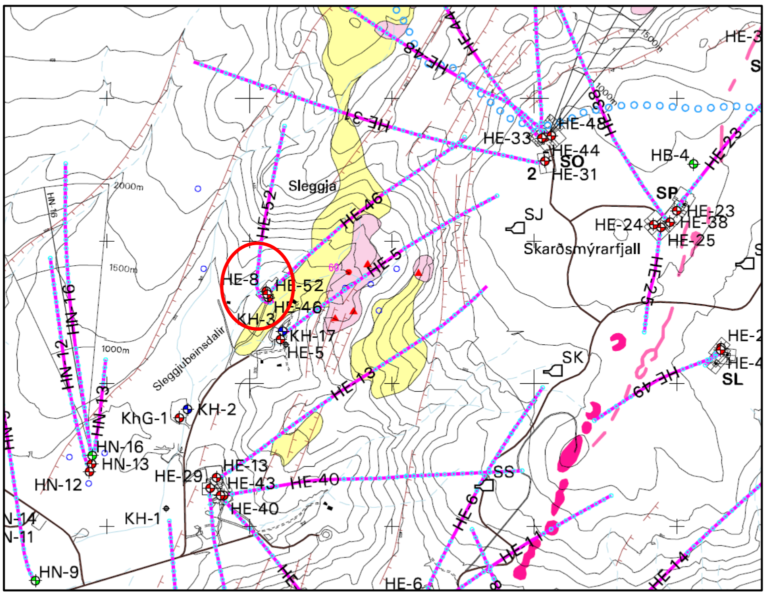

FIGURE 2: The western part of the Hellisheidi geothermal field and the location of well HE-52 with horizontal deviation

resistivity anomaly of the Hengill central volcano and is situated in its southern sector (Árnason et al., 2010; Helgadóttir et al., 2010).

NE-SW striking fractures and fault zones are dominant in the Hengill system. Some of the fractures in the area are intersected by easterly striking features which may affect the permeability of the Hellisheidi field (Hardarson et al., 2007). Major up- and outflow zones in the field are largely related to volcanic fissures of 5 and 2 thousand years of age (e.g. Saemundsson 1995, Björnsson 2004, and Franzson et al., 2005). These fissures have been one of the two main drilling targets in the Hellisheidi field. The second target focuses on large NE-SW fault structures at the western boundary of the Hengill graben which serve as major permeable zones of the hydrothermal system (Franzson et al., 2005). The location of reinjection wells have also been chosen from such targets in the area.

2.4 Geophysical studies in Hengill area

Resistivity measurements were carried out in the area in the 1970s and 1980s, and included methods such as DC-resistivity using Schlumberger and dipole-dipole soundings, aeromagnetic, Bouguer gravity and seismic surveys. In 1986 a detailed DC resistivity survey was done which delineated a 110 km^2 low-resistivity area at 200 m b.s.l. and furthermore showed a negative and transverse magnetic anomaly coherent with the most thermally active grounds. The anomaly is assumed to be related to a highly conductive layer, and the signal is presumably caused by high porosity, high temperature and ionic conduction in highly thermally altered rocks. Figure 3 shows that all surface manifestations in the Hengill area are located within the boundaries of the low-resistivity anomaly. The TEM resistivity survey conducted in the Hengill and Ölkelduháls areas revealed an extensive low-resistivity layer delineating a geothermal system with increasing resistivity below the low-

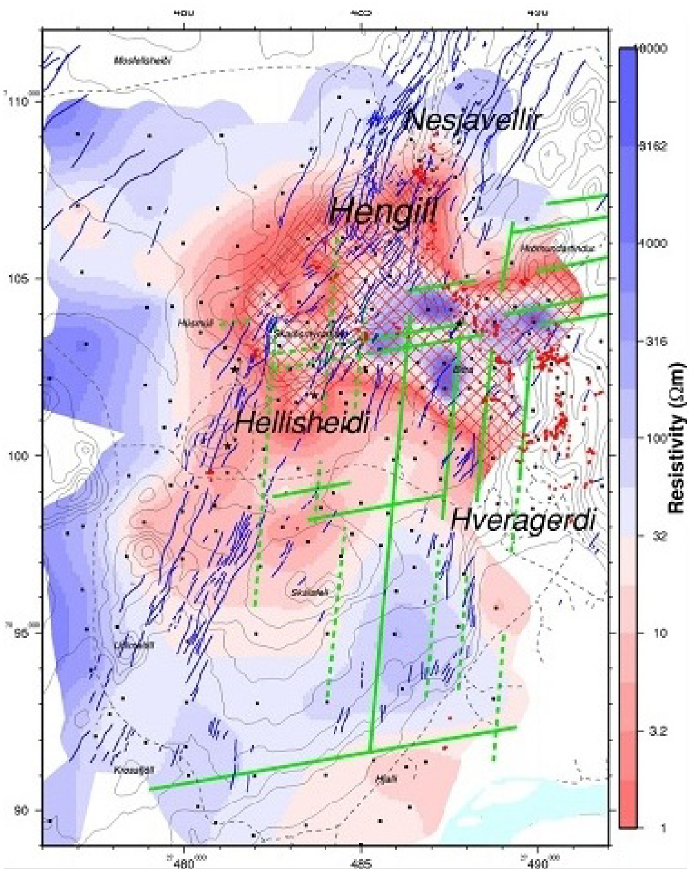

FIGURE 3: Resistivity map at 200 m b.s.l. based on TEM measurements in the Hengill geothermal area (Árnason and Magnússon, 2001)

resistivity layer. Interpretation of the higher resistivity signal was based upon the dominant alteration minerals from low-temperature clays (smectite and mixed-layer clays) to the formation of chlorite and less conductive alteration assemblages (Gebrehiwot, 2010).

3. BOREHOLE GEOLOGY OF WELL HE-52

3.1 Drilling of well HE-52

Well HE-52 (known as HE-8b prior to drilling) is a directional production well with a total depth of 2516 m. The drill site is located 309 m above sea level. The well platform is located at coordinates ISNET93: X=38066, 42E Y= 396301, 77W Z=309.30 (drill site). Well HE-52 was the third well drilled on the HE-8 drill site on Hellisheidi near Kolvidarhóll in 2009. It was drilled as a directional well and deviated northwards (N) to reach the high-temperature reservoir at the root of Skardsmýrarfjall Mountain north of well HE-5. To avoid intersecting HE-46 on the same drill pad, it was decided to start kick-off at 400 m, which is a bit deeper than usual, direct it first to the west and then to the north. The 2.5°/30 m inclination build-up was used up to 25° from vertical. Permeability in this area is mostly believed to be related to faults in the western part of the Hengill-graben. Below are brief descriptions of the well design and drilling process.

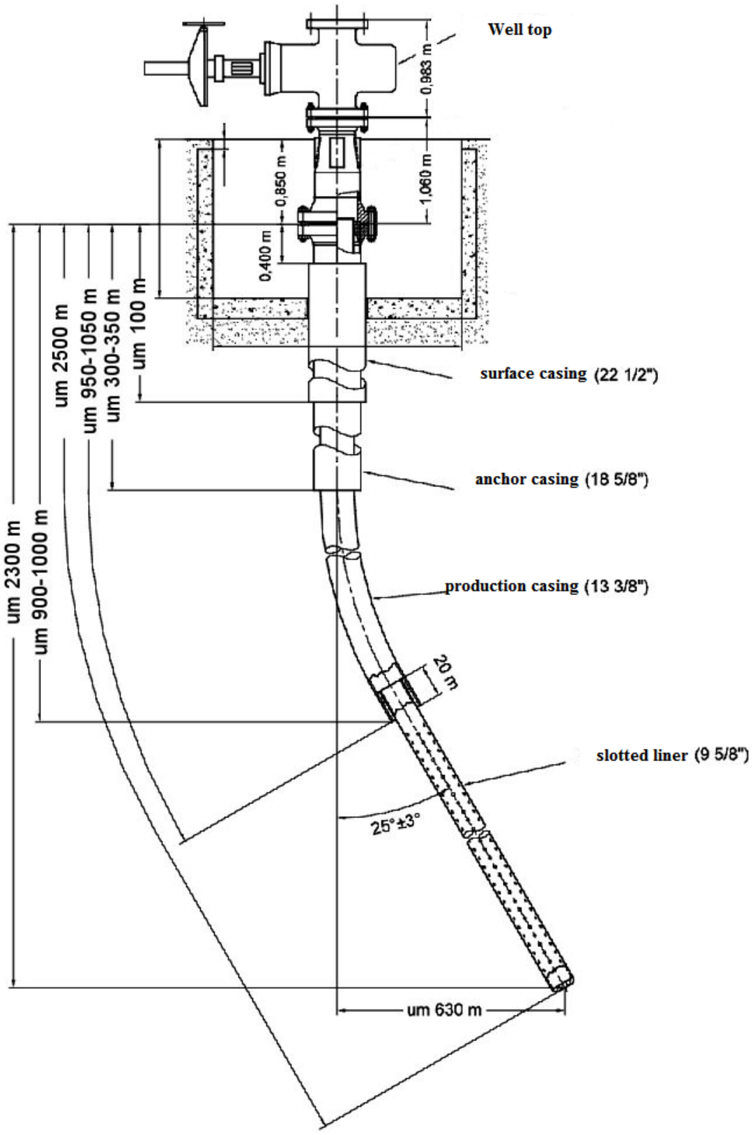

FIGURE 4: Schematic design of well HE-52 (Courtesy of Mannvit Eng.)

The well design of HE-52 is shown in Figure 4 and the drilling progress in Figure 5. According to the design, drilling was carried out in four stages: the pre-drilling stage down to 90-100 m; the first stage down to 300-350 m; the second stage down to 950-1050 m; and the third stage down to about 2500 m. The pre-drilling stage was done in March 2009 using a smaller drill rig to 85 m with a 26" drillbit and a 22½" casing down to 83 m. After that, drilling was continued with a large drill rig, Geysir. The first stage was drilled from 85 to 371 m using a 21" drillbit and was cased with 18⅝" casing. The second stage was drilled to 897 m with a 17½" drillbit. The well was cased using production casing sized 13⅜" cemented down to 896 m. The final stage, or the production stage, was drilled to 2516 m using a 12¼″ drillbit. A 9⅝" slotted liner was hung to 2511 m. Drilling mud was used during the first two stages of drilling but aerated water was used during the drilling of the production part. The drilling and completion of HE-52 took a total of 47 days, shown in Figure 5.

