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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 a geothermal exploration well located in the northwestern part of Hellisheidi in the Hengill high-temperature field. It is a directional well, drilled to the depth of 2516m to reach the high-temperature reservoir situated at the root of the Skardsmýrarfjall Mountain. Stratigraphically, this well is comprised of 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 (breccia, pillow lava and tuff). Lithological contacts, intrusions and faults are the main factors that controlled the permeability in the well. Hydrothermal alteration zones were divided into four zones below the unaltered zone: a smectite-zeolite zone (120-386m), a mixed-layer clay zone (386-586m), a chlorite zone (586-634m) and a chlorite-epidote zone (634-1190 m). Based on the intensity of alteration, the abundance of veins and lithological boundaries, seven weak aquifers were recognized in the uppermost 1000m. The sequence and assemblage of minerals showed increasing hydrothermal system temperature which was reflected from the high thermal gradients in well 52 with the depth. This condition is followed by cooling evidence envisaged by precipitation of calcite at a later stage. Fluid inclusions measurements were done at the depth of 874m. Primary and secondary inclusions in Calcite have shown a wide range of homogenization temperatures between 180°C and 285°C. Comparison of alteration minerals, fluid inclusions and formation temperature indicate large temperature variation in the geothermal system at 874m.

1. INTRODUCTION

1.1 Purpose of the Study

The objective of this paper is to study borehole geology through cutting samples in order to identify the stratigraphy and the subsurface geological formation of well HE-52 in Hellisheidi. The main aim of this study is to determine the geothermal conditions in the system through understanding of the hydrothermal mineralization and the sequence of mineral depositions in veins or vesicles to better assist the geothermal setting in the system, and to locate the aquifers to understand the preamble zones in the well and the water rock interactions.

1.2 Methodology

Some hundred cutting samples were collected at two meter intervals and ten thin sections made from the uppermost 1000m of well HE-52 with respect to the geology and hydrothermal alteration description. The methods used for analyses included a binocular microscopy for the cutting samples 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.

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, estimated to be about 1 cm/yr in each direction (Talwani and Eldholm, 1977). The majority of rocks composition in Iceland is basaltic, some intermediate and acid rocks, and minor sediments mainly of volcanic origin (Fridleifsson, 1983). Geothermal systems in Iceland are commonly classified as high-temperature and low-temperature systems. The high-temperature fields are typically above 200°C within the depth of 1 km. These fields are usually located in the central volcanoes or in their fissure swarms (Figure 1). The activity there is due to intrusions at shallow depth in the upper crust. The low-temperature fields mainly occur outside the volcanic rift zone; the temperature is lower than 150°C and they are usually fracture dominated systems (Bödvarsson and Björnsson et al., 1982 and 1990).

Hellisheidi is located in one of the volcanic zones which is characterized by active volcanoes, fissure swarms and normal fault strikes southwest to northeast. The uppermost 1000m in these zones are made of highly porous and permeable basaltic lavas and hyaloclastites with a heavy flow of groundwater (Pálmason and Saemundsson, 1979).

