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BOREHOLE GEOLOGY AND ALTERATION MINERALOGY OF WELL HE-9 IN HELLISHEIDI GEOTHERMAL FIELD, SW-ICELAND

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ABSTRACT

Well HE-9 was drilled down to 1604 m in Hellisheidi geothermal field in southwest Iceland in the summer of 2003. The goal of drilling was production of steam and to improve the existing conceptual model of the geothermal system. The main content of this report is to reveal how useful borehole geology is in the investigation of a geothermal field. The study emphasizes the uppermost 800 m of the well. Lithology of the well consists of hyaloclastite formations and basaltic lava flows. Hydrothermal alteration indicates four alteration zones: a smectite- zeolite zone, a mixed-layer clay zone, a chlorite zone, and a chlorite-epidote zone, respectively, down to 806 m depth. Calcite and pyrite are common in most parts of the well. Siderite is very common at 180-490 m depth. Alteration above 450 m is very low, indicating temperature less than 120˚C. Below that there is a sharp change indicating a high-temperature geothermal system characterized by chlorite, prehnite and wollastonite. The heating up of the geothermal system is deduced from correlation between alteration mineral temperatures and measured temperatures. Intrusions were identified at depths of 152-160, 180-186, 300-328, 388-430, 784-794, and 764-770 m. Aquifers were found at depths of 100, 120, 430 and 800 m where they are related to fractures along intrusion boundaries. Alteration mineral time sequences indicate heating up in the high-temperature geothermal system when prehnite and wollastonite have deposited after mixed layer clay.

1. INTRODUCTION

The deepest high-temperature geothermal well in Iceland (well HE-8) was drilled in Hellisheidi geothermal field in the summer of 2003, down to 2808 m depth, and was the last exploration well in the field. Well HE-9 was drilled before well HE-8. This report consists of borehole geology and alteration mineralogy of HE-9 in its upper 800 m. Hellisheidi high-temperature geothermal field is located in the southeastern part of Hengill central volcano, at a distance of about 30 km east of Reykjavik (Figure 1).

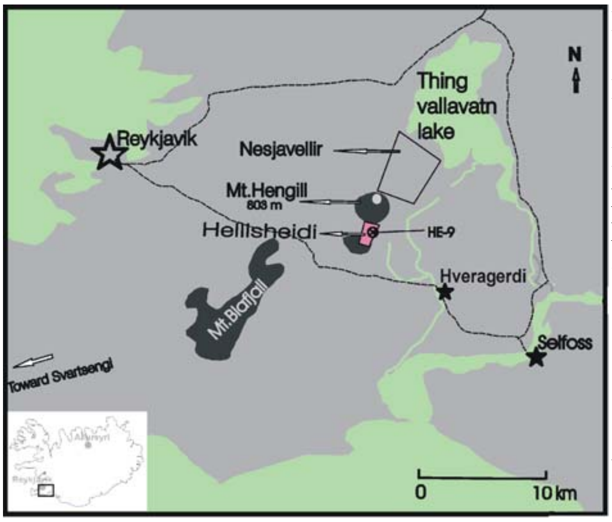

FIGURE 1: Location map of the study area

Hellisheidi geothermal field is a part of the Hengill central volcano and is located in the southern part of Mt. Hengill. Nesjavellir high-temperature geothermal field is located in the northern part of the Mt. Hengill area. There the Nesjavellir geothermal power plant was constructed; the biggest geothermal power plant in Iceland which generates 90 MWe and 200 MWt. The first step in the investigation of geothermal power potential in the Hengill geothermal area was carried out in the period from 1947-1949. From then to present, comprehensive development of research technology in the investigation processes of geothermal systems has taken place. The Reykjavik Energy Company decided to increase the investigation activities of the geothermal potential of Nesjavellir geothermal field, and carried out an extensive research program in the year 1980. At Nesjavellir 22 wells have been drilled with depths up to 2265 m, 15 are production wells. A maximum temperature close to 400˚C was reached at the bottom of one of them. Average power production for each well is 60 MWt or 8 MWe (Franzson, 2003). At the same time other fields in the Hengill area were explored as well.

The exploration drilling at Hellisheidi was in direct continuation of the final steps of the surface research programme. The main goals of the drilling were:

- To compare the results of the surface measurements with direct observation of the reservoir;
- To dissect the volcanic stratigraphical correlation with Nesjavellir as well as location of faults and fissures;
- To map the evolution of hydrothermal mineralisation and compare to measured temperatures in the reservoir; and
- To locate the main upflow zone in the field.

Wells HE-1 (KG-1), HE-3, HE-4, HE-5, HE-6, HE-7, HE-9 and HE-8, were drilled in the period from year 2000 to the summer of 2003. The wells HE-3, HE-5 and HE-6 were drilled directionally toward Mt. Hengill. Well HE-4 was directionally drilled under Mt. Reykjafell toward Hveradalir. The main reasons for adopting directional drilling were:

- Topographically, it is difficult to access the target zone;
- Crossing faults and fractures may be done with more assurance;
- To minimize the environmental impacts on the disturbed area. Wells HE-1, HE-7, HE-9 and HE-8 were drilled vertically.

2. GENERAL GEOLOGICAL INFORMATION

Iceland is a geologically young still undergoing a turbulent formation. It is an island in the middle of a young and expanding ocean on an active spreading rift zone, the Mid-Atlantic ridge; but is also affected by some transform faults. The oldest rocks on surface are about 16 million years. Regions of active extension and volcanism in Iceland are called *volcanic rift zones* (Figure 2), and cross the island from northeast to southwest for over 700 km. Most volcanic activity occurs along the eastern and northern volcanic zones, where plates drift apart 1.6 cm/year in either direction, on average, and lavas and pyroclastic deposits are erupted in the area (Saemundsson, 1979).