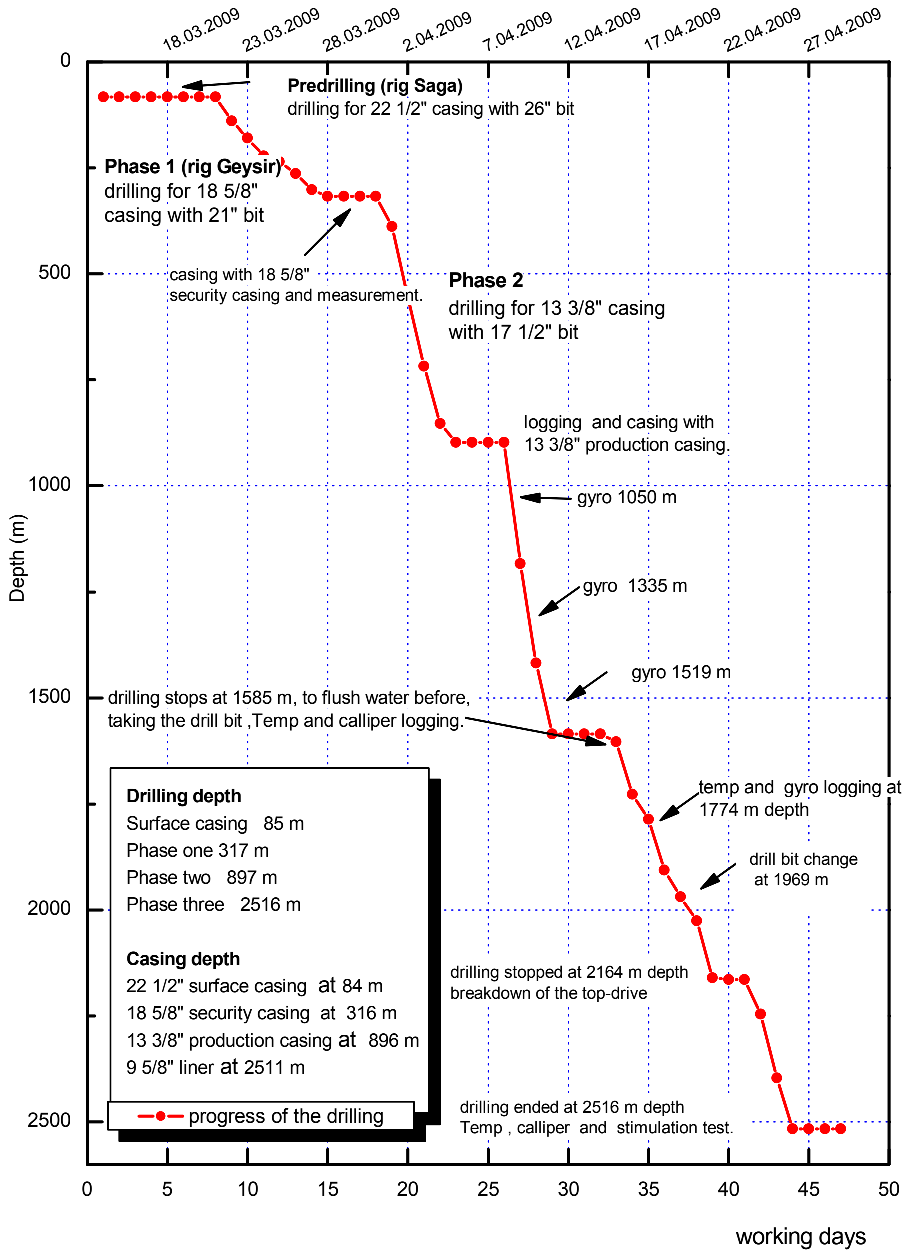

FIGURE 5: Drilling process of well HE-52

The drilling process started by the pre-drilling of well HE-52 on the 7th of March, which was the fourth workday of the project. The drill reached the bedrock at 16 m depth. On the 9th of March, drilling was stopped at a depth of 85 m. The well was flushed with water to get rid of cuttings from the bottom of the well. The first stage of drilling (anchor casing) started on the 21st of March, the 8th day of the project. The second stage (production casing) started on the night of the 30th of March. Since the alteration was quite high and the condition of the surrounding wells was well known, it was decided to stop drilling at a depth of 897 m, the final depth of the second stage. Drilling of the third stage (production part) started on the 8th of April and stopped in the afternoon on the 25th of April at 2516 m depth (Figure 5).

3.2 Stratigraphy

The stratigraphy of well HE-52 in the uppermost 1000 m, as shown in Figures 6 and 7, is divided into alternating sequences of hyaloclastite, lava series and minor sedimentary basaltic tuff sequences. These are subdivided into five hyaloclastite formations, three lava series and one layer of reworked basaltic tuff (sedimentary). The hyaloclastite formations are subdivided into:

1. Pillow lavas or glassy basalts that are partially crystallized with minor amounts of volcanic glass;
2. Basaltic breccias, which is characterised by a mixture of crystallized basalt and volcanic glass;
3. Basaltic tuff which is predominantly volcanic glass;
4. The lava series are classified into two fine- to medium-grained textures.

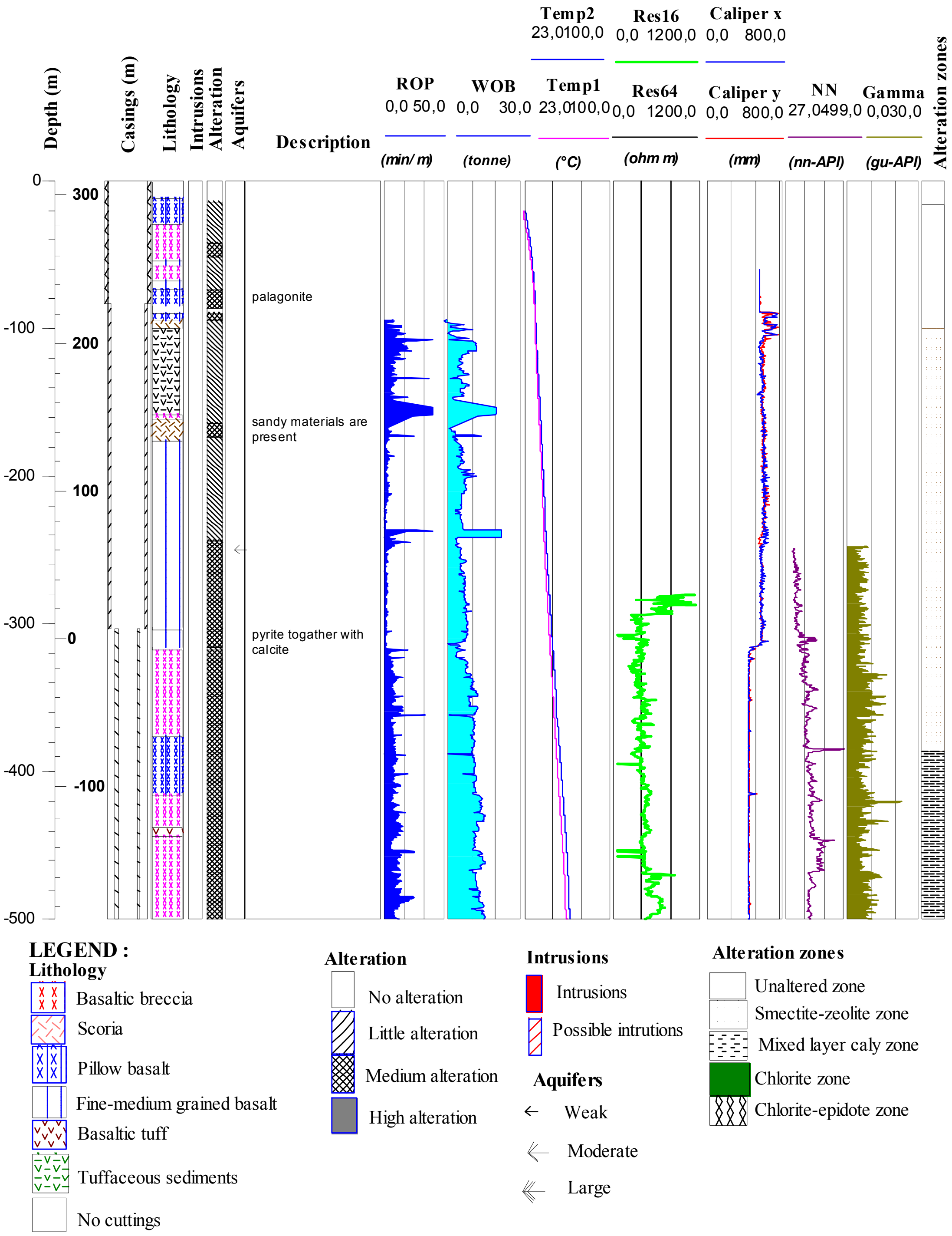

FIGURE 6: Simplified stratigraphic section and geophysical logs (0-500 m) in well HE-52

The porphyritic / aphyric texture of the rock was used to distinguish between the volcanic formations. Minor intrusions were recognized by their fresh and oxidized nature compared to the surrounding rocks. The stratigraphic descriptions are based on binocular microscope (cuttings) analysis and petrographic microscope (thin sections) analysis.

Hyaloclastite I (0-52 m): It is divided into two sub-units, a thin unit of pillow basalt (<30 m) and a unit of basaltic breccia (30-52 m). The unit is best described as a fresh and vesicular basalt with some oxidation and minor alteration. The rock consists of plagioclase porphyres, and crystallized and glassy

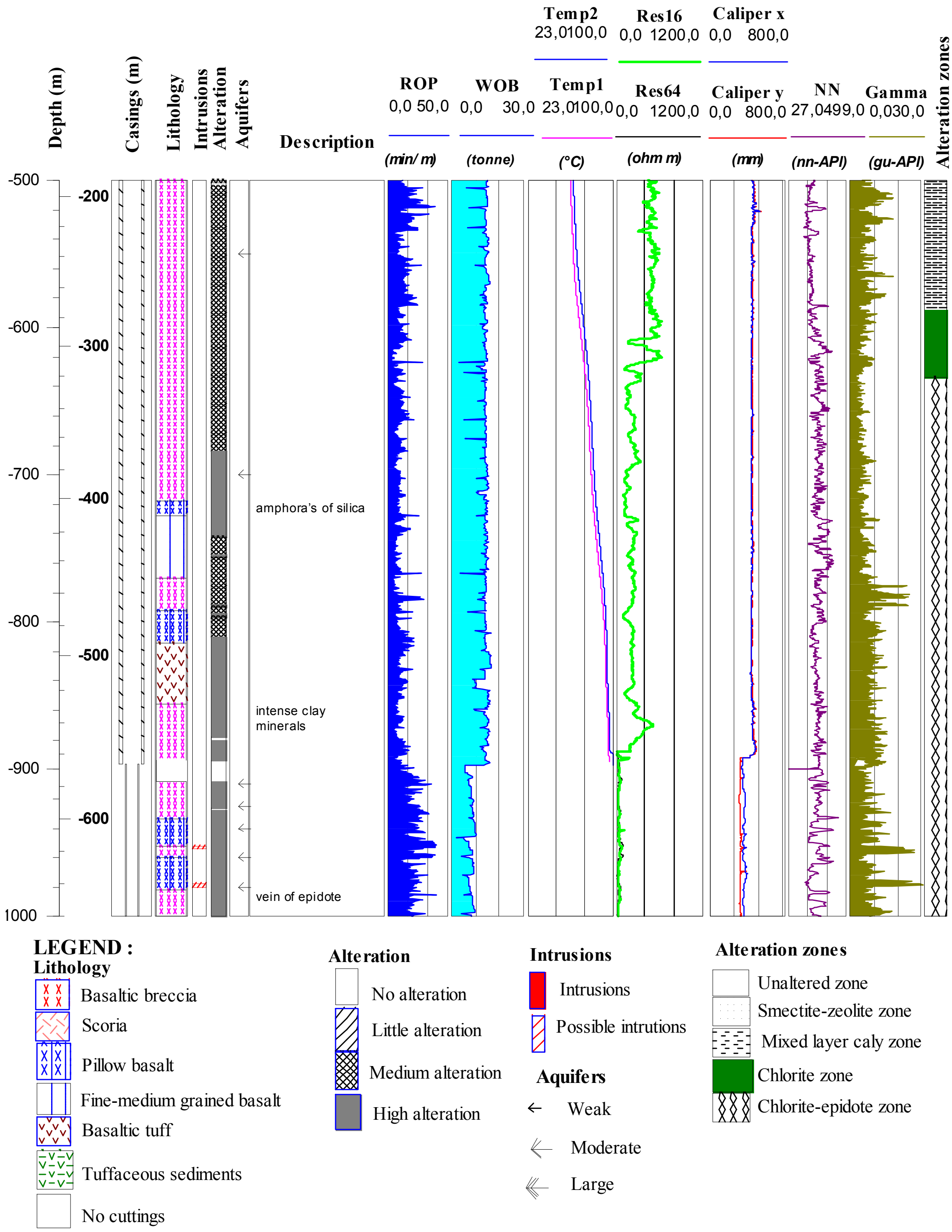

FIGURE 7: Simplified stratigraphic section and geophysical logs (500-1000 m depth) in well HE-52

fragments. The basaltic breccia observed has slight alteration with clay minerals and opal as vesicle fillings.