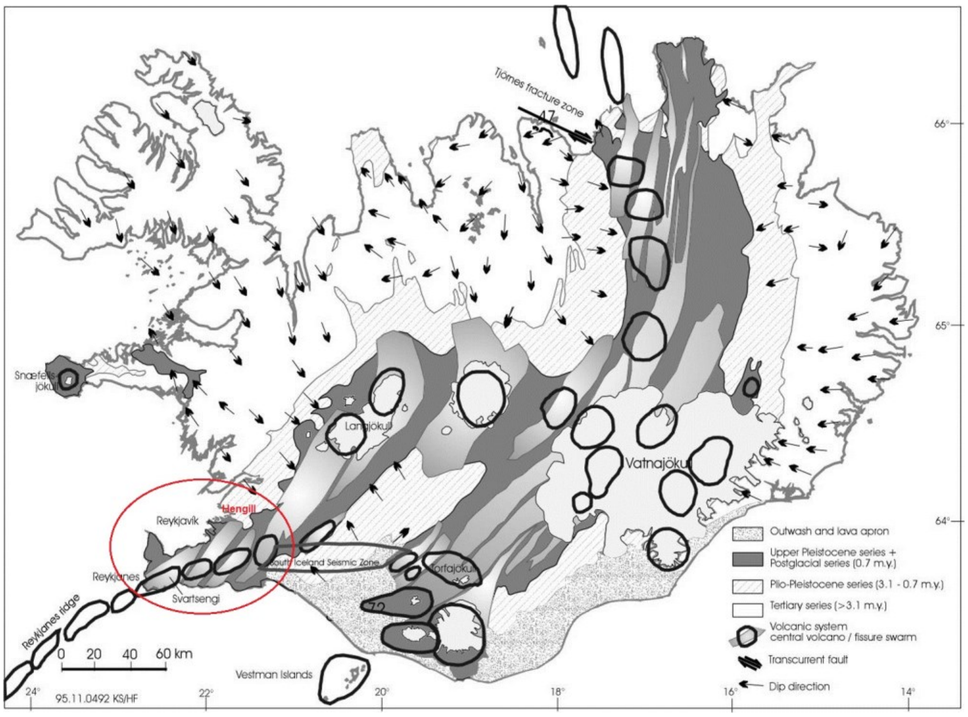

Figure 1: A simplified geological map of Iceland showing the volcanic zones, fissure swarms and central volcanoes (Saemundsson, 1979).

2.2 The Hengill High-Temperature Area

Hellisheidi is a high-temperature field in Hengill area where Well HE -52 is located (Figure 2). Hellisheidi and Nesjavellir 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 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 generates a total of 213 MWe. In 2010, the total installed power production capacity in the Hengill geothermal area was 333 MWe (Árnason et al., 2010). Since 2010, fifty seven production and exploration wells have been drilled and sixteen reinjection wells. The wells at Hellisheidi have predominantly directional range from around 800m to more than 3000m depth.

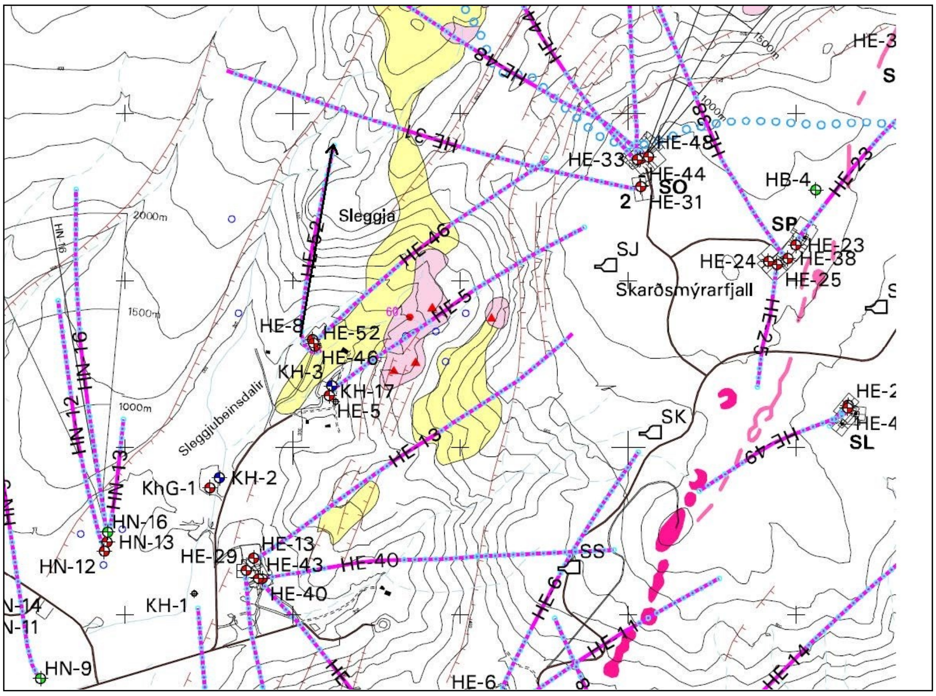

Figure 2: The western part of the Hellisheidi geothermal field and the location of well HE-52 with horizontal deviation.

2.3 Geological and Tectonic Setting of Hengill Area

Hengill area consists of a triple junction where the two active rift zones (the Reykjanes Peninsula volcanic zone and the western volcanic zone) meet the active transform zone (the South Iceland seismic zone). This volcano consists mainly of hyaloclastites formations (sub-glacial) which mostly accumulate in the surrounding lowlands, interrupted by interglacial lava successions. NE-SW striking fractures and fault zones are dominant in the Hengill system. Some of these fractures are intersected by easterly striking features which may affect the permeability of 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 (Saemundsson, 1995; Björnsson, 2004; and Franzson et al., 2005). These fissures have been one of the two main drilling targets in Hellisheidi field. The second target focuses on large NESW 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

The geophysical measurements that were carried out in the Hengill area included DC resistivity methods using Schlumberger and dipole-dipole soundings, aeromagnetic surveys, Bouguer gravity and seismic surveys that delineated a 110 km2 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 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).

