SUBSURFACE GEOLOGY AND HYDROTHERMAL ALTERATION OF WELL HE-4, HELLISHEIDI GEOTHERMAL FIELD, SW- ICELAND

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ABSTRACT

Intense geoscientific studies are needed before exploitation of geothermal resources commences. The studies involve multiple fields of geoscience including geology, geochemistry and geophysics during the exploration, production and monitoring stages. Well HE-4 is amongst the earliest deeper exploration wells in the Hellisheidi geothermal field with a total depth of 2008 m. The well was directionally drilled in 2001 towards SW from a drill pad east of Reykjafell mountain. This report covers the upper 1200 m of the well where binocular microscope, petrographic microscope, XRD-analysis, fluid inclusion analysis and geophysical logs were applied to gather and interpret data. The stratigraphy of well HE-4 is governed by two major formations which are hyaloclastite basalt and basaltic lava. Hyaloclastite basalt formations (including basaltic tuff, basaltic breccia and pillow basalt) alternate and dominate in the well, representing volcanic eruptions beneath a glacier. Basalt formations of fine- and fine- to medium-grained crystalline basalt appear occasionally, representing interglacial lava flows and intrusive rocks. Seven feed points were identified, two large ones located at 496 m and 1150 m and five smaller ones identified at 300 m, 580 m, 890 m, 900 m and 1100 m. Alteration zones are somewhat contradictory and are, therefore, based on two separate zones of clay minerals on the one hand and alteration mineral distribution on the other. Clay minerals show five zones within the well starting with an unaltered zone followed by a smectite zone at 82-642 m, which is interrupted by a thin layer of mixed layer clay at 450-458 m. A chlorite zone is then noted from 642-862 m, followed by a mixed layer clay zone from 862 to 1050 m and a chlorite amphibole zone from 1050-1200 m. The distribution of alteration minerals shows five zones starting with an unaltered zone, followed by a zeolite zone, then quartz and wairakite, epidote, and wollastonite zones. Correlation of alteration temperature and homogenization temperatures with the formation temperature of the system indicates that the upper part of the system is in equilibrium, the middle part from 414 to 784 m is heating up, while the lower part of the system is cooling.

1. INTRODUCTION

1.1 General information

Hellisheidi geothermal field is located in SW Iceland within the Hengill high temperature geothermal system. The other three geothermal fields within the system are Nesjavellir, Bitra, and Hverahlíd (Figure 1).

FIGURE 1: An aerial photograph of the Hengill area showing
four high temperature geothermal fields

After assessing geothermal surface manifestations, surface geology, geochemistry and geophysics, exploration drilling remains a key factor for sub-surface studies in order to make physical contact with the geothermal system and its rock formations. During sub-surface geological studies, binocular, petrographic, fluid inclusion and X-ray diffractometer analyses provide information about the rock types, their physical properties and alteration. In combination with geophysical logging, including temperature, gamma, caliper, neutron-neutron and resistivity, it is possible to obtain a better understanding of major lithological changes and help to define aquifers that may be countable for geothermal production.

Well HE-4 is an exploration well, drilled directionally to a total depth of 2008 m. The well is situated in a small valley east of Reykjafell within the Hellisheidi high temperature geothermal system, as shown in Figure 2. The main objectives of the drilling were to obtain information about the stratigraphy and its geophysical properties, temperature and permeability, and to explore the capability of the geothermal fluid between Reykjafell mountain and Hveradalir valley south of Reykjafell (Gudmundsson et al., 2001a).

This study is the result of knowledge and experience acquired from the six months UNU Geothermal Training Program 2014 about geothermal exploration, production, monitoring and utilization of geothermal resources. The main focus was on borehole geology, assessing the lithological stratigraphy and alteration of the formations as well as the precipitation of hydrothermal minerals to gain a better understanding of the geothermal system and the surroundings in well HE-4.
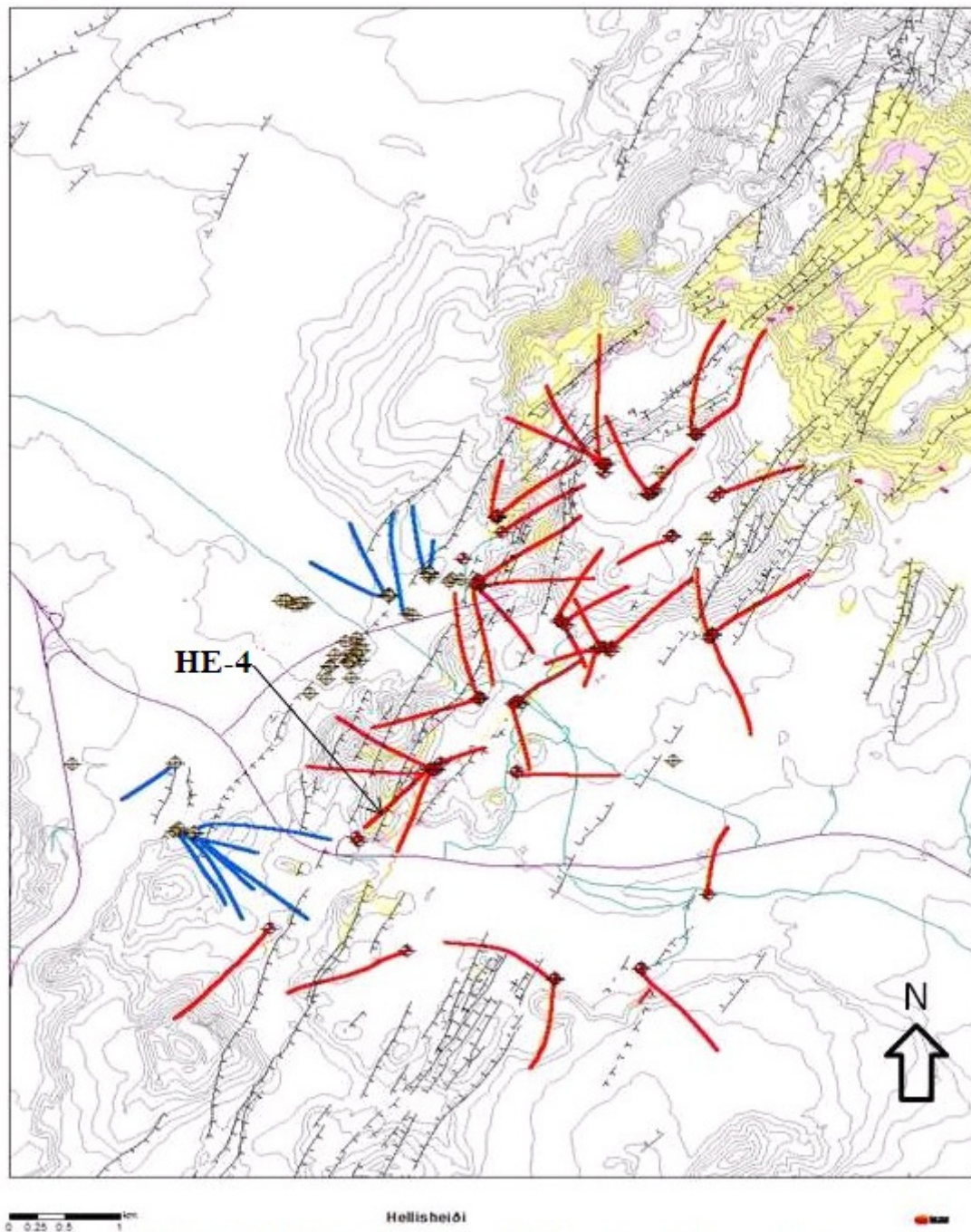
FIGURE 2: Hellisheidi geothermal field with exploration/production wells (red),
reinjection wells (blue) and the location of well HE-4
(modified from Gudmundsson et al., 2001a)

1.2 Regional geology of Iceland

Iceland lies on the rift between the Eurasian plate and the North American plate which has a relative motion of 1 cm per year in each direction. The divergence of these major plates favours volcanic eruptions and earthquakes and forms the Mid-Atlantic Ridge on which Iceland rests. Furthermore, Iceland resides on a mantle plume (hot spot) which has induced frequent volcanic eruptions from time to time. The rift system cuts across the country from southwest to northeast (Figure 3). The existence of the hot spot results in Iceland having been more volcanically active than the oceanic rift throughout its

existence (Saemundsson, 1979). Iceland is geologically very young with its rocks formed within the last 25 million years. The stratigraphic succession of Iceland extends across two geological periods: the Tertiary and the Quaternary, where the oldest rocks exposed at the surface are only 14–16 million years old. Geological formations are grouped into three as Tertiary (16-3.3 million years), Plio-Pleistocene (3.3-0.7 million years) and upper Pleistocene formations which are <0.7 million years. The surface geology is almost entirely composed of igneous rocks of which about 80-85% is basaltic (mafic) in composition; acidic (felsic) and intermediate rocks amount to about 10% (Figure 3). The amount of sediments of volcanic origin is 5-10% in a typical Tertiary lava pile, but may locally be higher in Quaternary rocks (Saemundsson, 1979).
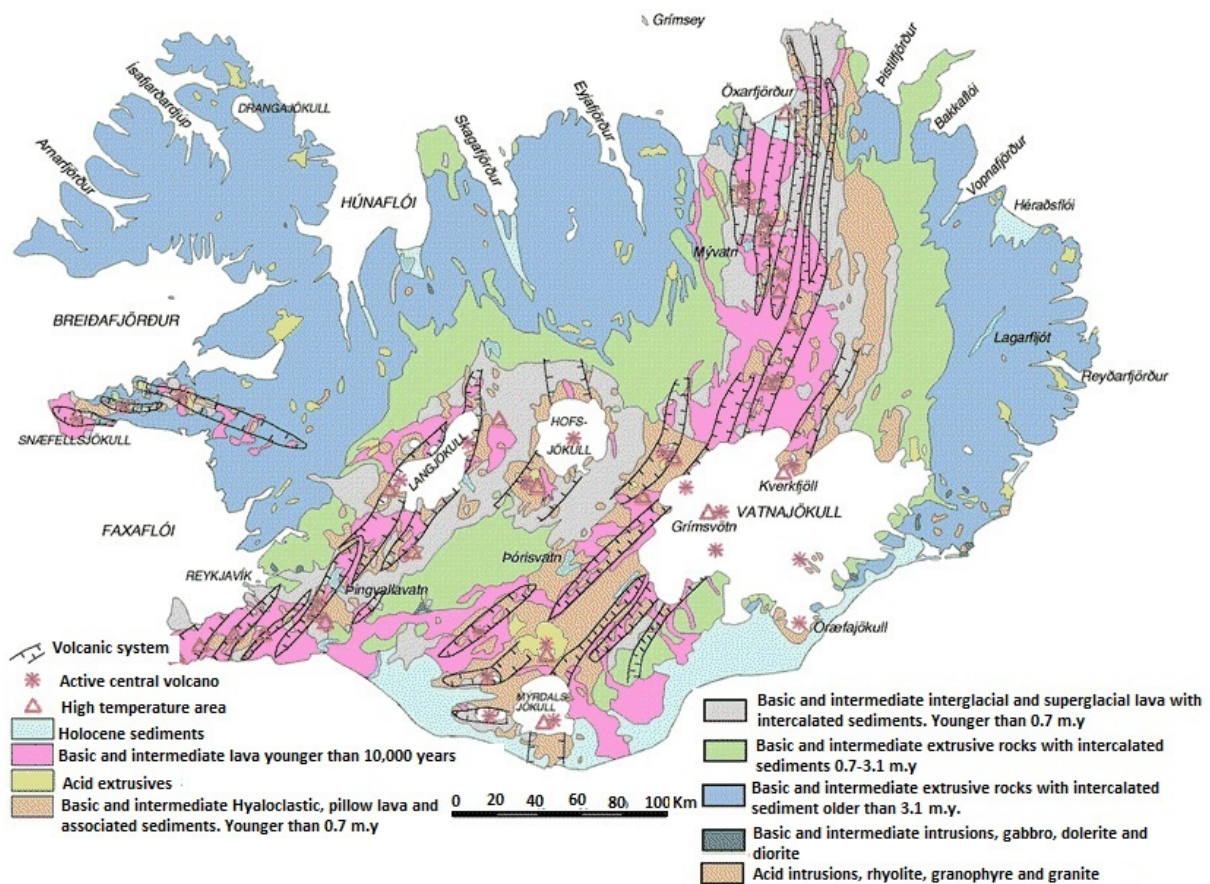

FIGURE 3: Geological map of Iceland showing oldest Tertiary rocks, Plio-Pliostocene eruptives, Holocene rocks and other young formations;volcanic systems follow the oceanic ridge (Jóhannesson and Saemundsson, 1999)

Volcanic rocks in Iceland are classified into three series: tholeiitic, alkalic and transitional. The tholeiitic rock series are confined to volcanic systems in the rift zones which delineate the crest of the Mid-Atlantic Ridge. The alkali and transitional series are confined to volcanic systems in the flank zones (Jakobsson et al., 2008). A volcanic system is the principle geological structure in Iceland; it consists of a fissure swarm, a central volcano and intrusives which often provide a potential for geothermal systems. Geothermal areas in Iceland are distinguished by its temperature at a depth of 1 km where areas with temperature ≤ 150°C are considered low temperature systems while areas with temperature ≥200°C are high temperature systems. The low temperature systems are mostly outside of the volcanically active zone and are related to active fractures and fault zones, as their heat source is hot rock at depth (Arnórsson et al., 2008).