Lava series I (52-74 m): Consists of two thin layers of fine- to medium-grained basalt with alternating layers of basaltic breccia. The composition is probably olivine tholeiite deduced by the abundant olivine crystals in the matrix.

Hyaloclastite II (74-176 m): Is composed of three units, the upper one being pillow basalt underlain by a 25 m thick scoria unit and lastly some 60 m thick reworked tuff unit. In general, this formation has a gray alteration colour and porous unfilled voids. The first appearances of limonite, pyrite and smectite were observed at this depth interval.

Lava series II (176-318 m): Consists of individual fine- to medium-grained basaltic lava flows. The primary minerals are pyroxene, plagioclase and opaques with gray to brownish colour of moderate alteration. The presence of calcite and pyrite infers the proximity of the geothermal system. Veins were found containing calcite and clay minerals. The alteration sequence observed was fine-grained clay as linings in vesicles, followed by scolecite and stilbite and lastly calcite.

Hyaloclastite III (318-730 m): The formation of this unit is alternating layers of basaltic breccia and glassy basalt. The thickness of the three layers of breccias is 360 m in total, while the sequence of two pillow basalt layers total 40 m. Three layers of basaltic breccias were encountered at 318-378, 416-440 and 446-718 m. The first appearance of laumontite was found at 358 m and extended to the end of the uppermost 1000 m of the well but seemed, in places, to be partially altered by the high-temperature minerals quartz and epidote. Replacement of plagioclase by either calcite or clay minerals was observed while pyroxene seemed to resist alteration. The layers of glassy basalt or pillow basalt were intersected at depths of 378-416 and 718-728 m. The colour of the alteration is a gray to brownish colour. The main secondary minerals are smectite, pyrite, heulandite, epidote, opal and magnetite. The representative alteration sequence is fine-grained clay → laumontite, laumontite → quartz, and calcite → quartz.

Lava series III (730-770 m): It is 42 m thick and composed of fine- to medium-grained plagioclase porphyritic basalt. Prominent occurrence of veins filled with calcite or clay and moderate to high alteration intensity was observed in this interval. Alteration minerals such as epidote, wairakite, prehnite and quartz were present as fillings in voids. Clay alteration was observed in plagioclase and pyroxene.

Hyaloclastite IV (770 – 896 m): Four sub-units were recognized totalling 124 m:

1. Basaltic breccias from 772 to 790 m;
2. Glassy basalt from 790 to 814 m;
3. Basaltic tuff from 816 to 856 m;
4. Basaltic breccias again.

The alteration assemblage in the unit included wairakite (first appearance), laumontite, albite and epidote with moderate to high alteration intensity. Plagioclase was highly altered by calcite and clay while opaques and pyroxene were apparently unaffected by alteration. The formation has a texture of porphyritic equi-granular fragments in an altered glassy matrix. Vesicle fillings were common, mostly calcite, pyrite and chlorite. The representative alteration sequence is chalcedony → chlorite, calcite → chlorite, and laumontite → epidote.

896 to 908 m. No cuttings were collected.

Hyaloclastite V (908-1000 m): This series showed alternating layers of pillow basalt and basaltic breccia. The entire sequence has a total thickness of about 92 m and the alteration intensity is similar as in the sequence described above. A sequence of three layers of basaltic breccias is 52 m thick, and two pillow basalt units are 40 m thick. The three layers of basaltic breccias were intersected at depths of 908-934, 952-960 and 982-1000 m. Chlorite, pyrite, epidote, laumontite, albite, wairakite, quartz, calcite, heulandite and wollastonite (first appearance at 922 m) were the secondary minerals which characterised the formation. Since laumontite and other zeolites are sensitive to temperature, they were partially to totally altered to epidote, wairakite and quartz. The two layers of pillow basalts were encountered at 936-952 m and 962-982 m depth. The upper one had a fine-grained texture with weak alteration intensity; the colour indicated relatively fresh rock compared with the surrounding rocks, which seem to be basaltic dykes, inferred in two intervals. An appearance of wairakite, epidote and laumontite was noted. The lower layer had chalcopyrite crystals that had lost its cubic shape (amorphous). Epidote veins were present as well. The alteration sequence seen was wollastonite → epidote and chlorite →calcite.

3.3 Intrusions

Intrusions are defined as a magma which moves from below into cracks in the crust and consolidates there. They are mostly characterised by their massive, compact nature, coarse-grained texture and as having relatively low alteration compared to the surrounding rock. Also, they can sometimes be identified by the oxidation adjacent to the intrusion which probably reflects a heating effect from the magma. High peak values in neutron-neutron and resistivity logs are good indicators of intrusions (Franzson et al., 2005). In the first 900 m of well HE-52, hardly any intrusions were encountered but two possible intrusions were found at 952 m and 978 m depth. Both of them are fresh, fine- to medium-grained basalt and are minor intrusions of about 2 m apparent thickness. The host rock is highly altered compared to the less altered dyke. The intrusions were marked by high peak values in neutron-neutron and low resistivity logs. Veins were also present at this depth.

3.4 Geophysical logs

The borehole logging programme in well HE-52 included temperature, calliper, cement bond, gamma ray, neutron-neutron and resistivity logs, all very useful in interpreting various geophysical properties in the well. These geophysical logs are used during and after drilling to monitor the performance and operation of the drilling and to obtain information about the condition of the reservoir. Geophysical logs are shown in Figures 6 and 7 and described below:

Temperature logs: The purpose of these logs is to locate aquifers and examine the temperature conditions in the well. These logs are often run during and after the completion of drilling. However, the temperature of the well during drilling is different from the formation temperature mainly because of the cooling (water or mud circulation) in the well. Temperature logs still give very valuable information on well and reservoir conditions. Feed zones and blow-out risks are located and evaluated by temperature logs (Steingrímsson and Gudmundsson, 2005).

Calliper log: The main purpose of a calliper log is to measure the diameter of the well and locate the zones of soft formation and cavities and is used in order to estimate the cement volume necessary to fill up the cavity between the casing and the formation. Some cavities or washout zones were located at the interval of 92-102 m in well HE-52.

Gamma ray log: This log is sensitive to radioactive isotopes within the rock. In Icelandic volcanic rocks, gamma ray radioactivity is related to the quantity of SiO_2 in the rock. According to Stefánsson et al. (1982), geochemical evidence supports this correlation, as the content of radioactive isotopes increases when going from basic to acidic igneous rock.

Neutron-neutron log: Variations in the Neutron-neutron log depend on the quantity of hydrogen in the formation. Low values usually refer to the water content in the formation which is the major source of hydrogen. The water content is an indicator of porosity or alteration (Stefánsson and Steingrímsson, 1990). High peaks, which are indicative of low water content and relatively fresh rock, are found at around 915, 960, and 980 m depth intervals in well HE-52.

Resistivity log: This log reflects to some extent the rock porosity and hydrothermal alteration and can often be used in differentiating between rock types and variable alteration. It should correlate with the surface electrical TEM and MT surveys. In well HE-52 it shows relatively low values at 570, 700, 783, 915 and 960 m depth intervals, indicating highly porous rocks and/or highly altered rocks, which, in turn, may infer permeable structures.

4. ALTERATION AND HYDROTHERMAL MINERALS

4.1 Alteration of primary mineral assemblages

The primary constituents found in well HE-52 are volcanic glass, olivine, pyroxene, plagioclase and opaque minerals (magnetite and ilmenite). Like elsewhere, primary minerals are unstable and therefore tend to alter into minerals that are either stable or at least meta-stable in the geothermal environment. The interaction between the wall rocks and the hydrothermal fluids is the main factor that leads to the replacement of hydrothermal minerals while the process of fluid circulation affects mineral deposition in veins and cavities (Browne, 1978). The degree of alteration of primary phases varies depending on formation permeability, and abundance and grain size of primary minerals. Table 1 shows the main primary minerals found in well HE-52, arranged according to increasing susceptibility to hydrothermal alteration.

TABLE 1: Alteration of primary minerals in well HE-52

Order of replacement		Primary phases	Alteration products
↓	Susceptibility	Volcanic glass	Clay, calcite
		Olivine	Clay, chlorite, calcite, quartz
		Plagioclase	Albite, calcite, clay, zeolite
		Pyroxene	Clay
		Opaque	Sphene

Volcanic glass is an amorphous (uncrystallized) product formed during the quenching of magma. Volcanic glass occurs in this well as matrix material which shows highly vitreous lustre and has good conchoidal fractures. Clay and calcite were the common alteration minerals of glass. The first replacement of glass to calcite occurred at 40 m and to clay at 100 m.

Olivine is one of the primary minerals formed in basaltic rocks (olivine tholeiite) and is very susceptible to alteration. In thin section it is distinguished by its high birefringence, distinctive irregular fracture pattern, and lack of cleavage. Along its fractures the alteration products usually are clay, chlorite and quartz. Olivine occurs at 242 m depth in well HE-52 and is there replaced by calcite dominated by the irregular fracture pattern. It occurs as part of the matrix in microcrystalline size and rarely as phenocrysts.

Plagioclase is a major constituent mineral in the Earth's crust and is an important diagnostic tool in petrology for identifying the composition, origin and evolution of igneous rocks. It is easily identified in the binocular microscope by its rod shape and by the twinning extinction angle in thin section under a polarizing microscope. The extinction angle is an optical characteristic and varies from labradorite to albite. In well HE-52 the plagioclase progressively alters as temperature increases and is finally replaced by albite, calcite and occasionally by wairakite and chlorite. It has euhedral to subhedral forms. It is present as phenocrysts in the first two hundred meters of the well and otherwise as an integral part of the groundmass. It is observed in the first few cutting samples under the binocular microscope. The plagioclase starts to alter to albite below about 660 m. Alteration to clay, calcite and zeolite was also frequently observed.

Pyroxene is, along with plagioclase, the most common mineral in basalt. In well HE-52 it was seen both as phenocrysts and in groundmass. Pyroxene is euhedral and subhedral in form and is relatively resistant to alteration; it was never seen totally altered in this well. It differs from olivine by the presence of better cleavage and inclined extinction. Pyroxene is observed to alter to clay and calcite at higher temperatures, first seen at a depth of 242 m in this well.

Opaque minerals: These minerals (magnetite and ilmenite) are common in basaltic rocks. They are generally resistant to alteration but when they do alter, the main product is sphene (titanite). Opaques were observed to alter to sphene in this well below 918 m depth.

4.2 Alteration mineralogy

The distribution of hydrothermal minerals in well HE-52 is mainly identified in binocular and petrographic microscopes, and by X-ray diffraction. The minerals found are: limonite, calcite, pyrite, different types of clays, zeolites (heulandite, thomsonite, stilbite, scolecite/mesolite, laumontite, analcime, chabasite), chalcedony, quartz, albite, sphene, prehnite, epidote, wairakite, wollastonite and opal. A brief summary of the alteration minerals is described below regarding their existence in the well and their temperature range (Figure 8).