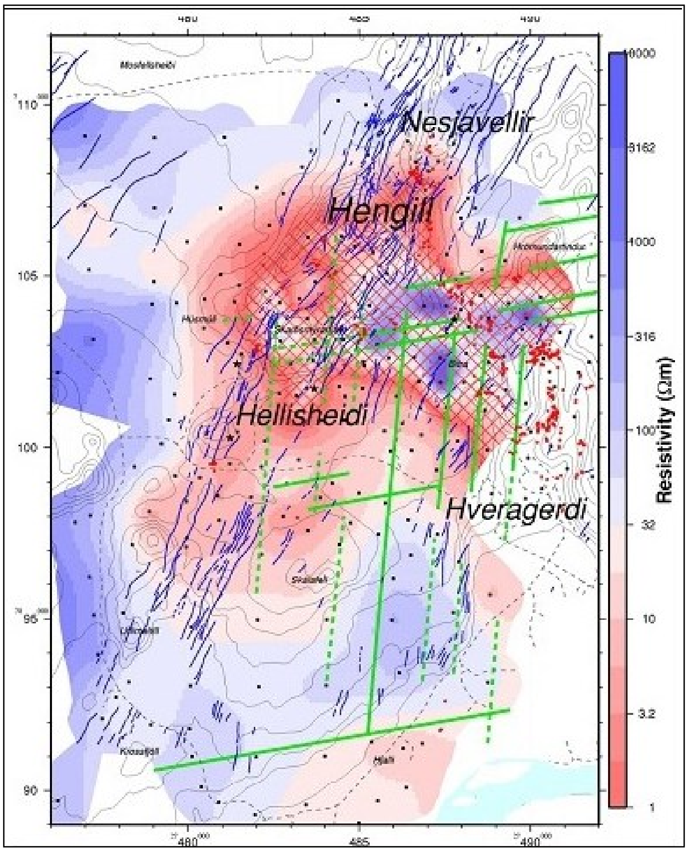

Figure 3: Resistivity map at 200m b.s.l. based on TEM measurements in the Hengill geothermal area (Árnason and Magnússon, 2001).

3. BOREHOLE GEOLOGY OF WELL HE-52

3.1 Stratigraphy

The stratigraphy of the uppermost 1000m in well HE-52 is divided into alternating sequences of hyaloclastite, lava series and minor sedimentary basaltic tuff sequences Figure 4.These are subdivided into five hyaloclastites formations (1.Pillow lavas or glassy basalts that are partially crystallized with minor amounts of volcanic glass; 2.Basaltic breccias, which is characterized by a mixture of crystallized basalt and volcanic glass; 3.Basaltic tuff which is predominantly volcanic glass; 4.The lava series are classified into fine- to medium-grained textures), three lava series (1.Thin layers of fine- to medium-grained basalt with alternating layers of basaltic breccias; 2.Individual fine- to medium-grained basaltic lava flows; 3.Fine- to medium-grained plagioclase porphyritic basalt) and one layer of reworked basaltic tuff (sedimentary).

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 description is based on binocular microscope (cuttings) analysis and petrographic microscope (thin sections) analysis.

3.2 Intrusions

Intrusions were hardly encountered in the first 900m of the well HE-52 but two possible intrusions were found at the depth of 952m and 978m. Both of these intrusions have about 2m apparent thickness of fresh and fine- to medium-grained basalt. They can be identified by the oxidation adjacent to the intrusion which probably reflects a heating effect from the magma. 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 these depths.