The high temperature areas are confined to the active volcanic zone of tectonic rifting and volcanism with central volcanoes, fissure swarms and sometimes calderas. They are thought to draw heat both from the regional heat flow and from local accumulations of igneous cooling (dykes and sheets) at a shallow level in the crust (Fridleifsson, 1979).

1.3 Geological and tectonic settings of the Hengill area

Hengill volcanic complex is a high temperature geothermal area located at a triple junction where the Western rift zone, the Reykjanes peninsula and the South Iceland fracture zone meet. The geothermal area is connected to an active NE-SW trending fissure swarm. The main component of the volcanic system is a 40 km long and 3-5 km wide fissure swarm where rifting is most active and volcanic accumulation is highest in the central part of the Hengill complex, as shown in Figure 4. Rock formations are mainly volcanic and the largest part is built up of hyaloclastite formations erupted during glacial periods, while interglacial lavas erupted in the highlands flowed to the surrounding lowlands. Intermediate and felsic rocks are found at the western edge of the volcano but have also been found as intrusives in drill holes throughout the geothermal field (Franzson et al., 2010).
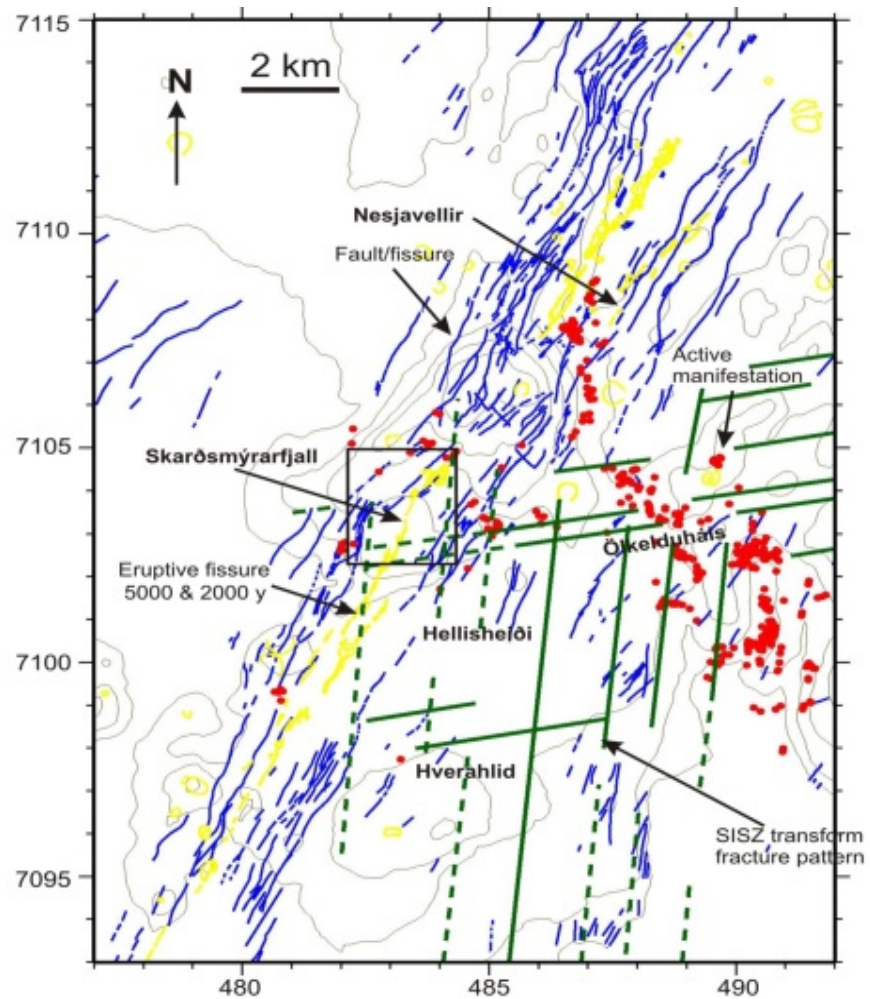

FIGURE 4: Map of the Hengill volcanic complex showing the topography, interpreted faults related to the transform fractures (green), faults related to the fissure swarm (blue) and postglacial eruptive fissures (yellow) cutting the central volcano (Franzson et al., 2010)
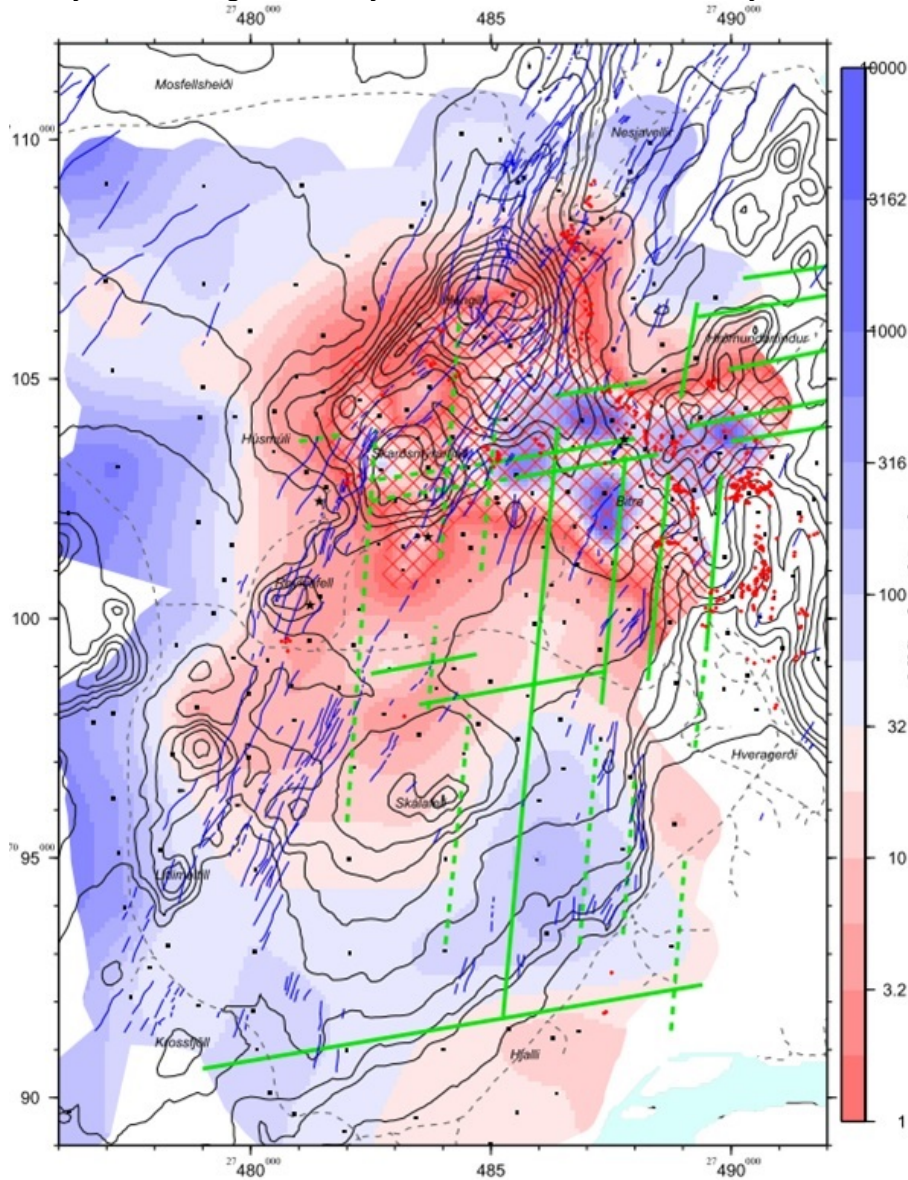
1.4 Previous geoscientific studies at Hellisheidi

Several scientific studies have been conducted in the Hengill area, including the Hellisheidi geothermal field, which show surface manifestations such as hot springs with temperatures ranging from 8°C to 99°C. Manifestations show both fossil and active thermal expressions such as steam vents, steaming grounds, warm soil and altered grounds (Saemundsson, 1995). The Hellisheidi surface area is characterized by two main features: hyaloclastite formations, which were formed sub-glacially, and postglacial lavas from volcanic fissures trending NE-SW. The age of the older is 5500 years and the

younger is about 2000 years (Saemundsson, 1995). The hyaloclastite and the lava series are generated from the Hengill central volcano. The hyaloclastite is categorised into three units based on glass contents: pillow basalt, breccia and tuff from low to high contents, respectively.

Various geophysical studies have been conducted in the Hengill area since the 1940s. Geophysical methods have been proven to be sensitive to alteration and the fluid content of the rocks and also reveal structures that influence the properties of the geothermal system. The most informative exploration method in defining the geothermal reservoir prior to drilling is, however, resistivity (Franzson et al., 2010). DC resistivity surveys using Schlumberger and dipole–dipole sounding, a Bouguer gravity survey, an aeromagnetic survey and a seismic refraction survey were conducted in the area in the late twentieth century (Hersir, 1980; Hersir et al., 1990; Thorbergsson et al., 1984; Björnsson and Hersir, 1981; Pálmason, 1971; Foulger, 1984). Replication of studies done in 1986 with detailed DC resistivity, which delineated a 110 km² low resistivity area at 200 m b.s.l, and a magnetic survey showed a negative and transversal anomaly coherent with the most active grounds. Transient electromagnetic soundings (TEM) were also conducted to upgrade the data that already existed (Figure 5). The study indicated that the high resistivity signal close to the surface related to an unaltered zone (fresh rock), the low resistivity signal related to low-temperature alteration minerals at shallower depth (smectite-zeolite), and deeper high resistivity to the formation of chlorite and less conductive alteration assemblages (Franzson et al., 2010).

FIGURE 5: Hengill area, resistivity at 100 m b.s.l. according to a recent TEM survey, faults (blue/irregular lines) and interpreted earthquake fractures from recent seismic events (green/straight lines); Scale to the right shows resistivity in Ωm (Árnason and Magnússon, 2001)

2. BOREHOLE GEOLOGY

2.1 Brief history of drilling well HE-4

Well HE-4 is a directional exploration well, drilled east of Reykjafell mountain to a measured depth of 2008 m. The well has the following coordinates: X - 383,491.82, Y - 393,716.71 and Z - 404 m a. s. l. The well was designed to intersect the active fault and the volcanic fissure which lies southwest of Hengill, and the aim was to provide information about geothermal heat between Reykjafell mountain and the Hveradalir valley (Jónsson et al., 2001; Guðmundsson et al., 2001ab).

Drilling commenced on 31st August 2001 and involved three phases, as shown in Figure 6. The first phase was drilled with a 17 ½" drill bit, and a safety casing of 13 ⅜" to a depth of 300 m. The surface casing had already been set at 78 m. The well was planned to deviate from 300 m to a direction of 208° (towards southwest). The drilling rate was slow: 2.5 to 3.5 m/h to avoid the collapse of soft formations near the surface. The drilling of the first phase stopped at 305 m where temperature and caliper logs were conducted before the casing was set. A total of 24 m^3 of concrete was used for cementing the casing. No circulation loss was encountered during this phase.

The second phase started on September 8th 2001. The phase was drilled with a 12 ¼" drill bit and cased with 9 ⅝" production casing; 50 l/s circulation loss was encountered at a depth of 496 m. Exercises to stop the leaking were not successful at first and various problems persisted, including eruptions due to high pressure in the hole. After repeated cementing and several