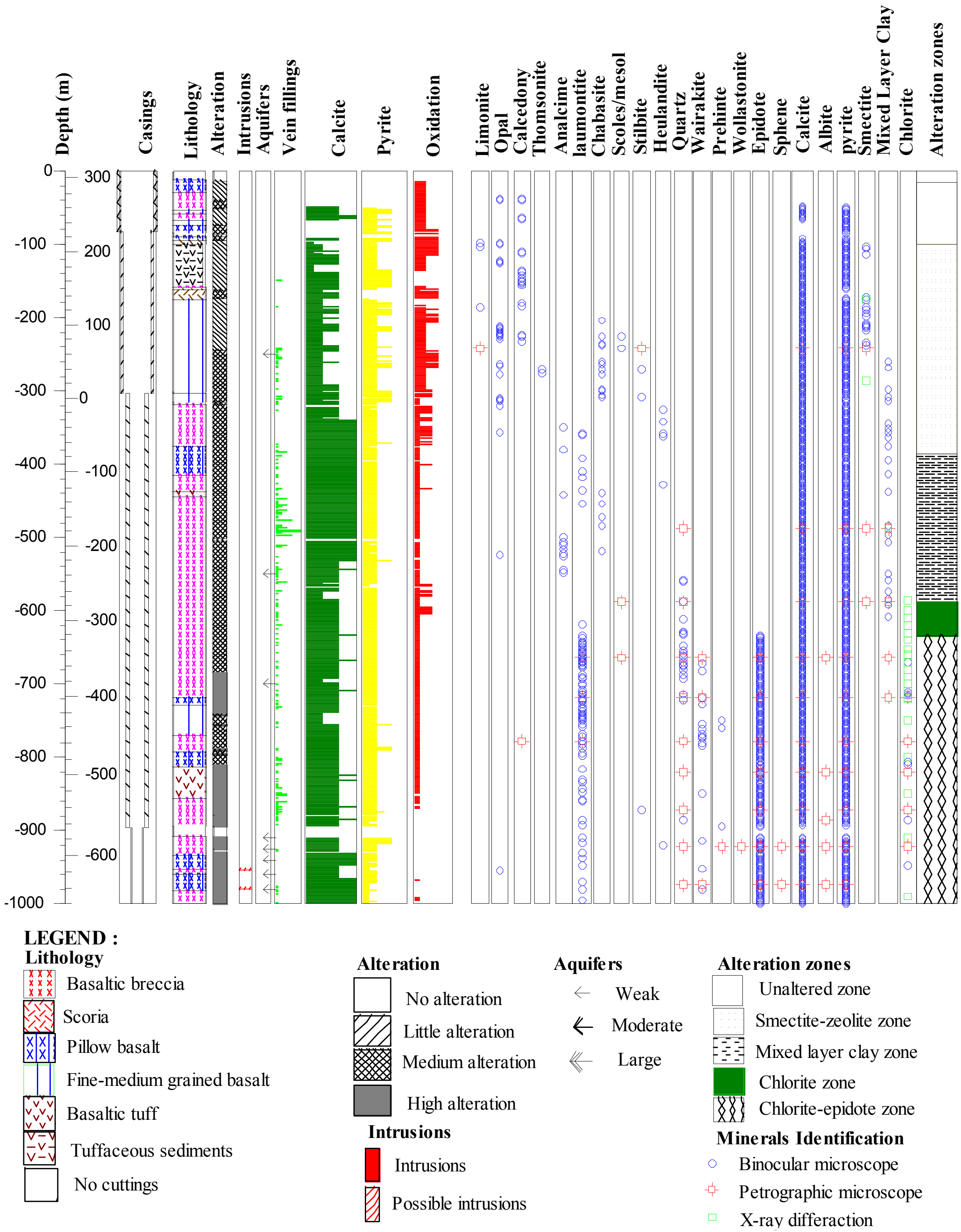

FIGURE 8: Distribution of hydrothermal alteration minerals in the upper 1000 m of well HE-52

Limonite is one of the minerals that form in the cold groundwater system above the geothermal system. It is a spherical mineral in shape and reddish in colour. It occurs from the near surface down to about 250 m.

Zeolites form by the chemical reactions between the different types of volcanic rocks and alkaline groundwater. The temperature of formation of these minerals, with the exception of wairakite, ranges from about 30°C to about 200°C. They include chabasite, thomsonite, scolecite, mesolite, stilbite laumontite. (Kristmannsdóttir and Tómasson, 1978; Kristmannsdóttir, 1979). The following zeolites occurred in this well:

Heulandite was observed in the cuttings by using the binocular microscope and was found between depths of 340 and 420 m. It has a colourless or white colour and a platy tabular sheet-like appearance. Crystals are monoclinic. They may have a characteristic coffin-shaped habit and perfect cleavage parallel to the plane of symmetry.

Thomsonite is a member of the zeolite group with radiating crystals. Spherical aggregates filling vesicles were seen through the binocular microscope as a whitish mineral, first identified at a depth of 280 m. Thomsonite crystallizes at low temperatures from about 30°C and appears in vesicles together with other low temperature minerals.

Stilbite was associated with heulandite in this well. It was characterised in thin section by a perfect cleavage parallel to the plane of symmetry and was found at a relatively shallow depth around 223 m and in a cutting sample at 275 m. The crystals are white and transparent to translucent, either colourless or white. It is an indicator of a minimum formation temperature of about 80°C.

Scolecite/Mesolite: Scolecite is structurally similar to mesolite and is characterised by a radial texture. These minerals are taken as a group as they form at a similar temperature range from about 90°C. They were observed in the binocular microscope and in thin sections at the interval of 220-680 m. These minerals usually precipitate in vesicles as threads or hairs and are colourless and transparent. They occur at similar temperature and depth intervals as other zeolite group minerals such as stilbite, thomsonite and chabasite.

Laumontite has a prismatic and fibrous structure and is mainly found as cavity fillings. It was found in two intervals in well HE-52, 380-480 and 620-1000 m. It occurred in an unstable form in vesicles, subsequently replaced by wairakite, epidote and quartz. According to theory it is unstable below 200°C. When pure, laumontite is colourless or white and transparent. It has perfect cleavage and it is very brittle (easily broken). It is frequently associated with other zeolites.

Analcime is a white, grey, or colourless mineral in cubic crystalline form. It occurs as cavity and vesicle fillings associated with calcite and other zeolites. Analcime has a minimum temperature of about 50°C. Distinguishing analcime from wairakite is difficult in binocular analysis. The occurrence of a mineral with these characteristics analcime in the mixed-layer clay zone would indeed be wairakite rather than analcime as wairakite forms above 200°C, as does mixed-layer clay.

Wairakite is one the calcium analogue of analcime which occurs in a distinctive form. Wairakite is characterised under the petrographic microscope by a very low relief, a dull dark-gray colour and crosshatched twinning. Fluid inclusions in its crystal structure usually give wairakite a typical cloudy look. It was first seen at 660 m depth and became abundant to the bottom of the sampled section of the well. It might have been encountered above, there analyzed as analcime. It precipitates in veins or in the core of vesicles, usually succeeding the higher temperature minerals of epidote, quartz and prehnite but sometimes prior to the appearance of platy calcite. It commonly replaces plagioclase and is observed to replace lower temperature zeolites. Wairakite is the only high-temperature zeolite, forming above 200°C (Saemundsson, and Gunnlaugsson, 2002).

Chabasite is characterised by its trigonal crystal structure with even fractures and typical twinning. These minerals are colourless or white. It is the mineral in the zeolite group with the lowest formation temperature. It is commonly recognized in voids and amygdales below 130 m in well HE-52.

Calcite is a common and widespread mineral filling veins and vesicles in well HE-52. Different shapes occur and it is dominant throughout the well (Figure 8). It is white to colourless in binocular microscope, but transparent to translucent with perfect cleavage in the petrographic microscope. It is easily recognized by its obvious cleavage, extreme birefringence, change of relief with rotation in thin section, and its reaction with weak acid in cuttings. Calcite is associated with pyrite from almost the top down to the bottom of the upper 1000 m of the well. It is relatively difficult to determine the temperature of calcite deposition but as a rule of thumb this mineral disappears at temperatures above 290°C (Franzson, 2000; Kristmannsdóttir, 1979).

Pyrite is a brass yellow, cubic, euhedral mineral readily identified by its colour and shape and occurs below 16 m in this well and continuously until about the end of the uppermost 1000 m. It is associated with calcite along the entire depth of the upper 1000 m of the well HE-52. A quantitative assessment of pyrite is shown in Figure 8. This mineral is sometimes used as a permeability indicator. The temperature range of pyrite is from around 120 to 260°C (Reyes, 2000).

Clay minerals are formed by hydrothermal activity and alteration. Clay minerals are the best tool used in geothermal exploration as temperature indicators (Kristmannsdóttir, 1979). Their characteristics can be identified readily by the binocular and petrographic microscopes and for more confirmation by X-ray diffraction. Clay minerals can be identified by using a binocular microscope but in some cases it may be difficult to distinguish between them. Petrographically these minerals can be distinguished as smectite, mixed-layer clays and chlorite based on their optical characteristics. X- ray diffraction is, however, considered the best overall method to distinguish between the three types of clay minerals. This method is mainly based on mixing the cutting samples with water and shaking them to get the dissolved particles, derived from the whole rock, which are then run in the XRD, giving an overall picture of the composition of the clays present in the rock.

Smectite is the clay mineral with the lowest formation temperature. It is formed from the alteration of glass or primary minerals and also forms directly from water rock interaction precipitating into voids and veins. It is fine grained, greenish to brownish in colour in the cutting and starts to appear at 100 m to 240 m. In thin sections it was identified first at 238 m, has light green colours in plane-polarized light, is slightly pleochroic and is found as vesicular linings and alteration of glass (palagonite). Smectite is an indicator of temperatures lower than 200ºC.

Mixed-layer clays (MLC) are basically an inter-layering of smectite and chlorite (fine grained – coarse grained) indicating temperatures between 200 and 230°C. It was detected through the cuttings and thin section and recognized between 260 and to about 700 m. It shows pleochroism, light to darker green colours in plane-polarized light, and in cross-polarized light shows high order strong yellow to brown colours. It often appears in voids as a coarse-grained clay mineral, coarser than smectite.

Chlorite: Some discrepancy occurred in the identification of the upper boundary of chlorite between binocular microscopy, petrographic microscopy and XRD analysis as is observed in Figure 8. Chlorite was not identified by binocular microscopy analysis until below 800 m, by petrographic analysis below 700 m and the XRD analysis showed the upper boundary to be at about 586 m. The upper boundary of the XRD analyzed chlorite is here used as the zonal boundary, and consequently the lower boundary of the mixed-layer clay zone in spite of the continued occurrence of the MLC below that depth. Chlorite is characterised by fine- to coarse-grained textures, and petrographically chlorite is light greenish in colour in plane polarized light, has a fibrous cleavage and no pleochroism. It is characterised in the microscope by a fine- to coarse-grained radial texture in voids. Chlorite occurs both as a replacement of primary minerals in the rock and as void fillings. Chlorite is an indicator of temperatures exceeding 230°C (Kristmannsdóttir, 1979).

Epidote has a distinctive yellowish to greenish colour in cutting. It displays strong pleochroic green colours in thin sections. It occurs together, as individual grains and crystal intergrowths. It was observed to be associated with quartz and wairakite and chlorite. Epidote is abundant in well HE-52 below 634 m and extends to the bottom of the well. The occurrence of epidote in significant quantities indicates temperature above 240-250ºC (Kristmannsdóttir, 1979). It precipitates as open space fillings in voids in the upper part of the well, and as vein filling in the bottom of the well. It is also found as a partial replacement of plagioclase phenocrysts.

Chalcedony is a cryptocrystalline form of silica aggregates. It is colourless to white and translucent with a waxy lustre. Chalcedony starts to appear at about 120°C (Kristmannsdóttir, 1979). It occurs in thin section as a thin lining inside vesicles. The first appearance was at 25 to about 240 m and may at 240 m be nearer to opaline and recrystallized to quartz at a deeper level.

Sphene/titanite occurs as reddish brown and monoclinic crystals. Sphene has a distinctive high relief, which, combined with the common yellow-brown colour and lozenge-shape cross-section, makes the mineral easy to identify. It was identified occasionally in petrographic microscope at the bottom of the well at 920 m. According to Reyes (2000), the occurrence of sphene indicates weak permeability and porosity in the Philippine geothermal systems.

Albite is a plagioclase feldspar mineral. Its colour is usually pure white in binocular microscope. Albite almost always exhibits crystal twinning often seen as minute parallel striations on the crystal facet. Albite occurs as the product of the alteration process known as albitization, where the calcium rich plagioclase (labradorite) is transformed into albite or sodium rich plagioclase. In thin section, albite can be distinguished from primary plagioclase by the lower refraction index and by the angle of extinction. Albitization was first observed at 664 m as a replacement of plagioclase. Albite alteration of plagioclase starts at temperatures about 220°C (Figure 9).