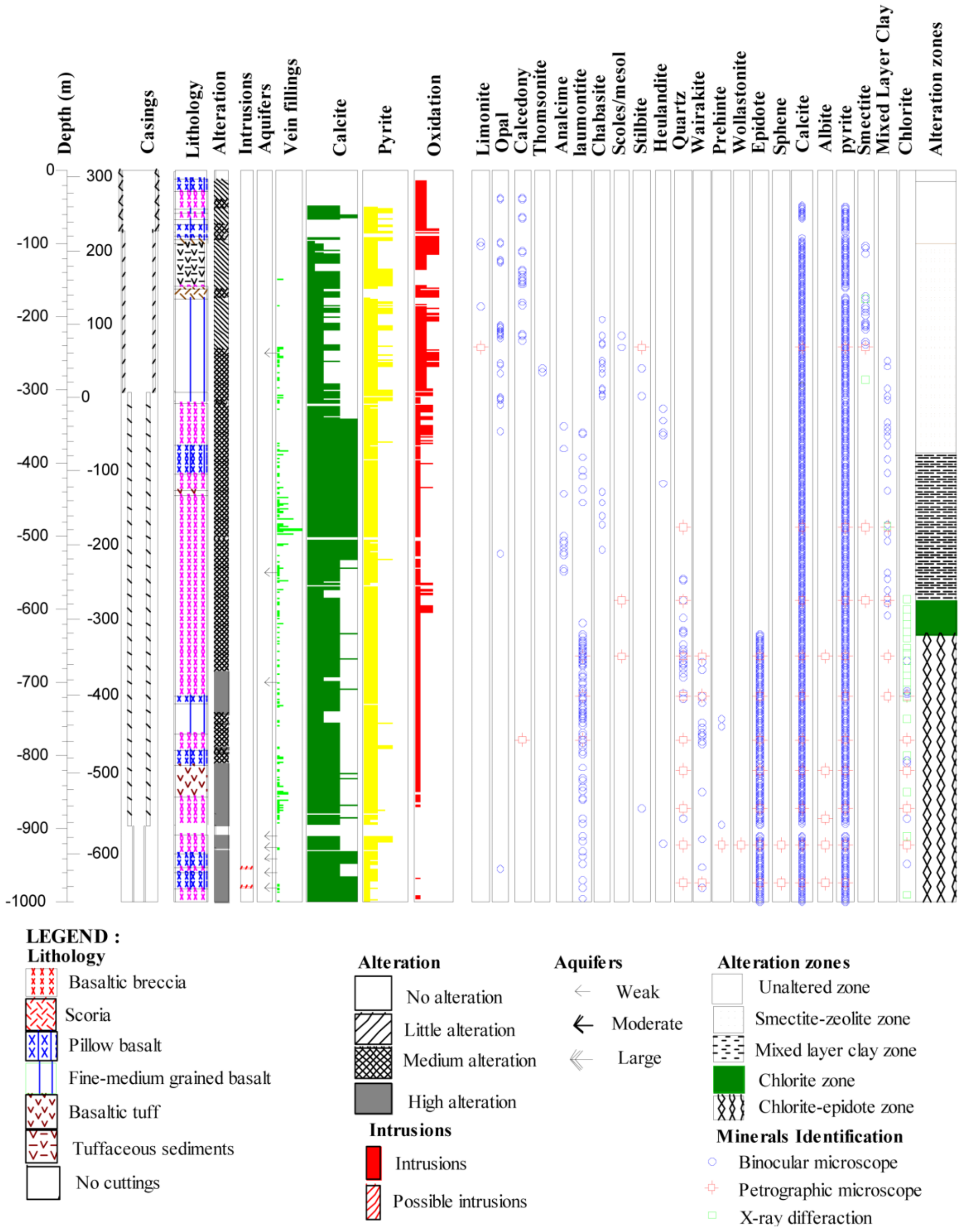

Figure 4: Distribution of hydrothermal alteration minerals in the upper 1000 m of well HE-52.

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 limonite). 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

4.2 Alteration Mineralogy

Hydrothermal mineral distribution is identified by using Binocular and Petrographic microscopes, and X-ray diffraction measurements. The alteration minerals recognized in well HE-52 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 these alteration minerals, regarding their appearance with depth in the well and their temperature range, is described in Figure 4.

4.3 Sequence of Hydrothermal Mineral Depositions

Hydrothermal mineralization assemblages are evaluated according to different factors which are temperature, fluid composition, rock types and 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 as follows:

Table 2: Mineral depositional sequence of well HE-52.

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

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 as fine-grained clay, usually occurring as linings on vesicle walls and partially filled with calcite, but 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 depth. This was emphasized by the three presences of laumontite, which is very sensitive to temperature, succeeded by quartz at a depth of 664m as shown in Table 2. 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 5). At the depth of 778 m, chalcedony precipitated and was succeeded by chlorite which would suggest that the reservoir is heating up with time. Calcite is present in the entire sequence and its presence 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 922m in well HE-52.