FIGURE 6: Drilling progress of well HE-4

temperature measurements, drilling started again after about a 4 day delay, still somewhat problematic. Drilling finally ended at 789 m where geophysical logging was conducted. After the casing had been set and cemented, gyro measurements were made, marking the end of phase 2.
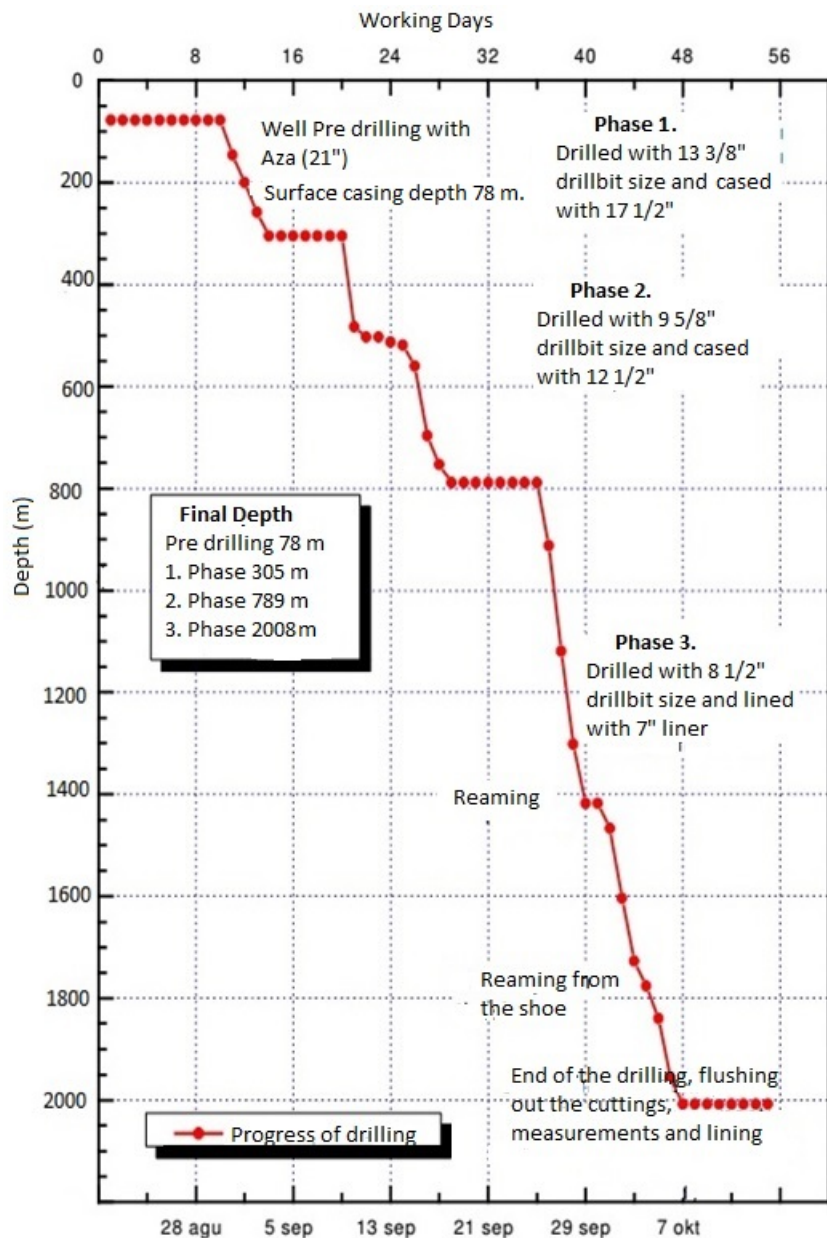
The third section started on the 25th of September 2001 and was drilled from 789 m to 2008 m with an 8 ½" drill bit. At 1148 m, a fairly large feed point was crossed which caused a circulation loss of 37 l/s; hardly any circulation was retrieved from this depth until 1184 m. At 1270 m, circulation was lost again and, at around 1400 m, the drill bit got stuck for a while. As soon as the bit was free, reaming and washing started but the problem persisted for some time until enough reaming had been conducted. Drilling then continued down to 2008 m where torque was substantial. Temperature logs and gyro measurements were made, followed by geophysical logging. Close to the bottom the inclination measured around 45° and the azimuth around 198°. When all logging had been conducted, the 7" liner was set down on the 11th of October. Soon afterwards well testing was finished and phase 3 was completed on the 14th of October.

2.2 Analytical methods

Binocular microscope analysis; rock cuttings were sampled at an interval of 2 m during drilling. It is important to analyse wet samples to have clear visibility of any obscured features in the cuttings. The analysis of samples in the binocular microscope helps with analysing the rock type with its primary minerals, grain size, oxidation, alteration minerals and alteration intensity, fractures and vein fillings. About 600 samples were sampled from the upper 1200 m of well HE-4.

Petrographic microscope; the petrographic analysis is based on 34 thin sections from different depth intervals as representative samples from the upper 1200 m of well HE-4. The analysis is used to correlate and add valuable information on rock type, texture, primary minerals and their alteration and secondary minerals along with alteration sequence and porosity.

X-ray diffractometer analysis; the analysis is used to examine crystallized materials with emphasis on the clay minerals. The samples were selected from different depths from the upper 1200 m, emphasizing the areas with signs of different clay alteration, for identification of their types. The samples were placed in crucibles, then washed with distilled water to remove all dust or mud that might be stacked on them. The recommended sample size is not less than one full teaspoon topped up with water and placed in the shaker for about 3 hours to separate the clay from the rock matrix. When finished, the samples were mounted on glass, dried and were then ready for XRD-analysis. This method is very important for identifying clays and amphiboles which, in turn, provide information on the alteration temperatures. The XRD analyses of clay minerals in well HE-4 are found in Appendix I.

Fluid inclusion analysis; the analysis is conducted using microthermometry by gradually heating up the sample to the maximum temperature (homogenization temperature) of the fluid inclusions, so that the bubble within the fluid inclusions, trapped during crystallisation, disappears. Primary inclusions are those that form due to imperfections on the crystal surface during crystal growth. Generally, the mechanism for forming secondary inclusions involves the development of post crystallisation fractures initiated during mechanical or thermal stress. These cracks are then sealed by later fluids to form the characteristic trails of secondary inclusions which typically cross-cut earlier generations (Shepherd et al., 1985). The analysis provides direct information on the temperature during the formation of the hydrothermal minerals and was used in this study (along with the temperature of first appearance of alteration minerals and the formation temperature) for the interpretation of the thermal situation of the geothermal system.

The selection of samples in well HE-4 was based on the different intervals of the upper 1200 m aided by temperature logs and formation temperature, focusing on areas of temperature change and/or aquifers. Clear quartz crystal and platy calcite were selected, being some of the best representatives for analysing fluid inclusions.

2.3 Stratigraphy of well HE-4

The subsurface geology of this study covers several units of rock formations, mainly distinguished by crystallinity and volcanic glass contents. Figure 7 shows the lithology of the well HE-4. Hyaloclastite basalt formations are found to alternate within the HE-4 well column including basaltic tuff (distinguished by its high content of volcanic glass) basaltic breccia (partially crystalline basalt mixed with volcanic glass) and pillow lava (partially crystallised basalt) which comprises the smallest content of volcanic glass. Fine grained and fine to medium grained crystalline basalt were also encountered within the well, forming either sub-aerial lavas or intrusions. The formations are also described
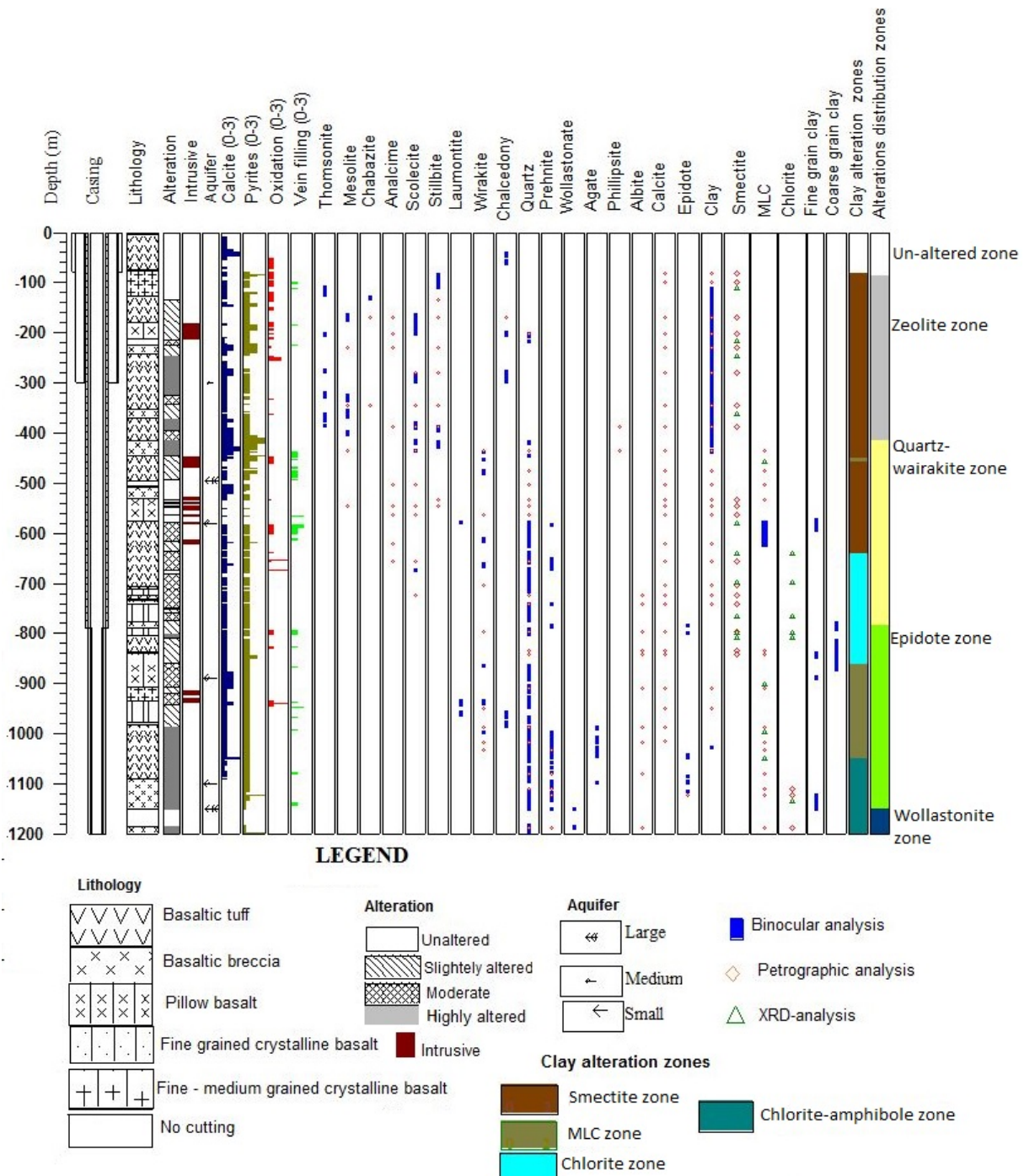

FIGURE 7: Lithology and distribution of alteration minerals in well HE-04 at 0-1200 m

according to their physical characteristics, mainly based on texture and the difference in alteration intensity from one unit to another. The description of the rocks is based on the binocular analysis with the aid of the petrographic analysis as explained below:

0–4 m. No sample

4–86 m. Basaltic tuff
Fine to medium grained tuff, with phenocrysts of olivine and plagioclase. Some of the tuff formation has been altered to palagonite. Some vesicles are seen in the upper part and some are filled by chalcedony while in the lower part the tuff is more consolidated with no vesicles. The colour ranges from dark – brown – grey and the rock shows slight alteration. Secondary oxidation minerals, such as limonite and siderite, appear more common between 52–72 m. Pyrite first appeared at 78 m. There are no cuttings from 74–76 m. It is very likely, however, that the tuff is continuous since it is homogeneous.

86–126 m. Crystalline basalt
Fine grained crystalline basalt, dark to grey in colour. Vesicles are filled with secondary minerals including stilbite and calcite. The rock is oxidized in the upper part where limonite and siderite are found. Pyrite also appears to be a common alteration mineral in this formation.

126–180 m. Basaltic tuff
Fine grained and dark grey in colour (consolidated tuff). In the lower section it is mixed with breccia basalt. The less oxidized formation has a high content of olivine. This formation is less vesicular than the one above and the vesicles are filled with calcite and amorphous silica. Clay alteration seems to appear in a disseminated way. Other secondary minerals are scolecite, mesolite and pyrite.

180–212 m. Basaltic breccia
Dark in colour, partially crystallised basalt cut through by fine grained basalt intrusives, with olivine and plagioclase phenocrysts. The formation is mixed with particles of transformed tuff. It is moderately oxidized showing some limonite alteration. Other secondary minerals are calcite, pyrite, thomsonite, chalcedony and clay in the lower part of the formation.

212–224 m. Basaltic tuff
The formation is dominated by light to green colours; it is fine grained and with olivine mottled phenocrysts. Clay alteration results in the green colours of the rock, and pyrite and calcite appear to be common.

224–242 m. Basaltic breccia
Fine grained and dark to brownish in colour, slightly fractured and filled with calcite and pyrite in the upper part. Olivine is altered to clay which is also deposited as vesicle fillings. Amorphous silica is also encountered.

242–352 m. Basaltic tuff
The formation is mixed with basaltic breccia in the upper part but dominated by fine grained basaltic tuff of brown to greenish colour. Fragments of crystalline basalt are encountered from 294 m to 312 m. The rock is slightly oxidized from 250–262 m, where the formation is also highly altered and more porous. Calcite, chalcedony and clay are common. Other alteration minerals are pyrite and zeolites (thomsonite and scolecite) in low amounts.

352–370 m. Basaltic breccia
Fine to medium grained basaltic breccia with brown to greyish colours. Fine grained basaltic tuff is encountered from 358 m to 360 m. Alteration minerals seem to be in low quantity but include clay, pyrite, calcite and zeolites (scolecite).

370–416 m. Basaltic tuff
Greenish to grey, fine to medium grained basaltic tuff. Some particles of fresh and fine crystallised basalt are encountered at 408 m which could be an indication of an intrusive. Pyrite appears in high quantity relative to calcite (platy calcite first appears at 392 m).

416–444 m. Basaltic breccia
Fine to medium grained basaltic breccia with colours ranging from light to grey to green. The rock is completely altered and more porous than before. Vesicles are filled with secondary minerals including platy calcite, clay, pyrite and zeolites (including thomsonite, stilbite and scolecite) are common. Quartz crystals first appear at 414 m, gradually increasing from there, and the high temperature zeolite wairakite appears a little bit further down (436 m according to the petrographic study).