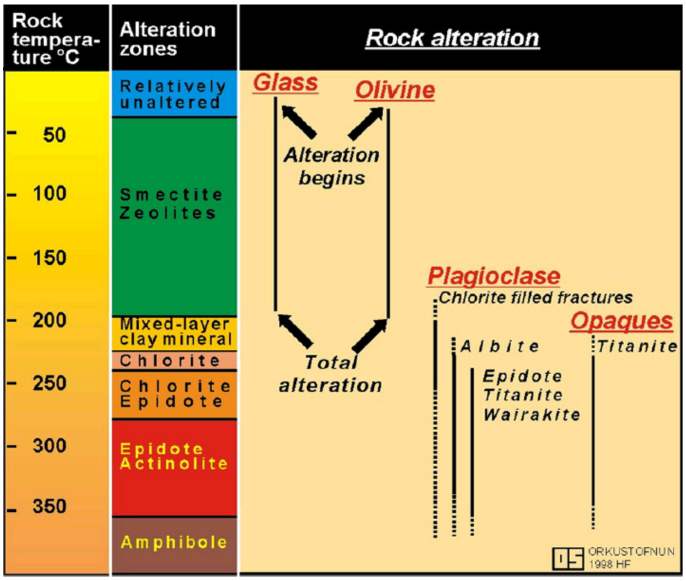

FIGURE 9: Mineral alteration-temperature diagram (Franzson, 1998)

Wollastonite is usually white as radiating, compact and fine fibrous aggregates filling vesicles. Associated minerals include quartz, epidote and calcite. It was first discovered at 900 m in thin section. The first appearance of wollastonite marks a temperature of 270°C and it can be stable to temperatures above 300 °C.

Prehnite is brittle with an uneven fracture, has a vitreous to pearly lustre, and is white to colourless in the binocular microscope. Prehnite occurs mainly as vesicle and vein fillings but also as a replacement of primary minerals. It has a round to nearly spherical shape in binocular microscope but in thin section its strong birefringence can be readily distinguished by a bow tie texture. "The low stability of prehnite is not precise; it appears to be able to form at temperatures above 200°C, and in some instances at about 250°C, and it is present in the geothermal systems to more than 300°C" (Browne, 1978; Saemundsson and Gunnlaugsson, 2002). It was found in association with epidote, quartz and wairakite and was first seen in binocular microscope and thin section below 750 m depth.

Quartz belongs to the trigonal crystal system. It is a colourless to white or cloudy (milky) and transparent to translucent mineral. Quartz occurs either as an alteration product of opal or chalcedony or as a vesicle or vein filling mineral. It is associated with epidote, prehnite, pyrite and calcite (Gebrehiwot, 2010). Low relief, low birefringence and a lack of cleavage or twinning are the main characteristics of quartz in thin section. In well HE-52, this mineral was seen at 500 m and continued to the end of the well. It has a temperature stability of ≥ 180°C. The appearance of euhedral and anhedral crystals of quartz in voids has been seen in both thin sections and the cutting samples. It was seen as a replacement of laumontite in this well.

Opal is deposited at a relatively low temperature and may occur in fissures of almost any kind of rock. Opal ranges from being transparent through white and blue in well HE-52. In thin section it was often found transparent to sub-translucent, as vesicle linings, or cavity fillings. It was found between 40 and 360 m depth, indicating a temperature below 100ºC.

4.3 Sequence of mineral depositions

Hydrothermal mineralisation assemblages are evaluated according to different factors such as temperature, fluid composition, rock types, the interaction between the hydrothermal fluids and the country rock. For well HE-52 the sequence of minerals was studied petrographically in order to deduce the relative time scale of their deposition. The results are summarized in the following sequence and in more detail in Table 2.

fgc > scol > stil > cc > laum > qz > chlo > epi > perh > wol >cc

TABLE 2: Mineral depositional sequence of well HE-52

Depth	**Early**	→									**Later**	**Degree of alteration**	**Type of rock**
242		Fgc									cc	Slight	Fine- to medium-grained basalt
			scole								cc		
			stil								cc		
488		Fgc									cc	Moderate	Breccia
588		Fgc									cc	Moderate	Olivine tholeiite (breccia)
664		Fgc			laum							Moderate	Breccia
					laum		qz						
718					laum		qz					High	Breccia
							qz		chlo		cc		
				cc			qz						
778					laum			epi				Moderate	Breccia
					laum			epi					
	chal								chlo				
820				cc					chlo			High	Olivine tholeiite
872								epi			cc	High	Olivine tholeiite (breccia)
922								epi			cc	High	Breccia
									chlo	Preh			
						wol		epi					
974				cc					chlo			High	Pillows

Explanation: slight = slight alteration, moderate = moderate alteration, high = high alteration, fgc = fine-grained clay, cc = calcite, scole = scolecite, stil = stilbite, laum = laumontite, qz = quartz, chlo = chlorite, epi = epidote, chalc = chalcedony, preh = prehnite, wol = wollastonite

The sequence observed started from low-temperature minerals such as fine-grained clay, usually occurring as linings on vesicle walls that were partially filled with calcite, and at increasing depth entirely filled with calcite. Further down, scolecite started to form at the same time as calcite and stilbite, replacing the already existing calcite. In the deeper parts of the well, higher temperature minerals such as laumontite, quartz, prehnite, chlorite, epidote and wollastonite became dominant. The sequence generally showed that the hydrothermal temperature increased with increasing depth. This was emphasized by the3 presence of laumontite, which is very sensitive to temperature, succeeded by quartz at a depth of 664 m. Quartz and chlorite came in later in the sequence, followed by calcite which is found near the boundary of basaltic breccias and pillow basalt at a depth of 718 m. Further down, because of the high sensitivity to temperature, laumontite became unstable and was succeeded by epidote at 778 m (Figure 10).

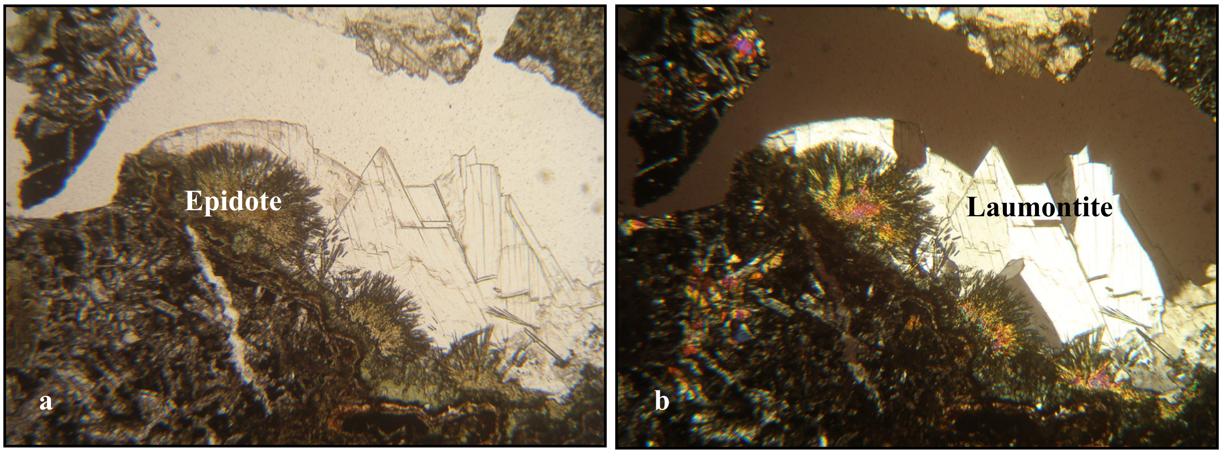

FIGURE 10: a) Epidote on top of b) laumontite in well HE-52, 778 m

At a depth of 778 m, chalcedony precipitated and was succeeded by chlorite which would suggest that the reservoir is heating up with time; see Table 2. Calcite is present in the entire sequence and the presence of it at the end of the high-temperature mineral sequence may imply cooling. At the lower part, the replacement of chlorite by prehnite and the presence of high-temperature minerals in the form of wollastonite overgrowth on epidote were observed at 922 m in well HE-52.

4.4 Vein and vesicle fillings

Veins or vesicles store fluids and are the primary factors that control porosity and permeability of a formation. The lithology of well HE-52 predominantly comprises hyaloclastite formations which are highly porous compared to lava flows. Veins and vesicles become gradually filled with secondary minerals with increasing fluid temperature, and change in fluid composition. In well HE-52, some vesicles were unfilled in the top of the sequence but gradually filled towards higher temperatures and the core of the geothermal system. The first minerals precipitating and starting to fill voids in basalts are calcite and clay minerals. Zeolites start to form at temperatures of about 40°C. The first appearance of zeolite was found in the top part of the well and was associated with clay, chalcedony and calcite. The clays dominated as linings in vesicles. Calcite is found in vesicles all the way to the bottom of the well.

The highest concentration of veins in the upper 1000 m of the well is in the intervals of ~240-316, ~380-740 and ~795-1000 m. The first cluster of vein fillings in this well are predominantly calcite fillings and to a lesser extent fillings by pyrite, opal and clay. The veins are confined within moderately altered fine- to medium-grained basalt from 240 to 316 m depth. The second vein cluster with calcite, clay and pyrite mineralisation is situated within the hyaloclastite, which is moderately to highly altered. This zone is characterised by minor aquifers. The third and deepest interval is on the contact between hyaloclastites (basaltic breccia, glassy basalt and basaltic tuff) and lava flows, where the alteration state ranges from moderate to high. Quartz, epidote, clay, pyrite and calcite are the dominant vein filling minerals observed below a depth of 780 m. Table 3 summarizes descriptions of the veins in well HE-52.

TABLE 3: Mineral deposition in pores and veins

No.	Depth (m)	Mineralization	Host rocks	Degree of alteration	Quantity
1	16-78	––	Glassy basalt, fine- to medium-grained basalt, breccia	Slight	––
2	78-178	cc	Glassy basalt, acidic tuff, scoria	Slight	2
3	178-318	cc, pyrite, opal, clay	Fine- to medium-grained basalt	Slight-moderate	23
4	318-728	cc, clay, pyrite	Breccia, glassy basalt	Moderate-high	86
5	728-770	clay, calcite	Fine- to medium-grained basalt	High-moderate	5
6	770-1000	cc, clay, pyrite, epidote, quartz	Breccia, glassy basalt, basaltic tuff	Moderate-high	46

4.5 Alteration mineral zonation

Examination of the mineralogy of the cuttings for well HE-52 reveals four (temperature-dependant) zones of hydrothermal alteration beneath a zone of unaltered rocks. These zones are characterised by an abundance of particular minerals related to increased temperature and depth. Commonly, minerals used as geothermometers are zeolites, clays and amphiboles (Browne, 1978; 1984). The four hydrothermal alteration zones are:

1. Smectite-zeolite zone,
2. Mixed-layer clay zone,
3. Chlorite zone, and
4. Chlorite-epidote zone.

The top of each alteration zone is defined by the depth of first appearance of the mineral. The result of the clay mineral analysis and binocular microscope analysis are used to support the evidence of the four alteration zones. The boundary is inferred mainly from clay mineral analysis.

Unaltered zone
Based on the assumption that a cold groundwater condition must have prevailed prior to hydrothermal and geothermal activity at the Hengill central volcano, this zone is composed of fresh rocks with no signature of alteration. The only secondary minerals present in this zone are limonite (oxidation), carbonates (mainly spherical "calcite") and opal which are related to a reaction between the rocks and the groundwater.

Smectite-zeolite zone
The first low-temperature alteration zone occurs below the unaltered zone, and is characterised by the presence of zeolites and low-temperature clays (smectite). The upper boundary of this zone is represented by the first appearance of smectite at 100 m in well HE-52. The zeolites present as secondary minerals in this zone are stilbite, scolesite/mesolite, chabasite and thomsonite. The XRD has shown that smectite is dominant to 286 m, which indicates that the temperature in this zone is below 200°C. The overlaying fine-grained lava 220 m is still relatively fresh and unaltered. Towards the bottom part of this zone, zeolites and smectites start to disappear and mixed-layer clays become more common.