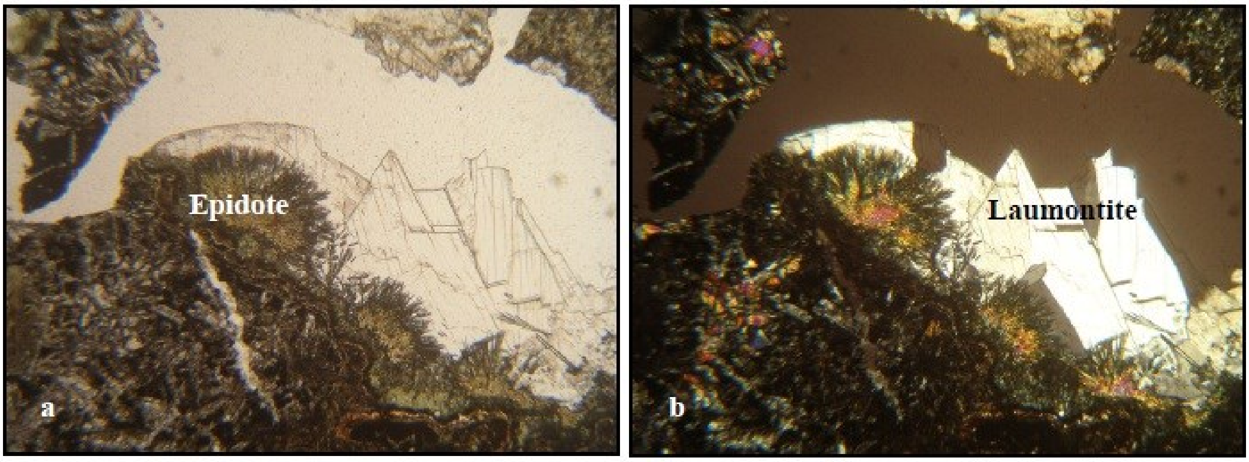

Figure 5: Mineral sequence: a) Epidote on top of b) laumontite in well HE-52, 778m.

4.4 Vein and Vesicle Fillings

Veins or vesicles are the primary controllers of porosity and permeability of a formation. The lithology of well HE-52 predominantly comprises of 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 at the top of the sequence but gradually filled towards higher temperatures and the core of the geothermal system. The first minerals that precipitated and started to fill voids in basalts were 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 concentrations of vein clusters in the upper 1000 m of the well occurred 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 mineralization, is situated within the hyaloclastite, which is moderately to highly altered. This zone is characterized by minor aquifers. The third and the deepest interval is on the contact between hyaloclastites (basaltic breccias, 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 780m.

4.5 Alteration Mineral Zonation

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

<u>Unaltered zone</u>

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, presented 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 at 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), heulandites 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 (appendix I). Pyrite and calcite were still common together with the assemblage of analcime and quartz. The temperature estimated for the first appearance of chlorite is 230°C (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 (appendix I). 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

Aquifers were identified from records of sudden change in the rate of penetration, intensity of alteration, anomalous geophysical logs, such as caliper, resistivity, neutron-neutron, and temperature logs during drilling, heating up and discharging (appendix I). 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 (250, 550 and 700 m) and four feed zones within the production part (910, 925, 940, 960-970 and 980-995 m) (see appendix I). 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.

4.7 Fluid Inclusions

A total of 45 fluid inclusions were measured in a platy calcite at 874m in well HE-52. 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°C to 215°C and the other from about 230°C to 285°C (Figure 6). 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.

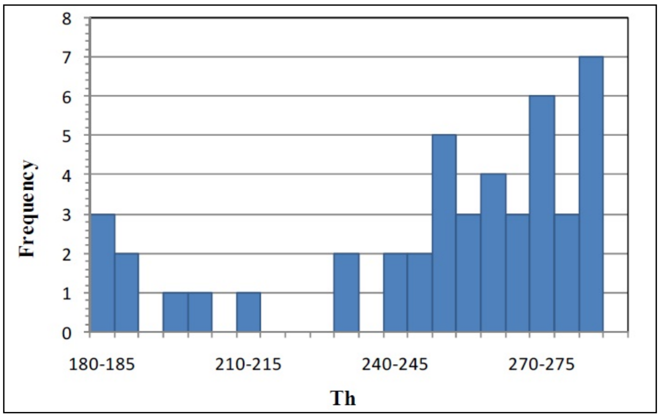

Figure 6: Fluid inclusions in calcite crystal at 874 m in well HE-52.

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 was further subdivided into five distinct formations according to 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 as weak to moderate alterations 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 type along the whole well may indicate that the system is now cooling. In this study, 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.