444–530 m. Basaltic tuff
The formation is highly porous, very fine grained (ash like) more vesicular and altered, light to greyish in colour, fractured with vein fillings of calcite and silica minerals. An intrusive of fine grained crystalline basalt appears from 448 to 468 m. There is an interval of no cuttings between 494 and 504 m (loss of circulation) which indicates a permeable zone. Dominant secondary minerals are pyrite, clay and low amounts of calcite. Wairakite is first seen in the binocular analysis at 452 m whereas in the thin section it was seen at 436 m. Zeolite minerals are scolesite, stilbite and analcime; quartz seems to be common in this unit.

530–576 m. Pillow basalt
The formation varies from light to grey in colour. It is fine grained and interrupted by multiple losses of circulation from 534 –538 m, 540–544 m, 548–562 m and 564–576 m. In the upper part of the formation there is fresh fine grained crystallised basalt with phenocrysts of olivine, considered an intrusive rock. Secondary minerals are quartz, calcite, clay and low amounts of pyrite.

576–706 m. Basaltic tuff
Altered basaltic tuff, fine to medium grained, green to brownish in colour. Primary minerals of pyroxene and plagioclase are seen. The rock is highly altered in the upper part down to 596 m and moderate alteration is seen from 598 m down to the bottom of the formation, fractured with micro veins filled by calcite. An intrusive of fine grained crystalline basalt is encountered from 618 m to 660 m. The representative alteration sequence is clay – calcites – clay – mixed layer clay – Sio2- quartz and pyrite appear to be disseminated. Wairakite, scolecite (zeolite) and prehnite were also encountered. Between 678 m and 682 m there is a gap with no cuttings but the lithology remains homogeneous above and below.

706–710 No cuttings

710–724 m. Fine grained crystalline basalt
Brownish to grey crystalline basalt, plagioclase and olivine primary minerals appear as phenocrysts. The formation is moderately altered and mixed with low amounts of basaltic tuff. Secondary minerals are quartz, pyrite, prehnite, wairakite and a smaller amount of clay and amorphous silica.

724–732 m. Basaltic tuff
Fine grained, highly altered basaltic tuff, brownish to grey in colour with phenocrysts of plagioclase. Alteration minerals include very low amounts of pyrite, calcite and clay. Other alteration minerals are prehnite and quartz. At 732–734 m there were no cuttings.

734–740 m. Basaltic breccia
Fine grained, grey coloured basaltic breccia as the dominant formation mixed with particles of brownish basaltic tuff. Alteration minerals seem to be in low quantity and include pyrite, quartz and calcite.

740–776m. Basaltic tuff
Consists of fine grained tuff, brownish to grey in colour with moderate alteration. The formation is highly vesicular and somewhat filled with amorphous silica and clay. Basaltic breccia appears at the interval of 752–758 m. Other secondary minerals are pyrite, quartz and calcite.

776-788 m. Basaltic breccia
The formation is a mixture of tuff and basaltic breccia with brown to grey colours, respectively. Coarse and fine grained clay, agate, calcite, quartz and pyrite are common and epidote (first appearance) is noted at 784 m.

788-804 m. Fine grained crystalline basalt
Dark grey, very fine grained basalt mixed with light brown basaltic tuff towards the bottom. Fractured and filled by calcite. Quartz, epidote, clay and pyrite are common alteration minerals.

804-838 m. Basaltic tuff
Highly altered fine grained, light brown tuff, mixed with basaltic breccia and greenish fine grained crystalline basalt. Multiple micro veins are seen, filled with calcite and amorphous silica.

836–906 m. Pillow basalt
Fine grained pillow basalt of yellowish to green colours. The yellowish green colour of epidote is seen in the formation but there are no well-developed crystals. Vesicles are filled with fine and coarse grained clay. An interval of dark to grey breccia basalt is seen from 870–874 m. Secondary minerals are quartz, pyrite and a high amount of calcite.

906–934 m. Fine – medium grained crystalline basalt
Green to dark, mixed with more fresh fragments of fine crystalline basalt at 910-914 m which presents an intrusive. The intrusive then reappears at 918–920 m, 928 m and 932 m, possibly representing traces of the intrusive from 910-914 m. In addition there is some amount of breccia and glassy basalt mixed in the lower section with brownish spots showing olivine that has been altered to clay. Other secondary minerals are quartz, pyrite, calcite, wairakite and laumontite.

934–978 m. Fine grained crystalline basalt
Green to dark, fine grained basalt, fractures filled with clay and chalcedony. Vesicles are filled with laumontite, clay and quartz. Pyrite is also seen.

978–980 m. No sample

980–1090 m. Basaltic tuff
Basaltic tuff is the dominant formation at this depth interval and is mixed with small amounts of breccia basalt. General texture is fine to medium grained and the colour ranges from light to grey to green. Coarse grained clay is seen and veins filled with calcite (platy calcite is also encountered). Other secondary minerals are quartz, pyrite, chalcedony, wairakite, agate; epidote is seen from 1040 m.

1090–1200 m. Basaltic breccia
The dominant lithology is basaltic breccia of greenish colour mixed with basaltic tuff all the way to the bottom. The lithology is interrupted by a gap of no cuttings from 1152-1184 m (circulation loss) but the lithology is believed to be homogenous down to 1200 m. Secondary minerals are epidote, quartz, pyrite and clay. Calcite is not seen in this unit. Wollastonite appears at 1150 m.

2.4 Intrusives

Intrusive rocks are identified by their compact nature, relatively low alteration, sometimes by oxidation found at their margins and they are normally younger than the host rock. Geophysical logs often show them to have relatively high n-n and resistivity values (Franzson et al., 2005). Intrusive structures are important features of geothermal systems as they relate to permeability. Several intrusives were encountered at various depths in well HE-4 and all are fine crystallized basalt, indicating rather thin dykes or sills, found at 182–212 m, 528–580 m, 614–660 m, and 912–920 m (reappearing occasionally between 930–938 m). Minor amounts of intrusive grains were identified from fresh particles of fine crystalline basalt, indicating an intrusive nearby at 408 m. The intrusives identified from cuttings through binocular analysis are presented in Figures 7 and 8.
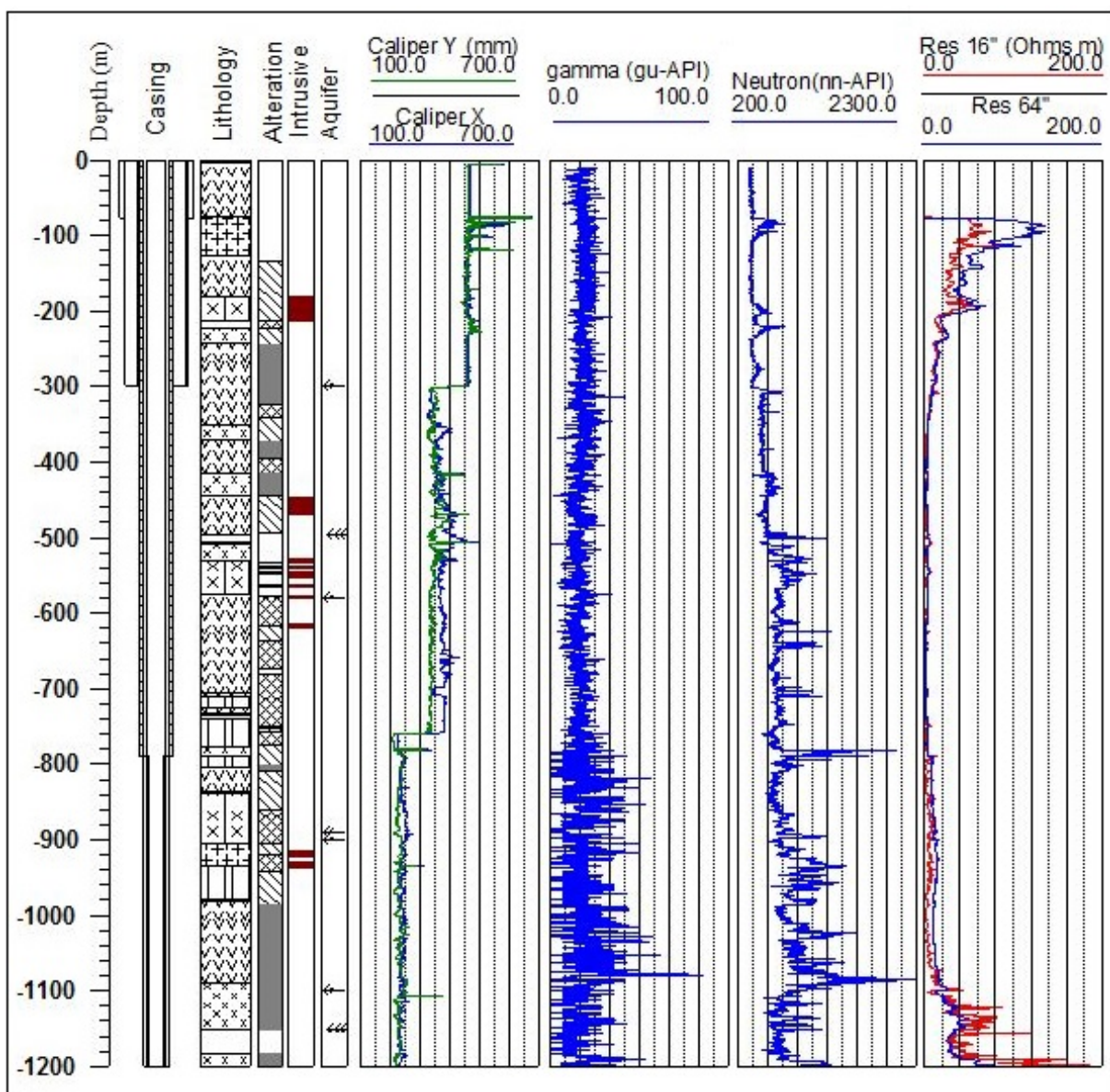

FIGURE 8: Feed points in relation to lithology, geophysical logs, intrusives and alteration intensity in well HE-4 (same legend as in Figure 7)

3. HYDROTHERMAL ALTERATION

Hydrothermal alteration occurs when fluids and reservoir rocks react to each other in hydrothermal systems. The reactions result in various changes by forming new rock properties including textures, changing porosity, permeability and chemical composition or generating new minerals commonly considered as secondary minerals. The factors that usually control alteration in geothermal systems are temperature, rock type, permeability, fluid composition and the duration of fluid-rock interactions (Browne, 1978; Elders et al., 1981).

Of all the different factors contributing to hydrothermal alteration, temperature plays a key role when studying and interpreting the changes of the original state of the reservoir rock by considering primary rock forming minerals and fluids within the reservoir. Temperature not only controls, to a degree, the composition of secondary mineral assemblages but also the rate of alteration processes (Reyes, 2000). The interpretation is based on the alteration minerals (secondary minerals) that have been studied according to their standard forming temperature. A comparison is made between the present information from surface to sub-surface geology through different methodologies including geochemical, geological and geophysical studies. Hydrothermal alteration helps with identifying and revealing present and past conditions in geothermal reservoirs.

3.1 Primary minerals

Primary minerals are rock forming minerals that form during rock crystallisation; these minerals are essential for the classification of the rock. The minerals form in a sequence or in sequential groups as detected by the chemistry and physical conditions under which the magma solidifies. Primary minerals tend to alter and form secondary minerals at conditions of high temperatures, high permeability and fluid activity in a hydrothermal environment (Gebrehiwot, 2010). Hyaloclastite and crystalline basaltic rock are the main rock types throughout well HE-4, and they are mainly composed of volcanic glass, olivine, plagioclase, pyroxene and opaques as the primary minerals. Their degree of susceptibility differs from one mineral to another as shown in Table 1 and Figure 9.
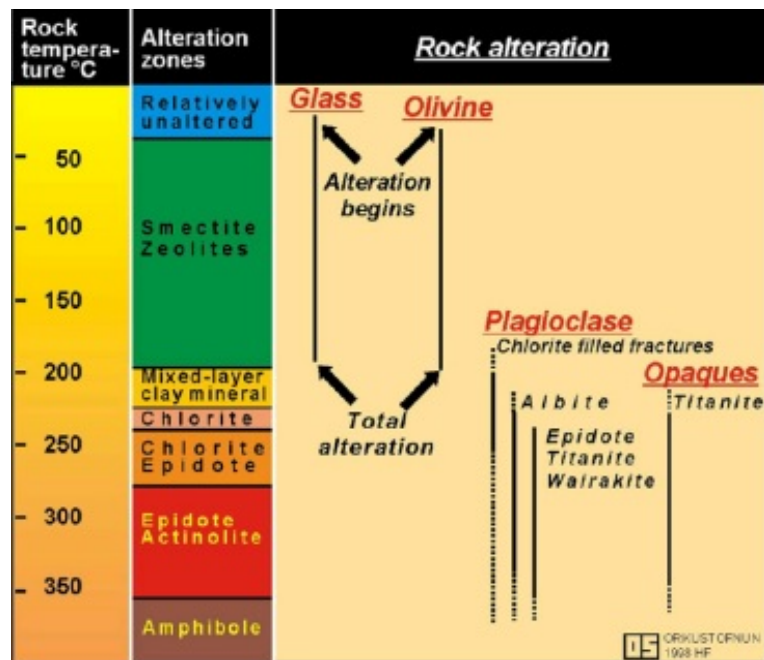
FIGURE 9: Mineral alteration temperature diagram
(Franzson, 1998*)*

TABLE 1: Primary rock minerals and their alteration products in well HE-4

Susceptibility	Primary Mineral	Alteration Mineral Product
↓	Volcanic glass	Clay, zeolite, calcite, quartz
	Olivine	Clay, calcite, quartz
	Plagioclase	Clay, calcite, albite, wairakite, quartz, chlorite, epidote
	Pyroxe	Clay
	Opaques	

Volcanic glass is an amorphous (uncrystallised) product formed during the quenching of magma. Volcanic glass occurs in well HE-4 as a matrix material which shows highly vitreous lustre and has good conchoidal fracturing. Glass has low resistance to alteration compared to primary minerals. In well HE-4, clay, smectite and calcite are the common alteration minerals of glass which was completely altered from 656 m.