Mixed-layer clay zone
The depth 386 m marks the top boundary of the mixed-layer clay zone. Mixed-layer clays are materials of intermediate products between the clay minerals smectite and chlorite, in which different

kinds of clay layers alternate with each other. This zone is characterised by the presence of analcime (or maybe the higher temperature variety, wairakite), heulandite and mixed-layer clays. The zeolites show indications of instability and alteration into quartz and wairakite. Calcite and pyrite continue to become more abundant in this zone. Binocular analysis shows dark green coarse-grained clays down to the upper boundary of the chlorite zone at 586 m. The range of the alteration temperature in this zone is 200-230°C.

Chlorite zone
The first appearance of coarse-grained chlorite at 586 m defines the top boundary of the high-temperature zone (chlorite zone). Coarse-grained chlorite appeared down to 634 m. Through XRD clay analysis, it was observed that this chlorite mineral was considered to be of an unstable variety due to the unchanged peaks 7 -7.2 Å for untreated and glycolated samples and that it collapsed completely after being heated to 550°C (see Appendix II). Pyrite and calcite were still common together with the assemblage of analcime and quartz. 230°C is the temperature estimated for the first appearance of chlorite (Browne, 1978; Franzson, 1987).

Chlorite-epidote zone
The top of the chlorite-epidote zone is defined by the first appearance of epidote at a depth of 634 m. Epidote continues to be present to the bottom of the well. Epidote occurs either as a replacement product or as an alteration product of primary minerals. The XRD analyses and interpretations show that chlorite has an unstable behaviour and never transforms into stable chlorite below this depth (see Appendix II). The mineral assemblage of quartz, analcime (wairakite), calcite and pyrite are still present. In addition, wairakite, prehnite and albite are witnessed as secondary minerals. Calcite and epidote are the main vein fillings. The temperature in this zone is above 250°C.

4.6 Aquifers and feed zones

Aquifers are underground layers of water-bearing permeable rock or unconsolidated materials. The main forces driving the movement of groundwater are permeability, porosity, temperature and pressure of the rock formation, natural recharge, and the hydraulic gradient. In volcanic rocks fractures, faults and joints are the main forces that control groundwater movement. Wire line well logging, especially temperature logging, is applied to locate aquifers and evaluate geological structures in the vicinity of the well. Temperature and pressure logs with information on circulation losses/gains during drilling, alteration and geophysical logs are the main sources for data used to locate aquifers (Franzson, 1998). Temperature logs, however, do not reveal the true formation temperature because of the cooling of the well by water or mud circulation during the drilling process, but the logs can still give us valuable information about aquifers and reservoir. Aquifers were identified from records of sudden change in the rate of penetration, intensity of alteration, and anomalous geophysical logs such as calliper, resistivity, neutron-neutron, and mainly temperature logs during drilling, heating up and discharging. Examination of rock cuttings is a direct indicative method to determine the locations of aquifers. A high penetration rate is sometimes associated with high permeability. Total loss of circulation is, as well, associated with highly permeable formations. It must, however, be noted that mud is used during drilling for safety and production casings. The mud blocks most permeable structures, making it difficult to distinguish aquifers from circulation losses or through temperature logs. The existence of a high intensity of alteration minerals and an abundance of vein networks are good indicators of aquifers and feed points. The abundance of quartz, anhydrite, pyrite, epidote, and the presence of adularia are good indicators of permeable zones (Franzson, 1998; and pers com). However, some other alteration minerals can be attributed to low permeable zones; these are minerals such as prehnite, and large quantities of laumontite and titanite (Reyes, 2000).

Seven feed zones were encountered in the uppermost 1000 m of well HE-52. These zones are categorized as weak aquifers according to the correlation of the characteristics of the formations' lithology, intensity of alteration, abundance of veins and vesicles, the stratigraphic boundary and the geophysical logs. There are three feed zones above the production part and four feed zones within the production part. A brief description of each aquifer is given below:

Aquifer 1 is a weak aquifer located at 250 m depth. It is associated with a fine-grained basaltic lava flow. The rocks at this depth have a moderate degree of alteration and large concentrations of veins. No circulation losses were recorded at this interval, which may be due to the fact that mud was used during drilling. Several temperature logs, from the end of drilling to the heating up period, show a slight temperature minimum, indicating that the circulation fluid may have percolated into the rock formation and cooled it, which leads to slower heating compared to the tighter rock above and below (Figures 11). A sudden change of penetration rates was observed at this depth.

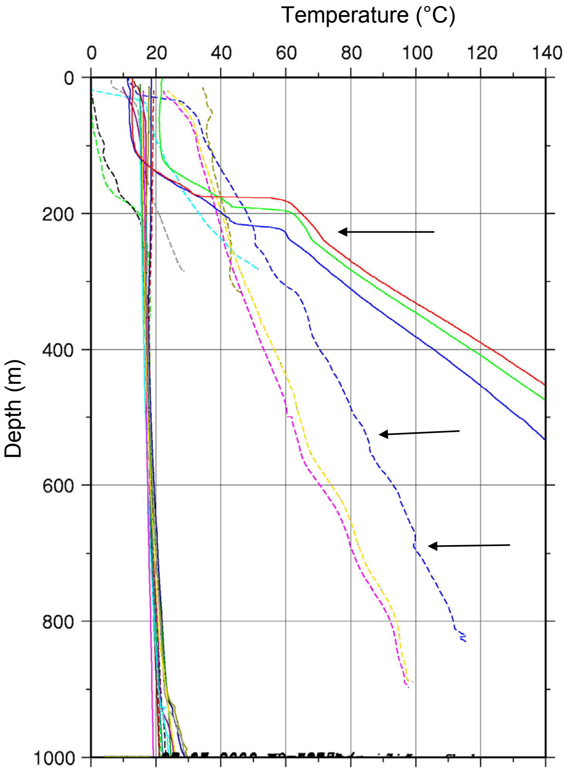

FIGURE 11: Aquifers in the upper 800 m of well HE-52

Aquifer 2 is a weak single-point feed zone encountered at 550 m. It was deduced from the temperature log as a temperature minimum during the heating up of the well, indicating a flow of cooler drilling fluid into the formation during drilling. It is situated within a basaltic breccia. The wall rock is characterised by moderate alteration and abundant veining at this depth. A high rate of penetration is observed at this depth. Mineralised vesicles, filled with amorphous silica and quartz, are also abundant. The measured temperature log stands at around 70°C (Figure 11).

Aquifer 3 is located at 700 m depth and is a weak aquifer. The aquifer is, similarly to the above aquifers, deduced from a slight minimum in the temperature logs. The formation is highly altered, vesicular hyaloclastite breccias of basaltic composition, with abundant pyrite and laumontite. Temperature logs indicate a likely formation temperature of about 220°C (see Figure 11).

Aquifers in the production part:
The production part extends from 897 m to the bottom of well HE-52. This part of the well was drilled with water instead of mud in order to keep the aquifers, already encountered, open. No circulation losses were reported from the end of the production casing down to about 1267 m depth where a loss of 3 l/s was measured. Another circulation loss occurred at about 1500 m and total loss took place at about 1700 m depth. Temperature logs provide the main evidence for aquifers from the casing end down to 1000 m depth, as indicated in Figure 12. While the aquifer evidence was temperature minima in the upper part of the well, inflow of water into the well (temperature maxima) is evidence for aquifers in the upper part of the production part of the well. This can be explained in such a way that the pressure of the largest aquifer near the bottom of the well controls the water table of the well. The water table (pressure) is lower than that of the upper aquifers so the upper aquifers flow into the well and downwards into the deeper aquifers, in this case located around 1600 and 1800 m depths. The temperature logs showing these features were done during the drilling operation and are shown on the left side of Figures 11 and 12 and in greater resolution in Appendix I.

Aquifer 4 **is** a small aquifer, seen in temperature logs at about 910 m depth (Figure 12). It seems to appear within a basaltic breccia.

Aquifer 5 is a small aquifer, seen in temperature logs at about 925 m depth as a temperature maxima.

Aquifer 6: Small aquifers are seen in temperature logs at about 940, 960-970 and 980-995 m as seen in Figure 12. They may be related to the presence of two minor basaltic intrusions seen at 950 and 980 m depths (uncorrected with respect to delay time).

Aquifers in the deeper levels of well HE-52:
This study is concerned with the uppermost 1000 m of the well. However, it is important to point out that aquifers are more common in the deeper part of the well. No circulation loss was recorded above 1000 m, as mentioned above, but it increased with depth until a total circulation loss occurred at 1700 m. Aquifers in this part are believed to be associated with faults and fractures along intrusion boundaries.

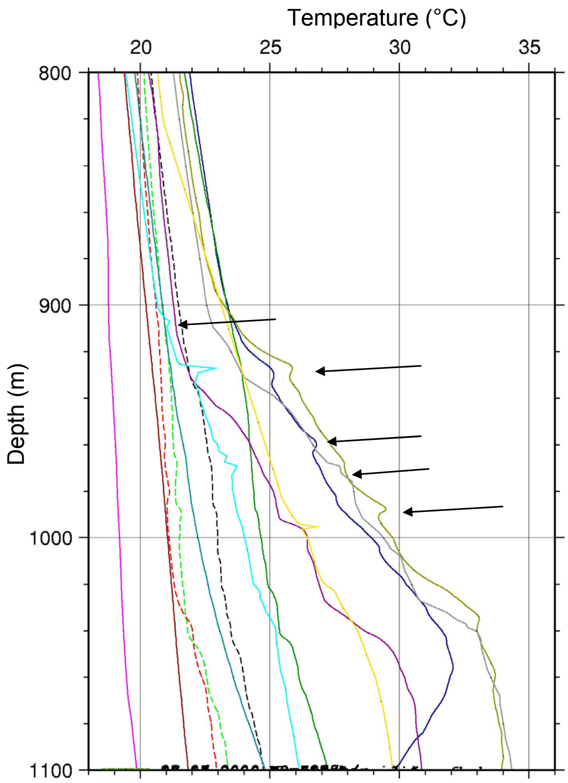

FIGURE 12: Aquifer in the production part of well HE -52

4.7 Fluid inclusions

A fluid inclusion is a tiny bubble of either water or gas trapped inside the crystal structure. The fluid inclusion can be formed during crystallisation (primary inclusion) or in a healed fracture formed at a later time (secondary inclusion). Fluid inclusions can be found in several types of minerals. Quartz and calcite commonly contain such inclusions in hydrothermal fields.

A total of 45 fluid inclusions were measured in a platy calcite at 874 m in well HE-52 as shown in Figure 13. The main purpose of these measurements was to record the condition of the geothermal system and evaluate whether the system was heating up or cooling down. According to the homogenization temperature (Th), the fluid inclusions concentrate into two population groups, the former ranging from about 180 to 215°C and the other from about 230 to 285°C. It is assumed here that the fluid inclusions formed both as primary and secondary fluid inclusions and that they record the temperature history of the system from the formation of the calcite crystal to later thermal changes. The implication of the fluid inclusion temperatures in relation to the formation and alteration temperatures are discussed in the next chapter.