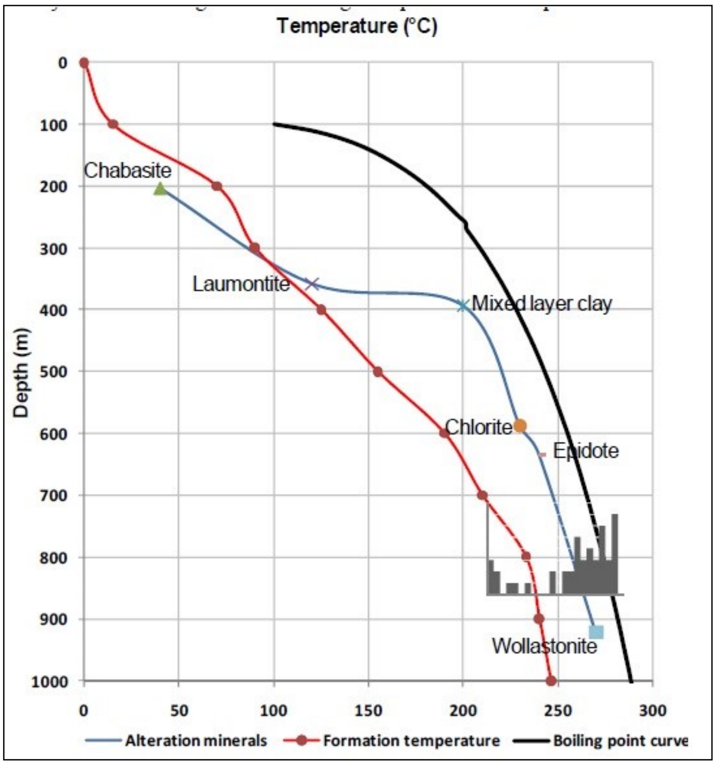

Figure 7: Plot of formation, alteration and fluid inclusion.

These curves are shown in Figure 7. The fluid inclusions have a wide range of temperatures (180°C - 285°C) found in a platy calcite crystal as primary and secondary inclusions, showing higher temperature than the formation temperature and the boiling point, which may possibly indicate a cooling process after the formation of the 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 increases 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