Olivine is one of the primary minerals formed in basaltic rocks (olivine tholeiite). It is the second most susceptible to alteration after glass. In thin section it is distinguished by its high birefringence, distinctive irregular fracture pattern, lack of cleavage, and its parallel extinction. Along its fractures the alteration products are usually clay, calcite and chlorite. Olivine can also alter to quartz although in well HE-4 there was no clear evidence of this. In binocular analysis, olivine mostly appeared as phenocrysts in the upper part of the well and seems to be completely altered from 724 m, according to the petrographic study.

Plagioclase is the most abundant primary mineral in igneous rocks. It is easily identified in thin section by its low relief, maximum interference colours are usually first-order grey or white, and twinning distinguishes plagioclase from most other minerals. Plagioclase is progressively altered to clay, calcite, albite, quartz, wairakite, chlorite and epidote as temperature increases. The first noticeable alteration of plagioclase in well HE-4 was to clay in cracks at 620 m which seems to increase the alteration at the lower depth of the well.

Pyroxene minerals are significant components of many intermediate and most mafic igneous rocks. Pyroxene is black or dark green in colour and forms prismatic crystals with vitreous lustre and perfect cleavage. Extinction at an inclined angle distinguishes it from olivine as well as its apparent cleavage and light brown colour in plain polarized light. Most pyroxenes seen in well HE-4 appeared in the groundmass and some as phenocrysts. Pyroxene started to alter to clay at 1032 m, showing more resistance than glass, olivine and plagioclase to high temperature.

Opaque minerals do not transmit light in transmitted light microscopes. They are usually magnetite (oxide mineral) in basalt. These minerals were hardly altered throughout the well although often there were signs of oxidation on their edges.

3.2 Distribution and description of hydrothermal alteration minerals

Hydrothermal minerals are derived from primary minerals or glass and form due to the physical and chemical composition in geothermal systems where temperature is the key factor (Reyes, 2000). In well HE-4, various hydrothermal minerals were observed including calcite, pyrite, clay, zeolites, quartz and epidote. These minerals are important in this study as the temperature at which they form is compared to the present formation temperature of the well and together they provide information about the situation of the current geothermal system surrounding the well. The distribution of alteration minerals encountered in well HE-4 is shown in Figure 7 and the standard temperature for the formation of some of the alteration minerals in Iceland can be seen in Table 2. A description of the alteration

TABLE 2: Some temperature dependent minerals in high-temperature areas in Iceland (Kristmannsdóttir, 1979; Franzson, 1998)

Minerals	Min. temp. (°C)	Max. temp. (°C)
Zeolites	40	120
*Laumontite	120	180
*Wairakite	200	
Smectite		<200
**MLC	200	230
Chlorite	230	>300
Calcite	50-100	280-300
Quartz	180	>300
Prehnite	240	>300
Epidote	230-250	>300
Wollastonite	270	>300
Actinolite	280	>300
*Belong to the zeolite group **Mixed-layer clay		

minerals along with their occurrence within the well is provided below:

Limonite forms by chemical weathering of iron rich minerals including olivine, pyroxene and magnetite, some of the main constituents of basaltic rock. Limonite mainly forms close to the surface where it is mostly associated with cold water with an abundance of oxygen. It is reddish brown in colour, and usually forms spherical precipitations within vesicles or fractures.

Siderite is a carbonate group mineral, spherical and brownish in colour and forms at shallow depths. It commonly appears together with limonite. These two minerals were encountered down to about 136 m in well HE-4.

Calcite is the most abundant alteration mineral in well HE-4, mainly filling pores and veins. The first appearance of calcite was at 20 m depth but was seen all the way to 1092 m. The temperature of calcite deposition is relatively difficult to determine, however, experience has shown that the mineral disappears at temperatures above 290°C (Franzson, 2000; Kristmannsdóttir, 1979). Different forms of calcite were encountered at different depths with platy calcite first appearing at 392 m and dog tooth calcite was clearly seen in a thin section at 280 m.

Pyrite belongs to the sulphides group and is most abundant in well HE-4 between 400-500 m, just above one of the large aquifers in the well (Figure 7). It is first noted at 80 m and seems to occur throughout the well with fluctuating intensity. Most of the pyrites are found to be deposited in disseminated forms and some as fillings in veins and vesicles. The existence of H_2S in geothermal systems results in the formation of pyrite and pyrite in abundance is often associated with permeability (Reyes, 2000).

Zeolites form a group of hydrous secondary minerals composed of sodium, calcium and aluminium silicates. Zeolites are generally white or colourless but they can show yellow or reddish colours due to impurities. As temperature indicators, zeolites form at relatively low temperature and they are dependent on the chemical composition of the solution. These minerals tend to precipitate in vugs and vesicles where they are classified into three different habits as fibrous/acicular, tabular/prismatic and granular (Saemundsson and Gunnlaugsson, 2014). In well HE-4, low temperature zeolites first appear at 84 m, only disappearing at 676 m. Remnants of them were identified in thin section at 834 m; below are the descriptions of the different types of zeolites encountered within well HE-4:

Analcime is clearly identified in the petrographic microscope through its trapezohedron crystal shape, by which it is also identified in the binocular microscope. It is colourless in plane polarized light (Figure 10) and almost isotropic in crossed polars. Analcime commonly has weak birefringence and may display lower first-order interference colours. These minerals commonly form at low temperatures at around 40°C and, in well HE-4, it started to appear at 170 m.

Thomsonite is an acicular radiating zeolite. These zeolites form dense masses of radiating clusters of prismatic crystals, filling vesicles or veins and are often associated with other zeolite minerals such as scolesite. Thomsonite tends
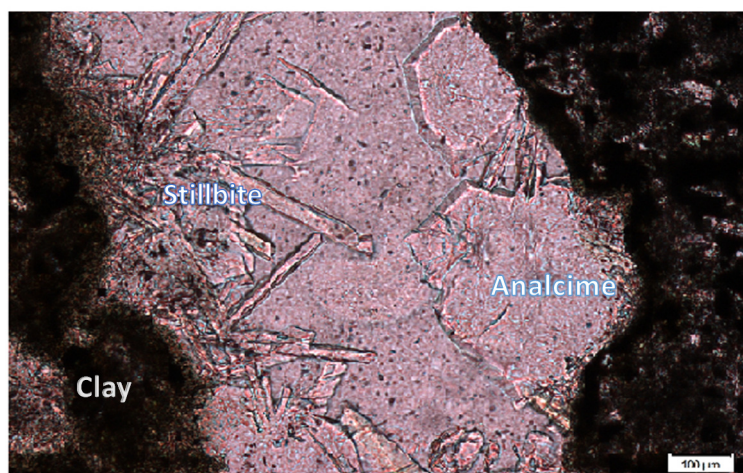

FIGURE 10: Photo from the petrographic microscope showing analcime, stilbite and clay at 280 m

to crystallize at a temperature of 30-40°C and was first noted at 106 m.

Scolesite/Mesolite: these are both fibrous zeolites with somewhat distinctive features where scolecite has thicker fibres while mesolite has thin fibres which are brittle and break easily. They are colourless or white with a vitreous lustre and often appear together in basaltic formations. They commonly form at around 70-80°C and, in well HE-4, they started to appear at 164 m.

Stilbite appears as rather thick, tabular crystals with pointed terminations. The crystals are white, transparent to translucent with a vitreous lustre, especially on the domed or oval ends of crystal bundles, while the broad face at the middle has a pearl lustre. Stilbite normally forms at temperatures around 90°C. In well HE-4 it was first seen at 84 m.

Chabazite forms at temperatures around 30°C. Chabazite was not identified in the binocular microscope and only seen in a thin section from 170 m in well HE-4. Chabazite occurs most commonly in voids and amygdales in basaltic rocks, the crystals are typically twinned and both contact twinning and penetration twinning may be observed.

Laumontite is a tabular zeolite that forms at somewhat higher temperatures than the low temperature zeolites. It is commonly white in colour and was first found at 934 m, indicating temperatures of 120°C. It is, however, not a reliable mineral for alteration temperature.

Wairakite is a high temperature zeolite forming at greater temperatures than 200°C. Wairakite was first seen at 452 m in the binocular analysis and in the petrographic microscope it was identified at 436 m by its conspicuous cross hatched twinning. It commonly occurs as an individual crystal or as glittering clusters (colourless crystals).

Quartz is colourless, milky to white or grey mineral with a conchoidal fracture. It forms hexagonal prismatic crystals which end in slanted faces meeting at a point. Quartz indicates temperature above 180°C and is considered a stable mineral. In well HE-4, quartz appeared between 202 m and 208 m, then disappeared and reappeared at 414 m. The shallow depth quartz seems to be a very local alteration brought on by an intrusive of fine grained crystalline basalt which probably caused localised raised temperatures. From the above scenario, quartz is considered to first appear at 414 m and is seen all the way to 1200 m in various basaltic formations within the well.

Albite is an alteration mineral derived from the alteration of the primary mineral plagioclase and sometimes occurs as precipitation filling vesicles. Albite is identified in thin sections by a cloudy appearance which makes the plagioclase twinning disappear. When well crystallised it has the appearance of the top of a roof. The albite alteration of plagioclase starts at a relatively high temperature, commonly forming at temperatures near 300°C (Kristmannsdóttir, 1979). It was first noted at 620 m in well HE-4. Albite is usually colourless or white and is, in some ways, similar to quartz but differs by its lower refractive index and its cloudy nature which is not seen in quartz. Albite was only seen as an alteration of plagioclase, not as a precipitation.

Chalcedony is the cryptocrystalline form of silica minerals; it has a waxy lustre, and may be semi-transparent or translucent. Most of the chalcedony seen in well HE-4 is white to grey or greyish blue in colour. Chalcedony forms at different depths, first seen at 112 m as a vesicle filling. The mineral appears and disappears all the way to 1032 m where it completely disappears.

Agate is a variant of chalcedony with bands of different colours generally following the contours of the cavity. Agate is commonly found with chalcedony and quartz and was seen at 784 m, disappearing again at 1098 m.

Prehnite appears as small spherical clusters of crystals, colourless to white in colour in the binocular microscope. In the petrographic microscope it is colourless in plane polarized light with a fairly high relief, while with crossed polars it shows strong interference colours and a bow-tie texture. In well HE-

4 it first appeared at 582 m in the binocular analysis and in thin sections it was found to be common from 988 m. This mineral indicates temperature above 240°C.

Wollastonite is commonly associated with high temperature minerals such as chlorite, epidote and actinolite. In well HE-4 it appeared together with chlorite radiating from the centre of the cavities, with a hairy like (fibrous) habit. It was found at 1150 m depth, indicating temperature of around 270°C.

Epidote is a high temperature alteration mineral and one of the most important ones for a geothermal production zone as it is usually easily identified by its yellowish green colour. The lower temperature stability of epidote is 240-250°C and it remains stable to well above 300°C (Browne, 1978). The mineral first appeared at a depth of 784 m and is found to be common from 1042 m, as seen in Figure 7.

Clay minerals are common alteration minerals associated with both weathering of rock and with hydrothermal alteration. Different types of clay form with respect to temperature variations from the surface to the bottom of the well, usually from low temperature to high temperature. Different methodologies have been used to distinguish the types of clay: binocular analysis and petrographic analysis are used to distinguish the presence of clay alteration minerals and their crystallinity with the help of XRD analysis of the cuttings. The following are the types of clay minerals found in well HE-4, arranged from low temperature to high temperature;

> *Smectite;* this is the low temperature clay mineral commonly found near the surface at less than 200°C. Smectite is well identified in the petrographic microscope with its reddish to brown colours (with both plain polarized light and crossed polars). At around 82 m smectite was first found, confirmed by the XRD analysis at 94 m.

> *Mixed layer clay (MLC)* is the complex of smectite and chlorite clay minerals. It forms at higher temperatures than smectite, in the range of 200-230°C, where smectite and zeolites are gradually replaced by chlorite as the dominant alteration mineral in the so-called mixed layered clay zone (Kristmannsdóttir, 1979). Mixed layer clay was suspected in the binocular microscope from its appearance of alternating bands of light green and dark green colours at 580 m and in thin section it seems to be common from 862 m. XRD analysis identified MLC first appearance at 450 m then disappearing and reappearing from 902 to 1050 m.

> *Chlorite* is a high temperature clay mineral commonly associated with other high temperature minerals such as wollastonite, epidote and prehnite. Chlorite is commonly light green in colour and well identified in the petrographic microscope from its smooth or flat appearance. In the binocular microscope it was found at 1150 m filling the vesicle together with wollastonite and, in the petrographic microscope, clearly seen at 1188 m, whereas the XRD analysis indicates that chlorite appears together with smectite at 642-862 m then reappearing at around 1050 m (Figure 9).