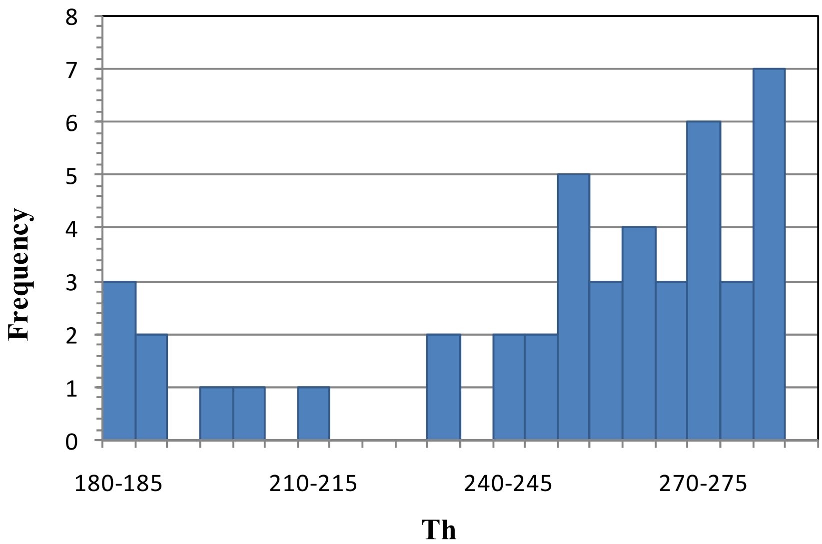

FIGURE 13: Fluid inclusions in calcite crystal at 874 m in well HE-52

5. DISCUSSION

Well HE-52 was drilled in the western part of the Hellisheidi area which in turn is part of the Hengill high-temperature geothermal field. The lithology of the uppermost 1000 m is depicted as alternating hyaloclastite formations with lava flows and some reworked basaltic tuff sections. Based on cutting analysis and confirmed by petrographic analysis, the hyaloclastite has further been subdivided into five distinct formations based on their texture (aphyric or porphyritic) while the lava series were subdivided into fine- to medium-grained basalts. The hydrothermal alteration increases progressively with depth. The abundance of alteration minerals increased markedly below 480 m where the first appearance of quartz occurred. Aquifers at shallower depths are related to the stratigraphic boundaries while the permeability in the deeper parts is believed to be related to faults and fractures. Intrusions were observed below 900 m and identified by weak to moderate alteration as compared to the adjacent rock. As a result of chemical reaction in the formation of well HE-52, hydrothermal alteration minerals were distributed in vesicles and veins and as replacements of the primary minerals.

The mineral assemblages are clay and zeolites (low temperature minerals) in the shallower depth and high-temperature minerals such as epidote, quartz, wollastonite, wairakite and prehnite in the deeper part of the well. This is a similar high-temperature assemblage as found at Nesjavellir at the northern sector of Hengill Mountain (Franzson, 2000). Based on the temperature dependent minerals and their first appearance, the alteration was divided into four zones below the unaltered zone: zeolite-smectite, mixed-layer clay, chlorite and chlorite-epidote zones. The mineral deposition sequence generally shows that the hydrothermal system is evolving from low to high temperature with depth and time but the evidence of calcite occurring as the last mineral species along the whole well may indicate that the system is now cooling. In this report, three types of temperature curves were produced: firstly the formation temperature, secondly the alteration temperature curve and lastly, for comparison, the boiling point curve. In addition, we have a histogram of the fluid inclusions from 874 m depth. These are shown in Figure 14. The fluid inclusions have a wide range of temperatures (180-285°C) found in a platy calcite crystal, showing higher temperature than the formation temperature and the boiling point which may possibly indicate a cooling process after the formation of the

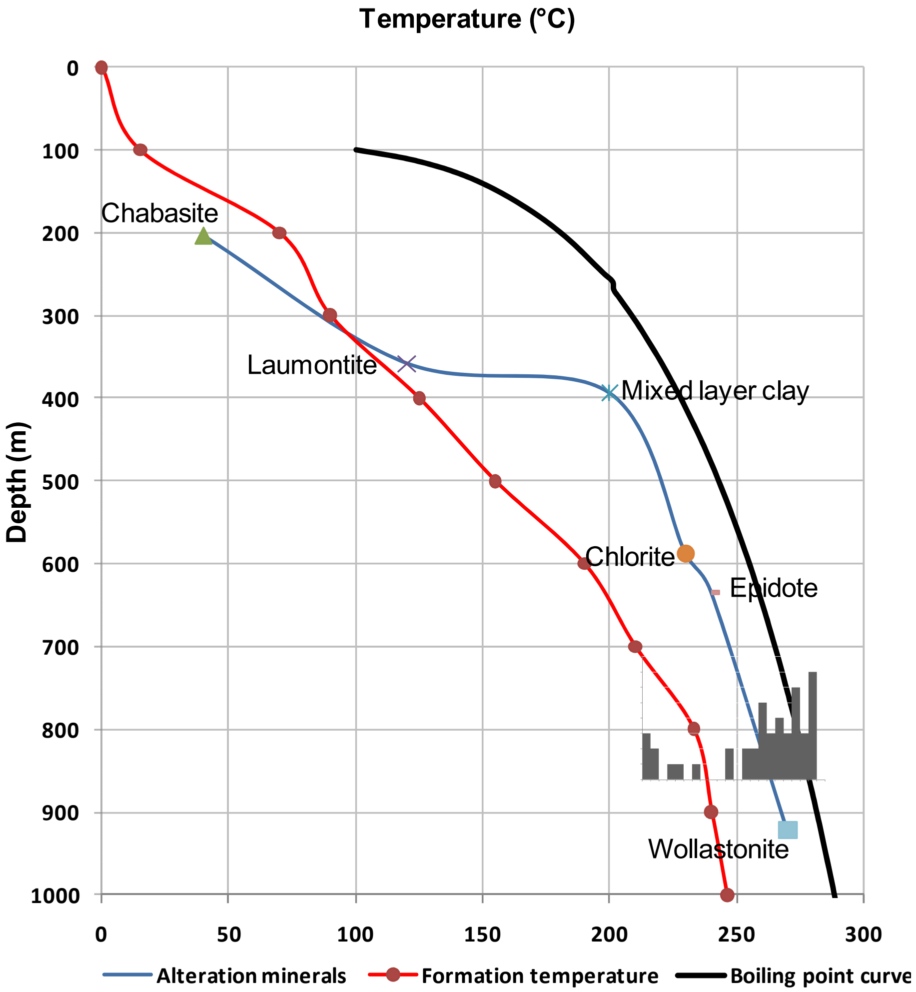

FIGURE 14: Plot of formation, alteration and fluid inclusion temperatures in well HE-52

calcite. A comparison between the boiling point curve and the alteration temperature shows that the geothermal system is far from boiling conditions down to about 400 m depth, but near to boiling conditions below that depth. A comparison between the alteration and formation temperatures distinctly shows the lower values of the latter, thus giving a clear signal of cooling from the maximum temperature state of the system. The high temperature in the platy calcite is likely to be near the boiling point, indicating boiling condition in the geothermal system during its initial crystallization.

6. CONCLUSIONS

The following conclusions can be deduced from this study:

- The stratigraphy of well HE-52 comprises alternating sequences of hyaloclastite units (glassy basalt or pillow basalt and basaltic breccia) and layers of lava (fine- to medium-grained crystallized basalt) and some reworked tuff which forms only in the upper part of the well.
- Permeability in the upper part of well HE-52 is related to lithological contacts, intrusive boundaries, major faults and fractures. This well is believed to be related to the faults and intrusions in the western part of the Hengill-graben.
- Four alteration zones were identified beneath the unaltered zone in this well according to the distribution of alteration minerals; they were classified as a zeolite-smectite zone (<200°C), a mixed-layer clay zone (200-230°C), a chlorite zone (230-240°C) and a chlorite-epidote zone (>240°C).
- The sequence of mineral deposition within this well ranges from fine grained clay (smectite) to coarse-grained clay (chlorite), epidote and wairakite. This means that the hydrothermal system has evolved from low- to high-temperature conditions, while in the last stage the precipitation of calcite indicates cooling.
- By studying the hydrothermal alteration minerals, it was observed that the temperature rises rapidly at about 486-650 m depth with the appearance of quartz, epidote, wairakite and chlorite. Below 650 m depth, alteration increased with the deposition of epidote, wollastonite, wairakite and chlorite.
- Fluid inclusions found in a calcite crystal showed a large range in temperature, indicating large temperature variation in the geothermal system at 874 m depth.

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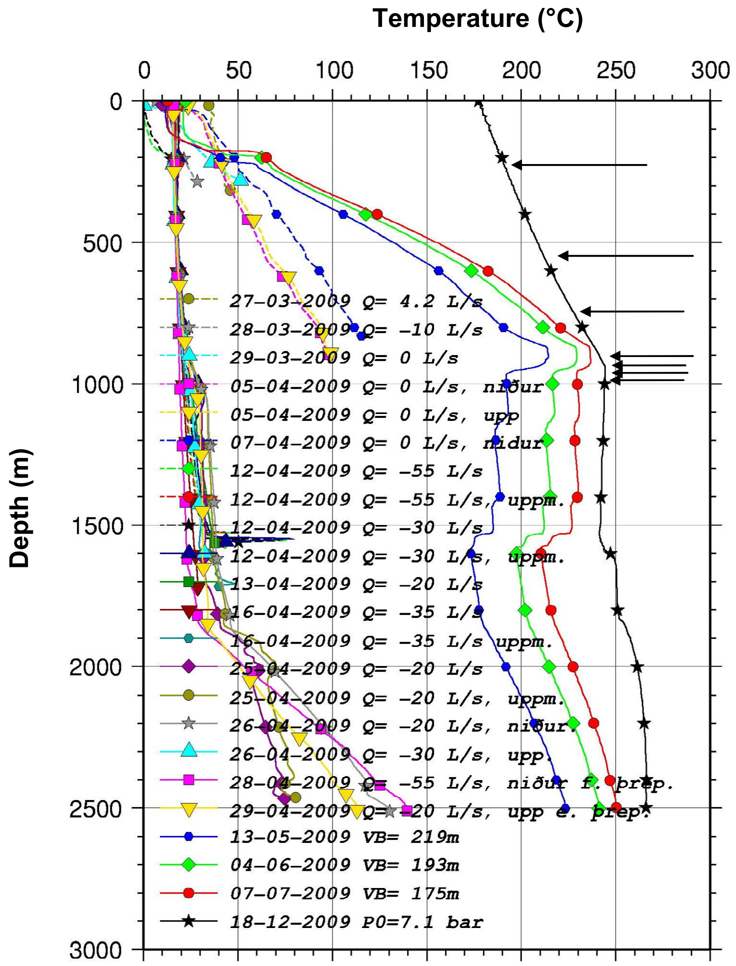
APPENDIX I: Temperature graphs showing location of feed zones in well HE-52



APPENDIX II: XRD clay mineral analysis results from well HE-52

TABLE 1: Summary of XRD analysis results from well HE-52

Depth (m)	Unaltered	Heated	Type of clay	Other minerals
176	15.771	0	Smectite	
286	15.187	9.714	Smectite	9.144
386	30.827/15.197	9.925	Mixed-layer clay	9.128
486	15.060/13.052	14.459	Mixed-layer clay	
586	14.681	14.599	Chlorite	
600	14.741/12.876	14.901	Unstable chlorite	
610	14.636/12.876	14.944	Unstable chlorite	
640	14.913/12.913	15.195	Unstable chlorite	9.695
690	14.961	0	Unstable chlorite	9.687
850	14.695	15.004	Unstable chlorite	
1090	14.996	14.734	Unstable chlorite	
1190	14.683	14.987	Unstable chlorite	8.563=amphibole
1290	14.637	14.94	Unstable chlorite	8.642=amphibole
1590	14.588	14.607	Unstable chlorite	8.619=amphibole
1680	14.7	14.283	Unstable chlorite	8.636=amphibole