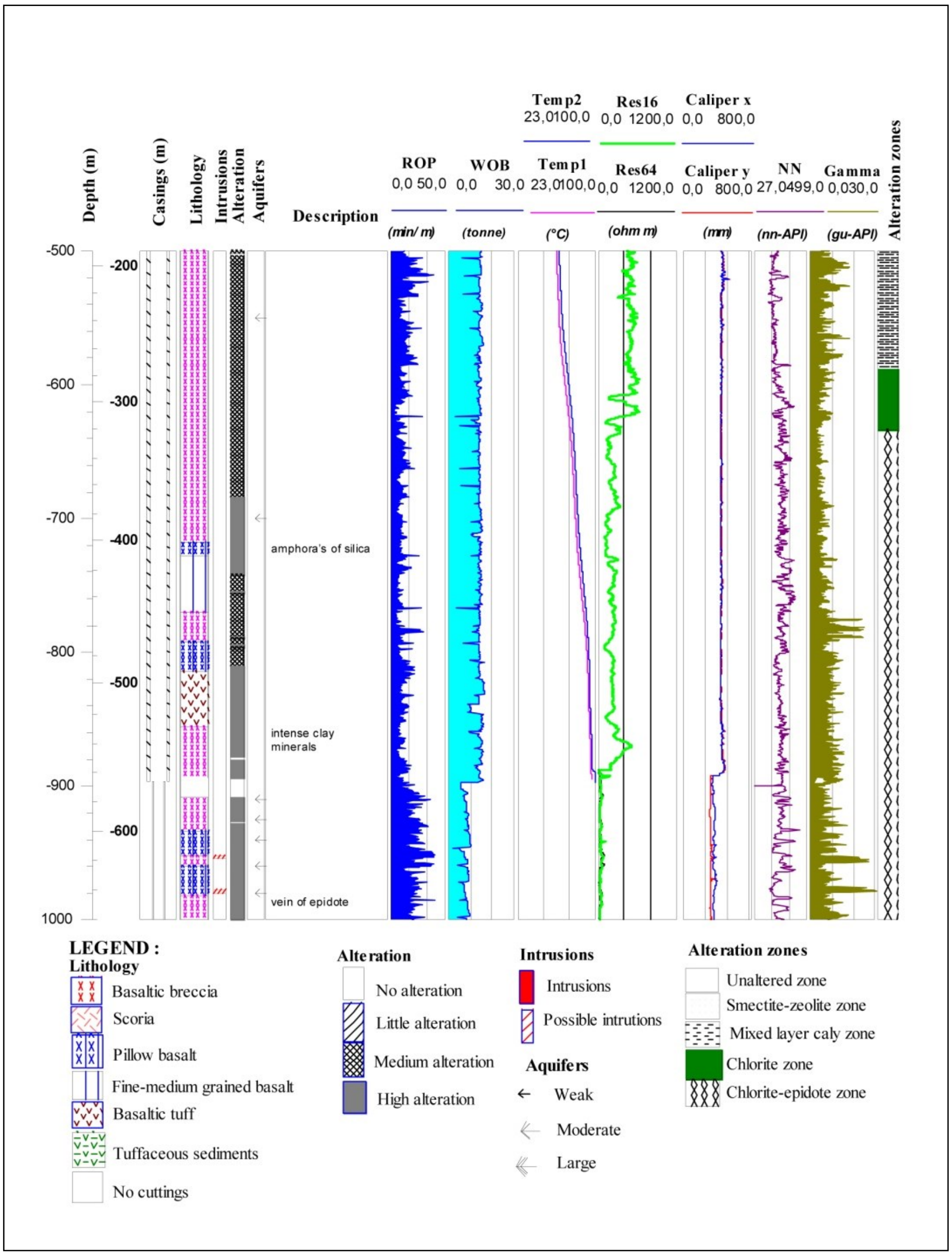

Figure 8: Simplified stratigraphic section and geophysical logs (500-1000 m depth) in well HE-52.

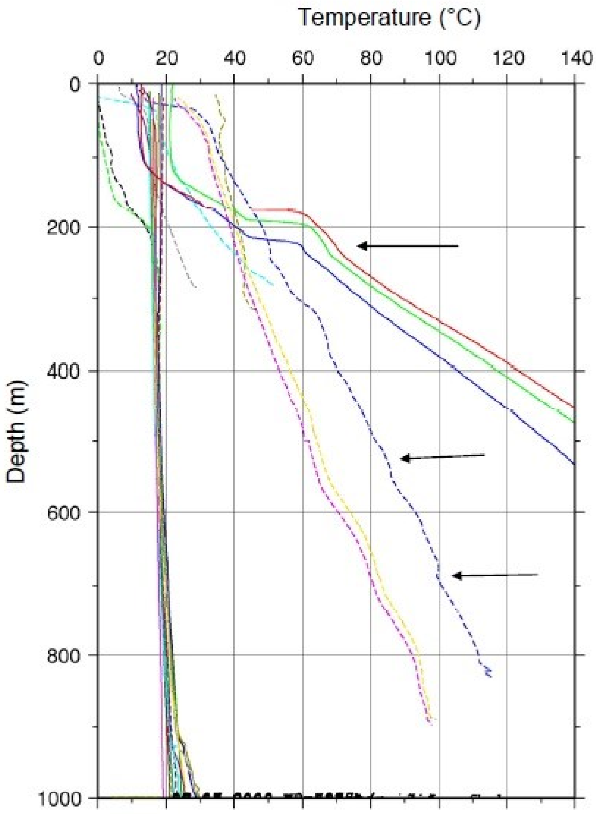

Figure 9: Aquifers in the upper 800 m of well HE-52.

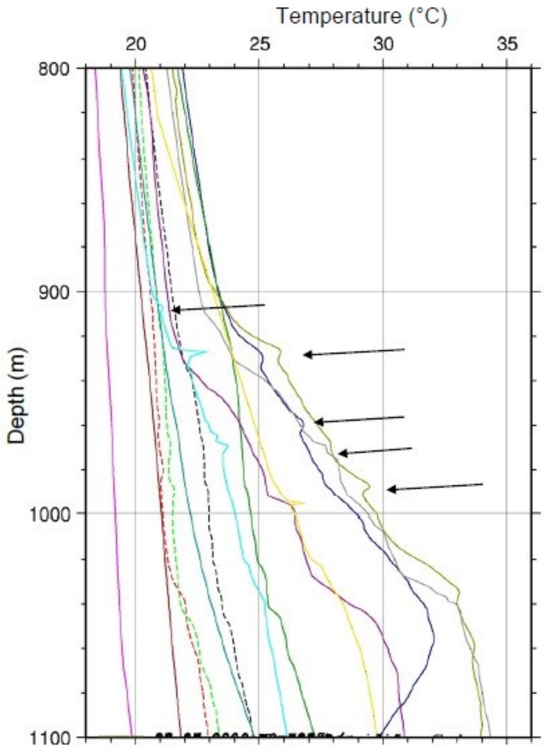

Figure 10: Aquifer in the production part of well HE -52.