Amphiboles are minerals of either igneous or metamorphic origin, the general group forms prism or needle like crystals and include tremolite, actinolite, tourmaline and hornblende. Colours can be green, black, colourless, white, yellow, blue, or brown. Actinolite forms as an alteration mineral in geothermal systems in Iceland but it was not identified in the binocular and petrographic analyses. Amphibole was, however, identified with XRD at 1050 m toward the bottom indicating temperature greater than 280°C.

3.3 Alteration mineral zonation

Alteration zones refer to the secondary minerals forming and dominating at a certain range of depth within the hydrothermal system, giving clues about the temperature. Alteration mineral zonation can differ from one geothermal system to another depending on the parent rock, the chemistry and temperature of the area. Icelandic geothermal systems are dominated with basaltic rock formations. From the group of alteration minerals identified in this study, and with respect to their temperature of

formation and sometimes the contradictory XRD clay analysis, the alteration zones in well HE-4 will be presented in two separate ways as follows;

1. Zonation depending on the distribution of alteration minerals
Based on the distribution and the first appearance of alteration minerals in well HE-4, which are stable at certain temperatures forming individual or groups of alteration minerals corresponding to Figure 9, six alteration zones were derived from low temperature to high temperature starting with an unaltered zone from the surface to a shallow depth, followed by the zeolite zone, quartz and wairakite zone, epidote zone and wollastonite zone.

2. Zonation depending on clay analysis
Five different zones of alteration were identified from the XRD analysis of clays, which was taken at different depths, combined with the petrographic analysis. The zones identified are as follows: from top surface to a shallow depth the zone is unaltered, followed by the smectite zone, chlorite zone, mixed layer clay zone and finally the chlorite-amphibole zone. On the basis of temperature and abundance of clay alteration within a certain depth interval, the following describe the clay zones with respect to depth:

a. *Unaltered zone (0-82 m);* from the two categorized zonations above, this zone is mainly comprised of surface alteration minerals forming from cold groundwater with temperature ranging from 0 to 40°C.

b. *Smectite zone (82-642 m);* defined by the first appearance and abundance of smectite clay where at a depth of 82 m it was identified through petrographic analysis in a slight amount (considered as first appearance), confirmed by the XRD analysis at 94 m. Temperature for the forming of smectite clay is less than 200°C.

c. *Chlorite zone (642-862 m);* the zone is comprised by the two independent clay minerals smectite and chlorite, where the existence of chlorite as a high temperature clay mineral indicates temperature above 230°C. Epidote first appears at 784 m, confirming that temperature.

d. *Mixed layer clay zone (862-1050 m);* is distinguished by a relatively high temperature above 200°C which is peculiar in well HE-4 because it forms below the chlorite zone. This could indicate fluctuations in the condition of the geothermal system.

e. *Chlorite-amphibole zone (1050-1200 m);* the zone is defined by the presence of abundant chlorite with amphibole alteration minerals first appearing at a depth of 1050 m. Both minerals are considered high temperature and, together, suggest temperatures more than 280°C.

3.4 Vein, vesicle fillings and mineral deposition sequences

Veins and vesicles act as hosts for the deposition of secondary minerals. Veins can appear as a single fracture or multiple veins within the rock, indicating active tectonic movements in the geothermal system. Rock porosity can be defined by the intensity of vesicles and veins throughout the formation. Hyaloclastite basaltic formations (glass rich rocks) seem to be more porous compared to lava formations (Kristmannsdóttir, 1979). Well HE-4 is predominantly comprised of hyaloclastite formations (basaltic tuff, basaltic breccia and pillow basalt).

In this study, the concentration of veins encountered along fractures that developed from intrusive events was quite common. This creates easy access for the deposition of secondary minerals. The deposition of alteration minerals infers a time sequence of deposition and temperature, this being one of the aids in determining whether the system is cooling or heating.

Concentrations of veins are found at different depth intervals within the well. Many of these relate to intrusions either nearby or fractures within intrusives. The intervals are: 142-148 m within basaltic tuff and near an intrusive, 446-492 m within basaltic tuff where veins tend to appear and disappear near an intrusive, 578-610 m within basaltic tuff near an intrusive, 789-796 m within fine grained crystalline basalt, 932-942 m within fine-medium grained crystalline basalt, and 1138-1144 m in basaltic breccia. The mineral sequence in well HE-4 is mainly comprised of clay and calcite as analysed in the petrographic analysis and its description in Table 3, showing the formation and deposition of secondary minerals with relation to time at different depths.

TABLE 3: Sequence of alteration minerals in well HE-4

Depth (m)	Lithology	Sequence from older to young
100	Fine crystalline Basalt	Clay→ calcite
134	Basaltic tuff	Clay → zeolite → calcite
170	Basaltic tuff	Zeolite → calcite → clay
202	Basaltic breccia	Smectite → calcite
230	Basaltic breccia	Smectite →calcite→zeolite
344	Basaltic tuff	Clay→ calcite
388	Basaltic tuff	Clay → calcite →zeolite
436	Breccia basalt	Sample 1: Zeolite → clay → calcite
		Sample 2: Calcite → zeolite
476	Basaltic tuff	Clay → zeolite → calcite
504	Basaltic tuff	Clay→ calcite
532	Pillow Basalt	Clay → calcite
546	Pillow Basalt	Fine grained clay →.calcite
562	Pillow Basalt	Low temp clay high temp clay→ calcite
620	Basaltic tuff	Clay → calcite → sio2 → quartz
656	Breccia basalt	Clay→ calcite → quartz
704	Breccia basalt	Clay → calcite → quartz
724	Fine crystalline basalt	Clay → calcite→ quartz
740	Basaltic breccia	Sample1: Clay →calcite → albite
		Sample 2: Clay → calcite → quartz
796	Fine crystalline basalt	Calcite → -clay
		smectite → mixed layer clay
834	Basaltic tuff	Clay → calcite
882	Pillow Basalt	Mixed layer clay → quartz
950	Fine crystalline basalt	Calcite → Wairakite
988	Basaltic tuff	Clay → calcite
1016	Basaltic tuff	Mixed layer clay → calcite
1080	Basaltic tuff	Mixed layer clay → quartz
1112	Basaltic breccia	Mixed layer clay → prehnite

Calcite as the major secondary mineral filling the veins (and vesicles) in well HE-4, first appeared at 84 m and remains all the way to 1092 m where it seems to disappear (indicating temperatures above 290°C). Other vein filling minerals in the well are chalcedony, pyrite, clay, amorphous silica and occasionally quartz. Other secondary minerals are mainly found in vesicles.

The deposition sequences (Table 3) show low temperature alteration minerals followed by high temperature alteration minerals, indicating heating up of the system. Clay and calcite dominate in a wide range within the well from the shallow depth to 834 m, whereas at lower depths from 882 m, mixed layer clay appears to be common with other high temperature alteration minerals, including quartz and prehnite. High temperature alteration minerals are also confirmed by the resistivity curve in Figure 8 where high peak readings are noted from 1050 m where chlorite, epidote and wollastonite are the dominant alteration minerals.

4. AQUIFERS/FEED ZONES

An aquifer is an important parameter in geothermal production as the main water-bearing permeable rock where steam and water phase originate. Location of the production casing and depth of the production part is dependent on aquifers within the well. Integrations of different data are used during interpretation. In this study, aquifers were identified mainly from the interpretation of temperature logs (Figures 8 and 11), caliper and neutron logs, circulation losses and the correlation of lithological units with intensity of alteration, presence of veins and lithological contacts. Based on neutron log interpretation, as explained by Steingrímsson, 2011, the slowing down process of fast neutrons in the rock formations is primarily controlled by the abundance of water in the surroundings, either water in pores and fractures in the rock formations or water bound in minerals, in other words: in geothermal alteration minerals.

Other considered parameters are penetration rate and pressure drops which can also support the deducing of aquifers within a geothermal system.

FIGURE 11: Temperature logs from the time of drilling showing aquifers with relation to temperature change in well HE-4

A total of seven aquifers were encountered in the upper 1200 m of well HE-4, classified as small or large. The aquifers in relation to various parameters used to identify them can be seen in Figure 8.

At 496 m a large aquifer is identified (total loss of circulation) and another large aquifer is at 1150 m (37 l/s loss of circulation). Aquifers at 300, 580, 890, 900 and 1100 m are all considered small.

Feed point 1: is a small feed point located at 300 m, identified by change in the inclination of the temperature log (Figure 11).

Feed point 2: this feed zone is found at 496 m within a basaltic tuff formation with high porosity. Circulation loss of 50 l/s was encountered during drilling and low readings of neutron and high peak of caliper are noted (indicating increased width of the well at that depth). The temperature logs show a slight change of temperature (inflow of water from the aquifer to the well) and the formation shows a number of vein fillings from 438 m to 496 m.

Feed point 3: is a small feed point at 580 m, identified by a slight change in temperature. The presence of a small intrusive is noted.

Feed points 4 and 5: these are small feed points located at 890 m and 900 m, respectively, both showing an increase in temperature. Lithologically it is within a pillow basalt unit. At this depth no loss of circulation was encountered, but low readings of neutron is seen.
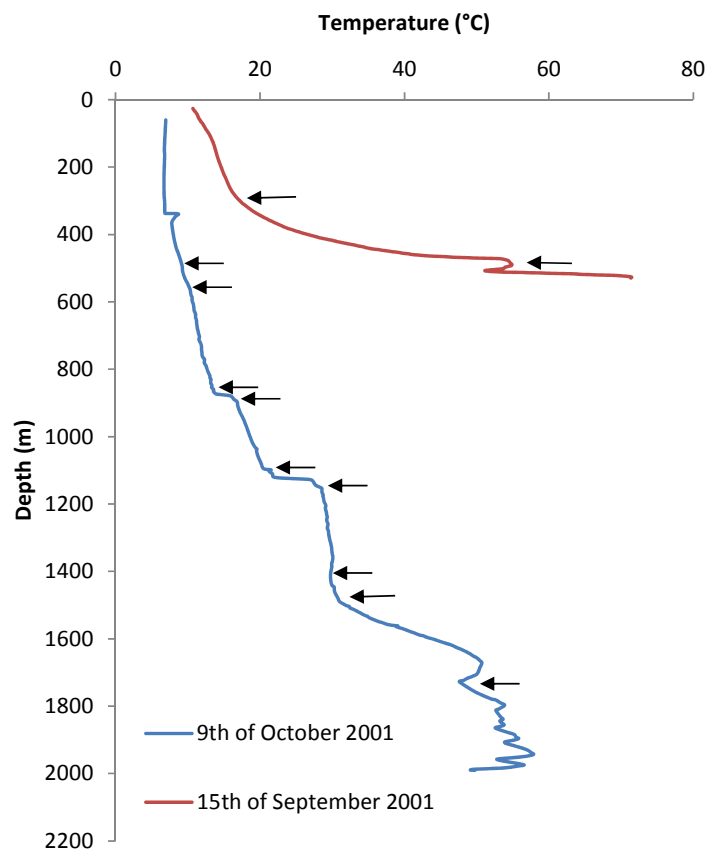
Feed point 6*:* at 1100 m it was identified by a sudden increase in temperature which correlates with an increase in caliper and a decrease in neutron readings. The formation is dominated by highly altered basaltic breccia.

Feed point 7: this large feed point is at 1150 m and caused a fluid loss of 37 l/ s. The lithology is dominated by basaltic breccia with high alteration and low neutron readings.

5. FLUID INCLUSIONS

The study of fluid inclusions reveals the temperature of fluid trapped during crystallisation of the minerals, which helps with determining the past conditions of the geothermal system. By comparing the temperatures of fluid inclusions to the present condition of the geothermal system, it is possible to determine whether the system is in equilibrium, cooling or heating.
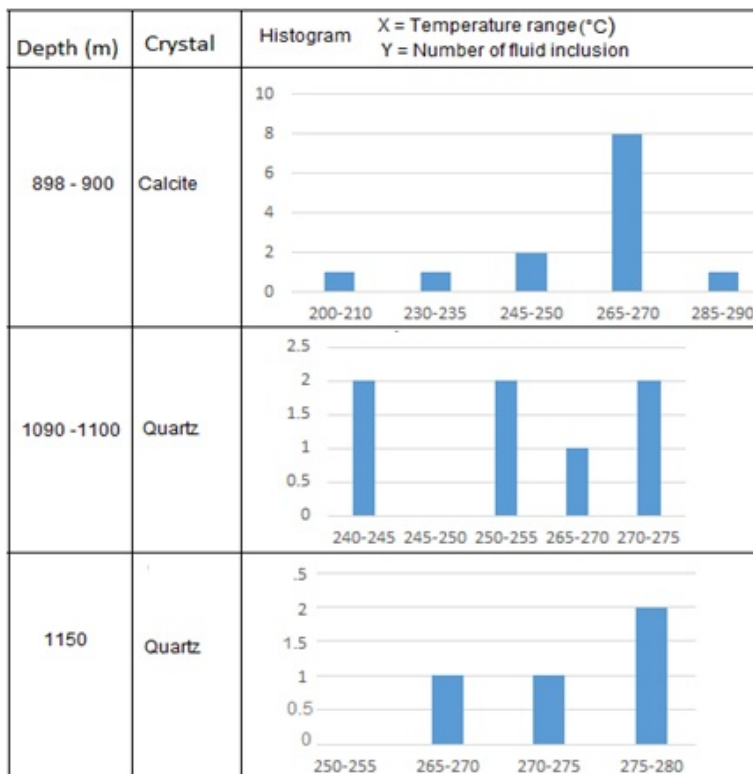
Platy calcite and quartz crystals were studied through micro thermometry as representative samples from the system within the well at different depth intervals ranging from 898-900 m, 1090-1100 m and 1150 m, in close proximity with feed zones in the lower part of the studied well. A total of 24 fluid inclusion measurements were carried out which showed a range of homogenization temperatures (Th) from 200°C as a minimum temperature and 290°C as a maximum temperature for calcite and 240-280°C for quartz, as described in Figure 12.