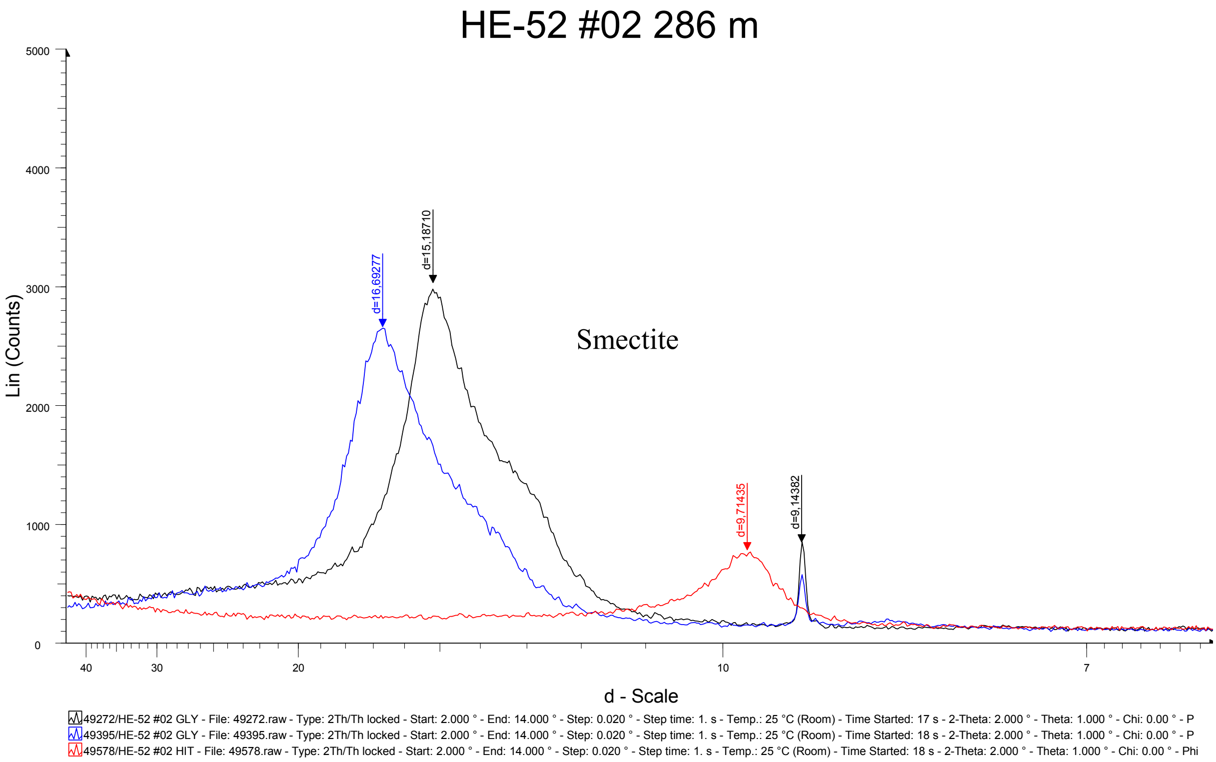


FIGURE 1: XRD analysis showing peaks for smectite

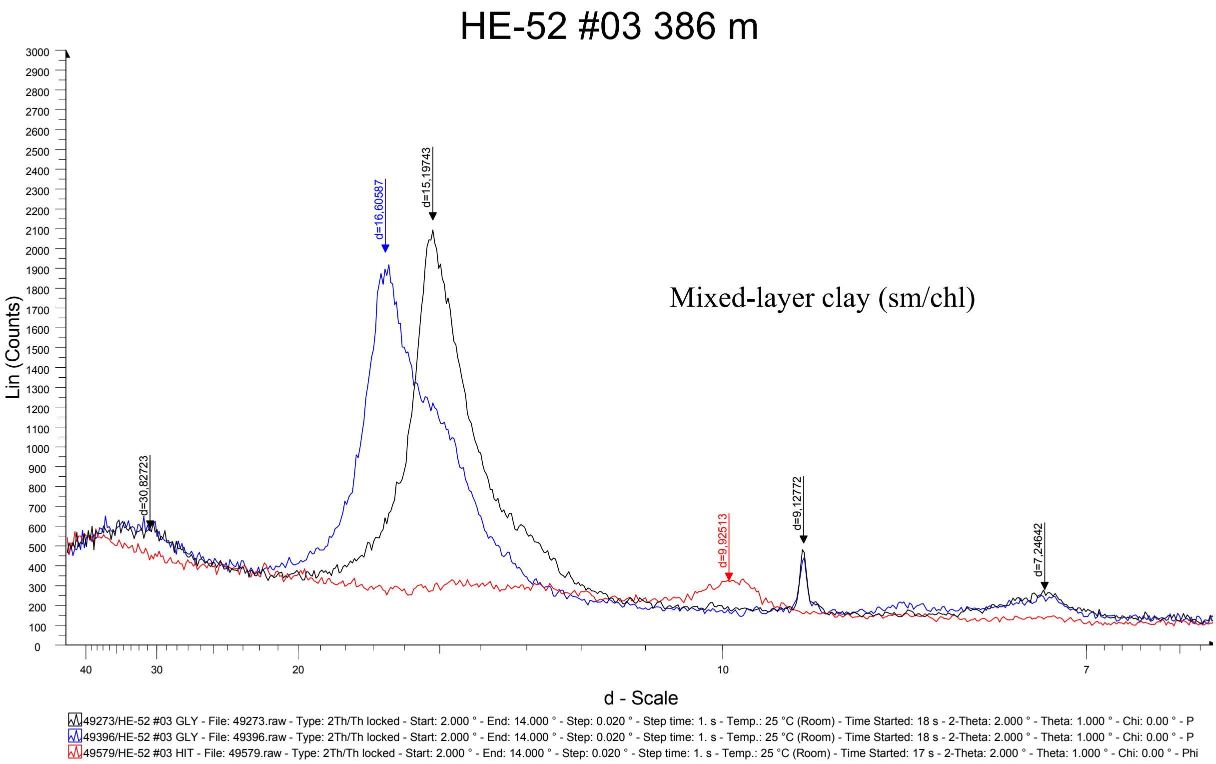


FIGURE 2: XRD analysis showing peaks for mixed-layer clays

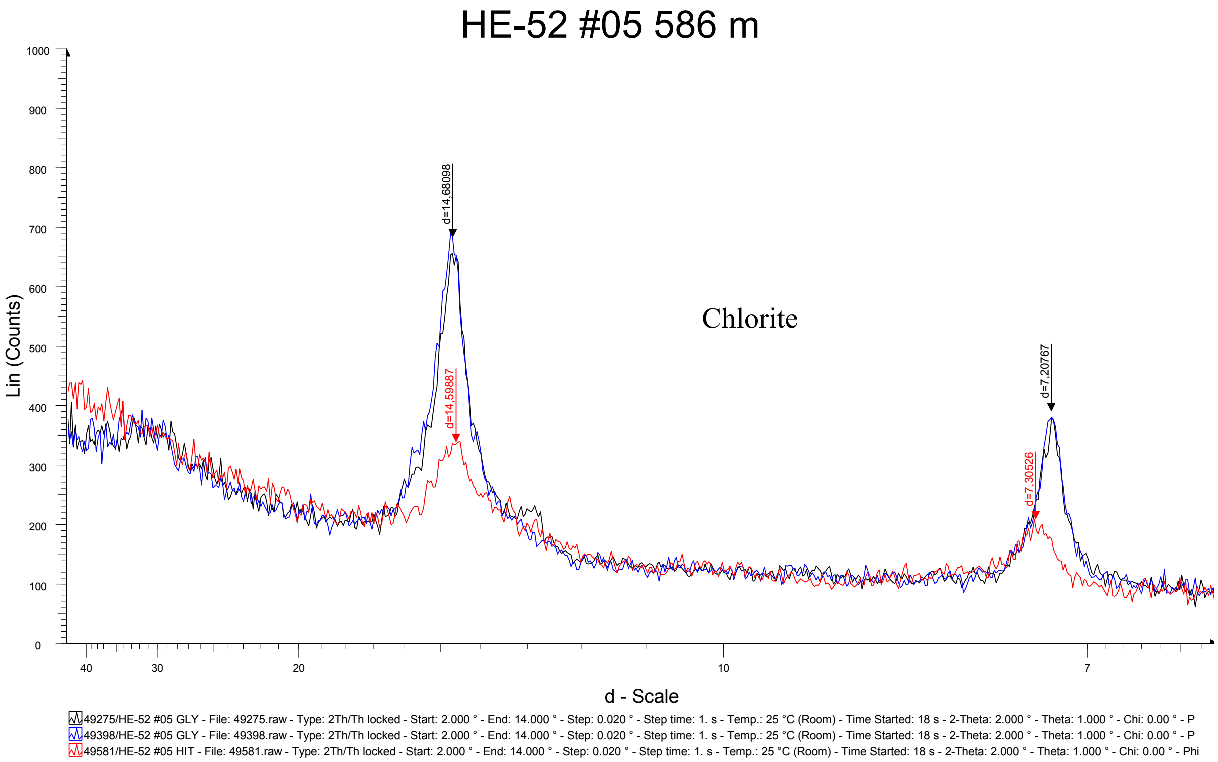


FIGURE 3: XRD analysis showing peaks for chlorite

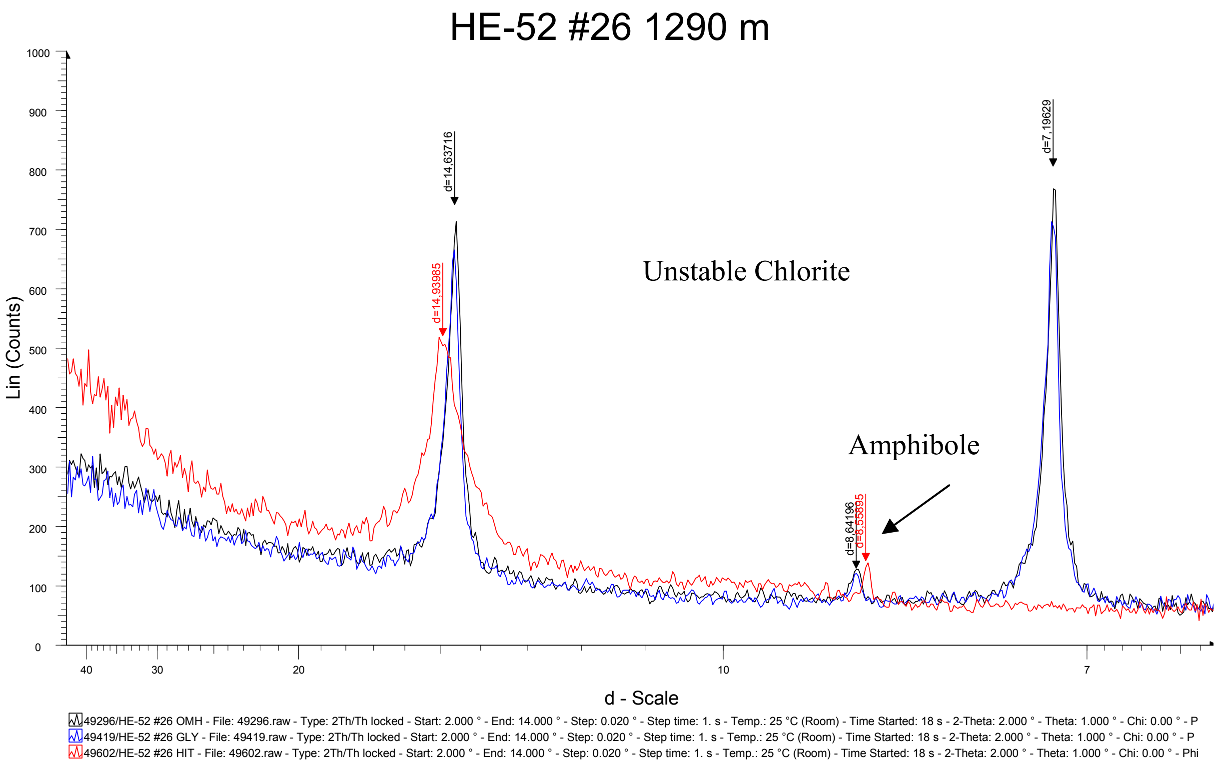


FIGURE 4: XRD analysis showing peaks for unstable chlorite and amphibole