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

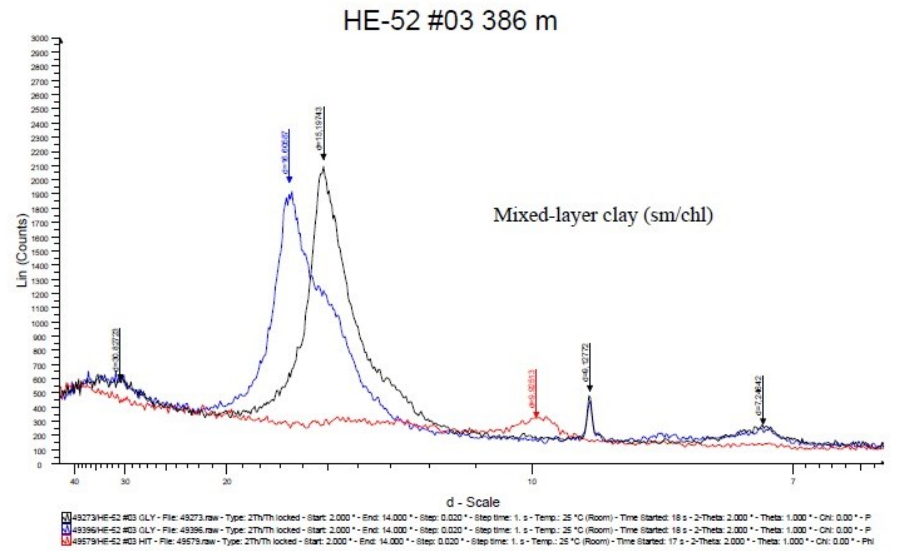

FIGURE 2: XRD analysis showing peaks for mixed-layer clays

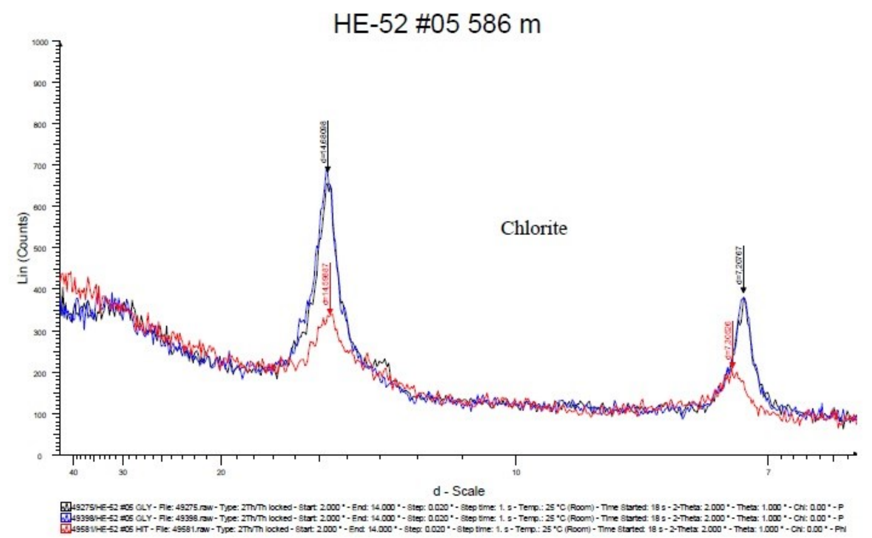

FIGURE 3: XRD analysis showing peaks for chlorite

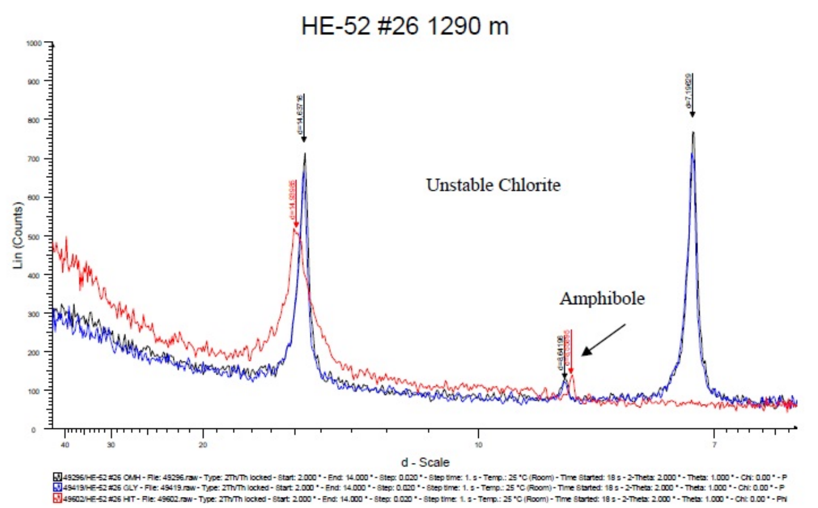

FIGURE 4: XRD analysis showing peaks for unstable chlorite and amphibole