The homogenization temperatures show a wide range for the calcite, deviating quite a lot from the formation temperature and show temperatures all the way to the boiling point curve, but also down to 200°C, 60°C lower than the formation temperature of 260°C.

FIGURE 12: Histogram diagram showing the variations of homogenization temperatures with depth in well HE-4

The most common homogenization temperature for the calcite mineral is, however, close to the formation temperature. The quartz homogenization temperature is in a narrower range and is similar or slightly higher than the formation temperature.

6. DISCUSSION

The subsurface geology of well HE–4 is covered by two major formations which are hyaloclastite basalt formations and basaltic lava formations. Basaltic tuff, basaltic breccia and pillow lava seem to alternate and dominate in the well. Crystalline basalt appears in moderately thick layers of fine- and fine- to medium-grained crystalline basalt, representing interglacial lava flows and intrusive rocks.

The distribution of alteration minerals in well HE-4 ranges from low temperature to high temperature starting with chalcedony, siderite and limonite found at a shallow depth in the well. Smectite, zeolite minerals appear at 82 and 86 m, respectively, followed by moderate temperature alteration minerals as zeolites are replaced by quartz, mixed layer clay, and wairakite from 414 m, 450 m and 452 m, respectively, in the middle zone of the well. High temperature alteration minerals like prehnite, epidote and wollastonite are common at the lower depth of the well from 1150 m.

Clay minerals show five zones of alteration starting with an unaltered zone from the surface, followed by the smectite zone at 82 m to 642 m, but interrupted with a mixed layer clay zone at 450-458 m. The chlorite zone is seen from 642-862 m, then the mixed layer clay zone at 862 to 1150 m, and the chlorite amphibole zone from 1050 m to 1200 m. From the sequence of the clay zones explained above, it can be deduced that it is different from the normal zonation of the area. Chlorite and mixed layer clay appear to alternate, and mixed layer clay is seen below chlorite suggesting lower temperatures at that depth. This is contradictory to other alteration data, such as the appearance of epidote at 784 m.

FIGURE 13: Formation temperature, alteration temperature, boiling temperature curves and homogenization temperature of well HE-4

The first appearance of five alteration minerals in different intervals within the well, depending on their standard temperature of formation in geothermal systems, derived a representative alteration curve and appears to be a little bit below the present formation temperature. Basing on the alteration curve in Figure 13 the system seems to be in equilibrium in the zeolite zone at the upper part to around 300 m. The onset of the crystallisation of quartz, mixed layer clay and epidote between 414 and 784 m seems to indicate lower temperatures than the current formation temperature, indicating heating up of the system.

The alteration mineral deposition sequence is, in general, dominated by clay and calcite from the shallow depth to near the bottom which shows the deposition sequence from low temperature alteration minerals to high temperature alteration minerals. Mixed layer clay seems to be more dominant in the alteration sequence from 842 m, followed by other moderate and high temperature minerals including quartz and prehnite, as identified from the petrographic analysis.

Fluid inclusion analysis of calcite shows the temperature range from 200°C to 290°C at 890-900 m. About 9 inclusions show higher temperature compared to the present formation temperature which does not exceeds 260°C, perhaps indicating cooling of the system. On the other hand, about five inclusions from the same crystal sample show a homogenization temperature lower than the formation temperature, perhaps indicating the heating of the system. This could represent fluctuations within the system at this depth.

At a depth of 1100 m, homogenization temperature of quartz crystal ranges from 240 to 275°C, showing the crystallisation to be in relative equilibrium with the formation temperature, while at the depth of
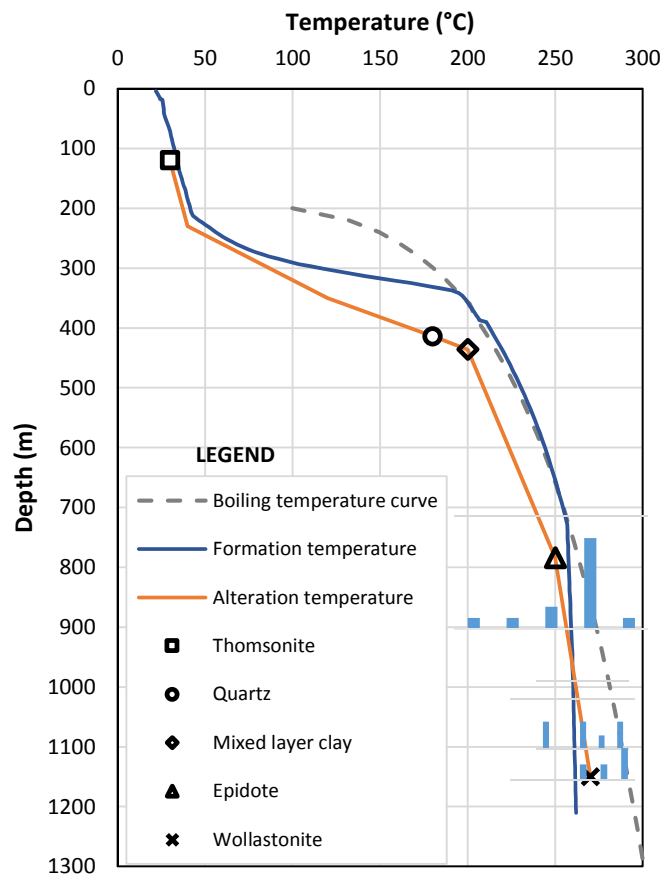
1150 m, the homogenization temperature for four inclusions shows relatively higher temperature than the formation temperature, indicating cooling of the system at the lower depth.

The occurrence of wollastonite at 1150 m makes the alteration temperature at the lower bottom of the well override the formation temperature, which correlates to the homogenization temperature of the quartz crystal at the same depth, as shown in Figure 13. The comparison of alteration temperature and homogenization temperature studied in well HE-4 with the formation temperature correlates well to the cross-section in Figure 14, showing the condition of the geothermal system in the area between wells HE-4, HE-7 and HE-6, indicating heating in the upper part and cooling in the lower part of the system.

A total of seven feed points were identified in the upper 1200 m. The small feed points at 580, 890 and 900 m are mainly related to pillow lava units. The larger feed points encountered at 496 and 1150 m are both associated with circulation losses with high peak of calliper at 496 m (indicating weakness in the rocks in that area) and a low reading of neutron. Furthermore, the alteration intensity towards the lower part can suggest increased permeability and may be related to the feed point at 1150 m. An intrusive is associated with the aquifer seen at 580 m.
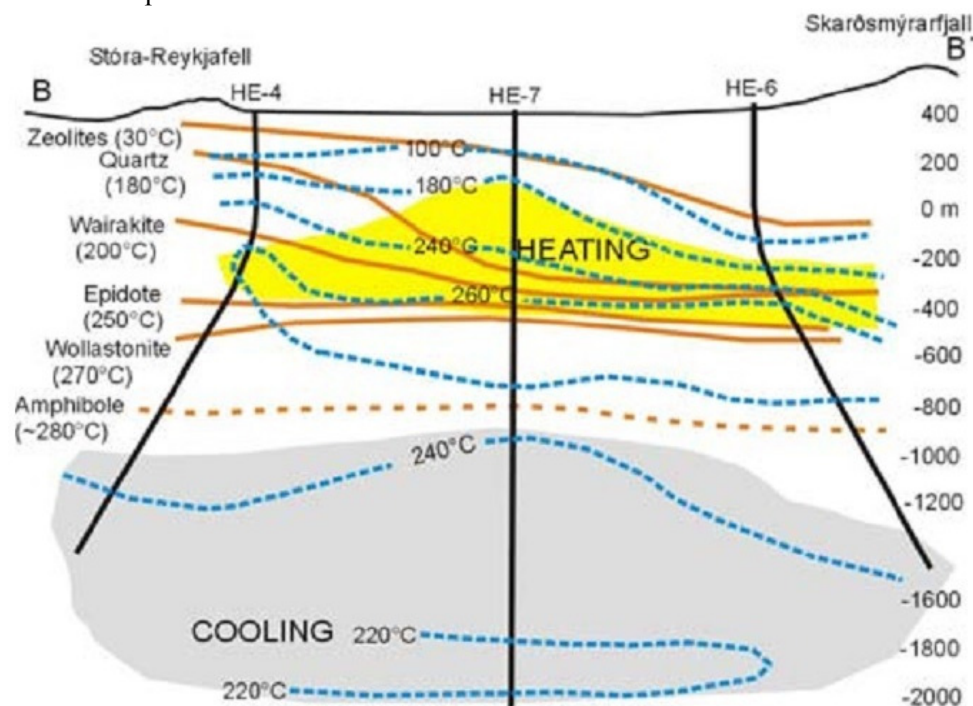
FIGURE 14: A cross-section showing a comparison of alteration and formation temperature between wells HE-4 and HE-6 in Hellisheidi, SW- Iceland (from Franzson et al., 2005)

7. CONCLUSIONS

From this study the following conclusions may be deduced:

- The stratigraphy of well HE-4 covers two major formations: a hyaloclastite basalt formation and a basaltic lava formation. Basaltic tuff, basaltic breccias and pillow lava (all part of the hyaloclastite formation) seem to alternate and dominate in a large part of the well. Crystallised basalt appears in moderately thick layers of fine- and fine- to medium-grained basalt, representing interglacial lava flows and intrusive rocks;
- Because of somewhat contradictory results between clay minerals and other temperature dependent minerals, it was decided to make two types of alteration zones: with respect to clay minerals on the one hand, and other alteration minerals on the other. Five alteration zones were

identified on the grounds of hydrothermal alteration mineral distribution from low temperature to high temperature, starting with an unaltered zone, followed by the zeolite zone, the quartz and wairakite zone, the epidote zone and the wollastonite zone. Clay alteration minerals also generated five zones starting with an unaltered zone, then the smectite zone which was interrupted by a thin layer of mixed layer clay, followed by the chlorite zone, the mixed layer clay zone and finally the chlorite amphibole zone;

- The feed points at 580 and 890 m are associated with the pillow lava units which can sometimes be more permeable than the surroundings, while the two large feed points at 496 and 1150 m are associated with circulation loss and high alteration intensity at 1150 m. Furthermore, an intrusive is clearly related to the feed point at 580 m; and
- Correlation of alteration temperature and homogenization temperature with formation temperature shows that the system is experiencing variable conditions. In the upper part of the well it seems to be in equilibrium, in the middle part from 414 to 784 m the system seems to be heating and in the lower part the system seems to be cooling.

ACKNOWLEDGEMENTS

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APPENDIX I: XRD clay mineral analysis results from well HE-4

TABLE 1: List of samples with XRD clay mineral analysis results from well HE-4

| No.	Depth (m)	Untreated (Å)	Glycolated (Å)	Heated (Å)	Clay type
1	94	15.5	17.6	0	Smectite
2	112	16.68	16.68	10.44	Smectite
3	212	15.1	17	9.8	Smectite
4	218	15.64	15.64	10.44	Smectite
5	248	15.64	15.64	10.44	Smectite
6	286	15	17	9.8	Smectite
7	360	15	17	9.8	Smectite
8	362	13.05	13.05	10.17	Smectite
9	450	30/14.6/12.77	31/17.3/15	12-13/9.8	Smectite+MLC
10	458	14.55	14.55	7.19	MLC
11	472	30/14.4/12.9	31/17/15.5	12-13/9.8	Smectite+MLC
12	506	30/14.4/13	31/17/15	12.5/9.8	Smectite+MLC
13	522	No clay	No clay	No clay	No clay
14	530	15.2/12.77	17.02	9.8	Smectite
15	564	30/14.7/12.9	31/16.9/14.1	12/ 9.8	Smectite+MLC
16	580	14.59	14.59		Smectite
17	600	12.7	16.9	9.8	Smectite/ill
18	642	14.3/13.03	14.3/13.03	10.11/7.15	Smectite-Chlorite (illite)
19	644	14.88/12.75	16.98/15	9.8	Smectite-Chlorite (illite)
20	676	15.01/12.73	16.98/15	9.8	Smectite-Chlorite (illite)
21	698	14.01/13.03	14.01/13.03	10.11/7.15	Smectite-Chlorite (illite)
22	700	14.85/12.82	16.98/15	9.8	Smectite-Chlorite (illite)
23	734	14.94/12.89	16.86/14.35	9.9	Smectite-Chlorite (illite)
24	762	15.13/12.73	17.02/14.3	9.8	Smectite-Chlorite (illite)
25	766	14.95/13.83	14.95/13.83	10.11/7.26	Smectite-Chlorite (illite)
26	786	30/14.01/12.73	31/16.94/14.76	12/9.8	Smectite: ill. (MLC)
27	798	14.14/12.98	14.14/12.98	10.11/7.26	Smectite Chlorite.
28	802	15.01/12.88	16.9/15	9.8	Smectite-chlorite
29	810	14.16/13.08	14.16/13.08	9.93/7.26	Smectite
30	832	15.03/12.79	16.94/14	9.8	Smectite
31	862	30/14.4	31/15.4	12.1	Smectite/Chlorite.unst.
32	876	No clay	No clay		No clay
33	896	30/14.4	31/15.4	12.1	Smectite/Chlorite.unst.
34	902	31.07/14.59/12.64	31.07/14.59/12.64	7.26	MLC
35	930	30/14.69/13	31/16.94/15.58	10	Smectite+MLC
36	980	30/15.09/13.1	31/17.06/15.5	10	Smectite+MLC
37	996	31.61/14.59/12.64	31.61/14.59/12.64	7.26	MLC
38	998	30/15.09	31/17	14	Smectite/Chlorite.unst.
39	1036	30/15/12	31/17/15	12	MLC/Smectite/Chlorite
40	1050	30.45/14.30/12.34	30.45/14.30/12.34	7.26	MLC
41	1074	30/14	31/15	13	Smectite/Chlorite.unst.
42	1104	30/14	31/14.8	14.5	Chlorite. +MLC.
43	1136	14.3	8.6	7.2	Chlorite-Amphibole
44	1144	30/14	31/14.8	14.5	Chlorite-Amphibole.
45	1194	No clay	No clay	No clay	No clay
46	1230-1234	14.3	14.3	14.3	Chlorite. unst.
47	1236-1244	14.3	14.3	14.3	Chlorite. unst.
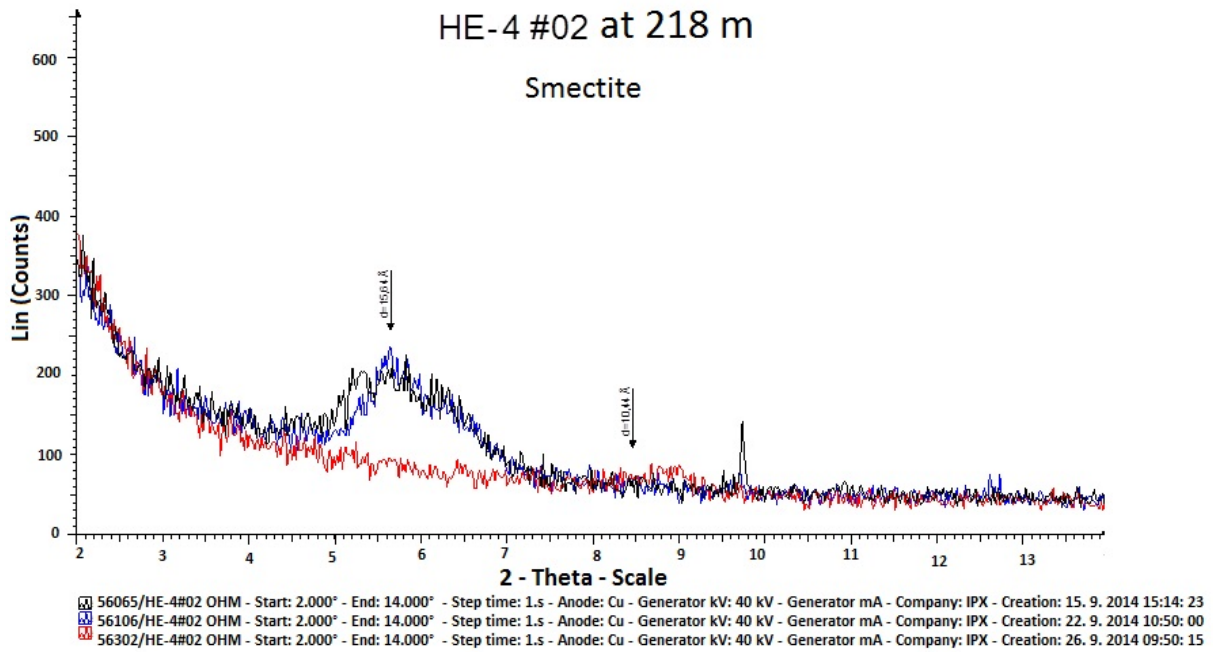
FIGURE 1: Well HE-4, XRD analysis showing the smectite clay minerals at 218 m
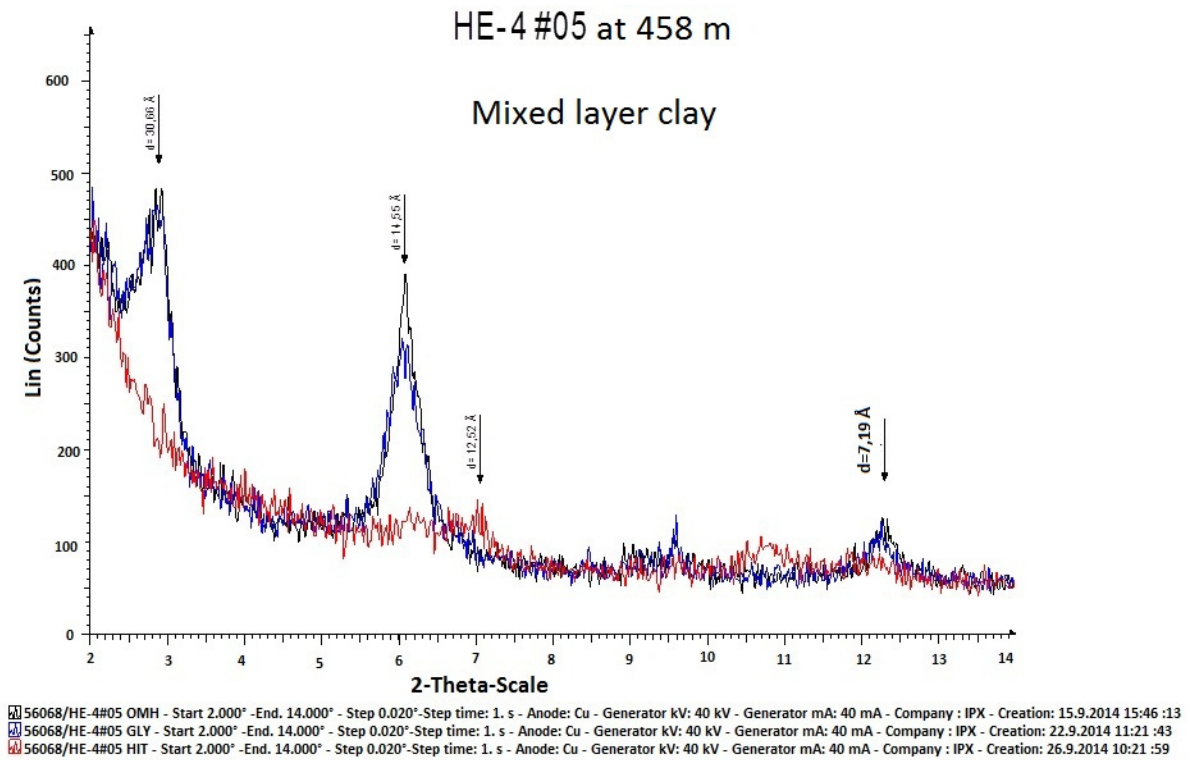

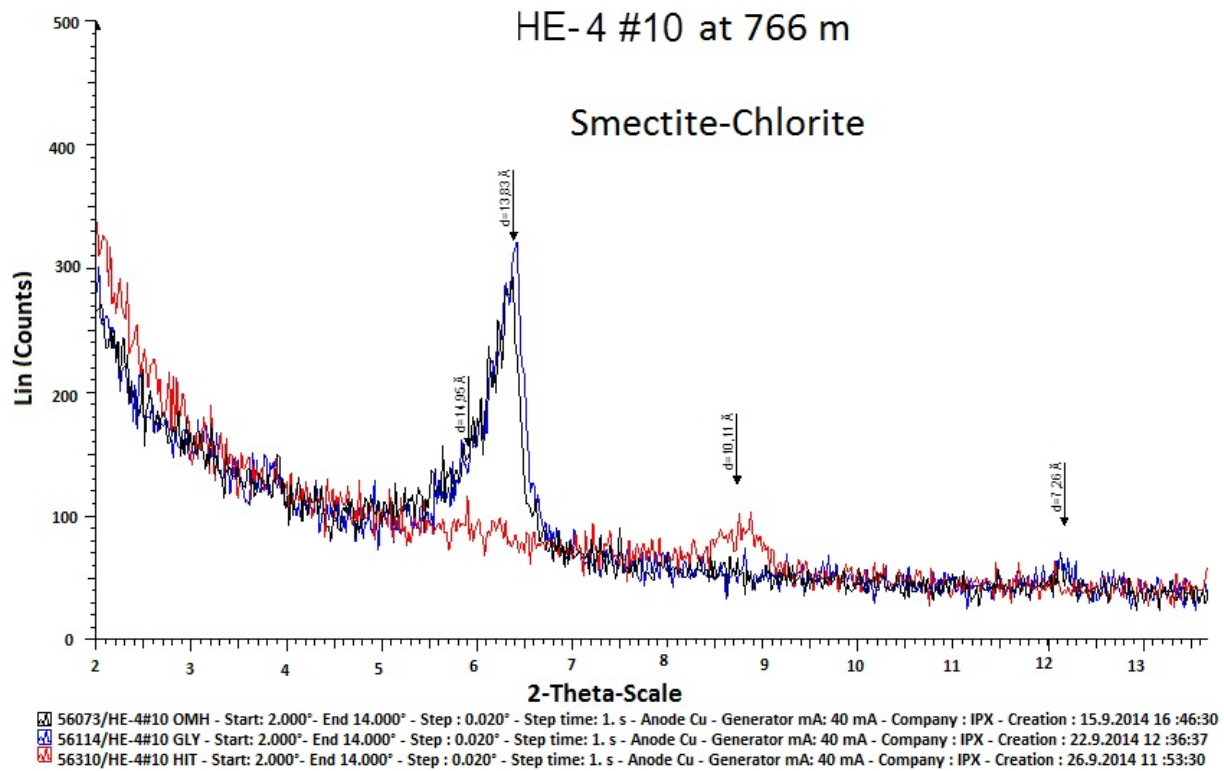FIGURE 2: Well HE-4, XRD analysis showing the mixed layer clay at 458 m

FIGURE 3: Well HE-4, XRD analysis showing the smectite-chlorite clay minerals at 766 m
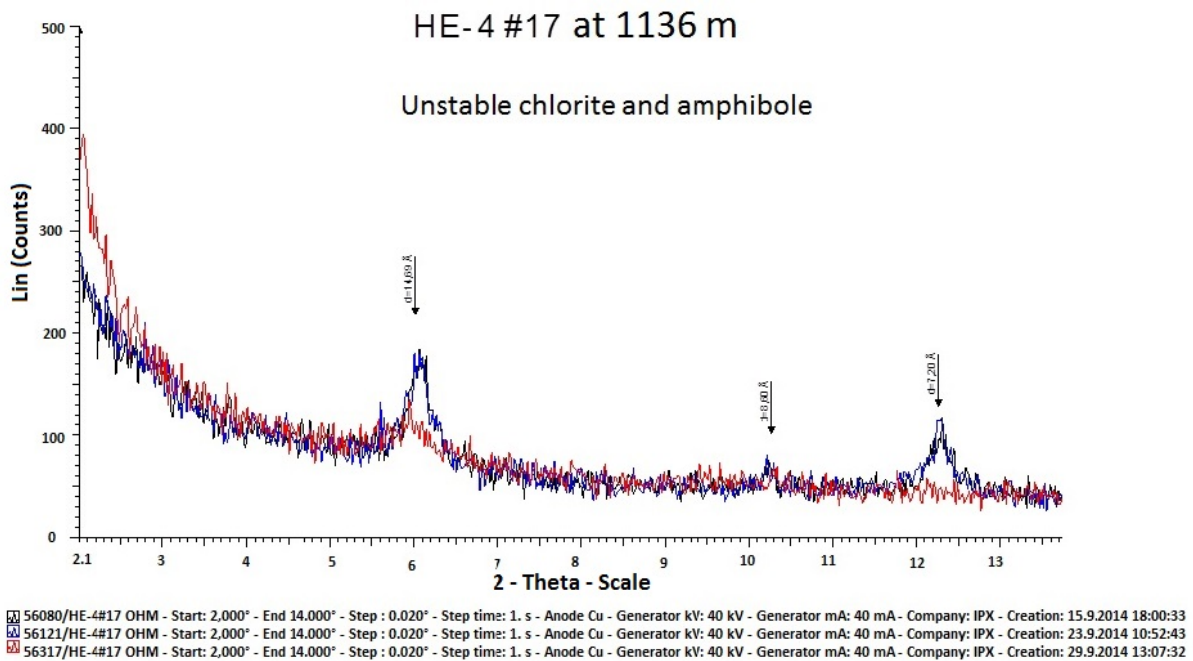

FIGURE 4: Well HE-4, XRD analysis showing the unstable chlorite and amphibole minerals at 458 m