Fissure swarms in the active volcanic zones are 5-10 km wide and 30-100 km long. Each zone consists of nested grabens, where near-vertical normal faults are exposed at the surface. Figure 2 illustrates active volcanism, faulting and geothermal systems that occur along the fissure swarms in the active volcanic zones of Iceland. High-temperature geothermal systems are associated with the young volcanic systems along the active tectonic rifts. They are expressed by some manifestations like specific alteration minerals which colour the surface, mud pots, natural hot springs, fumaroles and geysers. There are well over 100 volcanoes in Iceland, exhibiting nearly every type of activity. At least 20 have erupted in historical times, with more than 150 recorded eruptions. Fissures often become long, thin volcanic vents; and Iceland is the classic area for fissure eruptions in which lava often fountains out and forms lava floods of vast extent. Each fissure represents a small amount of crustal extension, perhaps about a metre on average (Saemundsson, 1979).

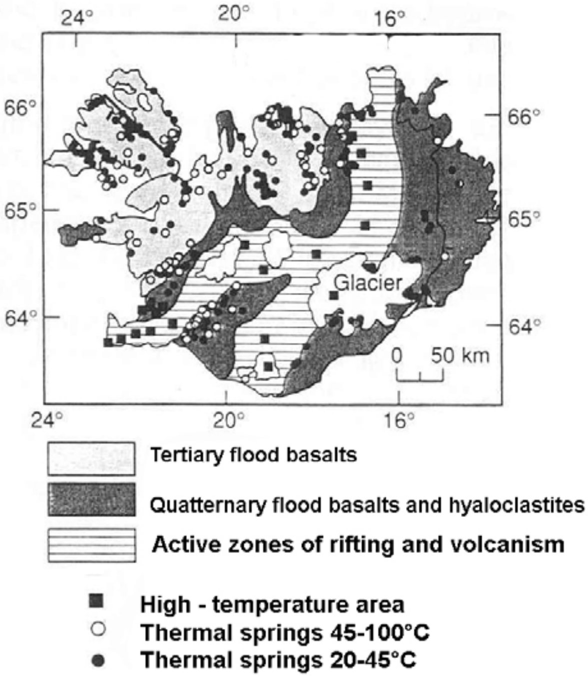

FIGURE 2: Simplified geologic map of Iceland showing the distribution of geothermal manifestations and their relation to the active volcanic zones (Fridleifsson, 1978)

The Hengill geothermal area is one of the largest high-temperature fields in Iceland. Geothermal activity in this part of South Iceland is linked to three volcanic systems. Reykjadalur and Hveragerdi are part of the Grensdalur system, which is now considered extinct. North of this is the Mt. Hrómundartindur system, which last erupted some 10,000 years ago. Geothermal activity in the Ölkelduháls area is connected to that system. To the west of these fields is the Mt. Hengill volcanic system, with its fissure swarms running southwest to Innstidalur, Kolvidarhóll and Hveradalir, and northeast via Nesjavellir to Lake Thingvallavatn. The Hengill system has erupted a number of times in post-glacial time, and occasional earthquakes are periodically felt at Nesjavellir, as elsewhere in the area. General geothermal studies started in the Hengill geothermal area in 1947-49. Studies and drilling of wells have continued intermittently to this date (Saemundsson et al., 1990; Hersir et al., 1990).

3. SURFACE EXPLORATION

3.1 Surface geology

Investigation of the Hengill volcanic complex indicates that super critical conditions are found at shallower depth than 5 km, and perhaps at less than 3 km depth associated with the youngest volcanic structure in the western part of the Nesjavellir system. The Hengill volcanic system is active, and it is estimated to discharge a power of 1000 MWe. By geophysical methods, the Hengill central volcano has divided into the Hveragerdi-Grensdalur system (eastern part of the area) that was active between 700,000 and 30,000 years ago; but now partially eroded down to the chlorite zone; the Hrómundartindur centre, whose surface formations are younger than 115,000 years and the currently active Hengill systems (Fridleifsson et al., 2003).

Hellisheidi geothermal system is located in the southeastern part of the Hengill mountain. The Hengill mountain itself was mostly accumulated in one or two large subglacial eruptions during the last glacial period. New geological data presented in 2002 suggest that the lower part of the mountain may have formed during the 2nd last glacial period (Fridleifsson et al., 2003). Hyaloclastite deposition, a typical formation in Iceland, is a fine, glassy debris formed by the sudden contact of hot and coherent magma with either cold water or water-saturated sediments, in Iceland usually associated with glaciers. Rapid heat loss from the magma to the ice sets up tensile thermal stress in the magma carapace as it cools, chills, and contracts, causing the glassy, chilled magma to fragment and form quench-fragmented debris. If the deposit remains in contact with water after its formation, the glassy debris can easily be hydrated to form palagonite. The Hengill triple junction sits between the Reykjanes Peninsula rift zone, the western volcanic rift zone, and the South Iceland Seismic (transform) zone, in SW-Iceland.

Geology of the Hellisheidi geothermal field is characterized by the presence of two kinds of common formations – hyaloclastite formations and basaltic fissure lavas produced in an active fissure swarm.

Hyaloclastite formations: Subglacial fissure eruptions produce elongate ridges that are 1-5 km wide, tens of kilometres long, and a few hundred metres thick. The cores of these ridges consist of permeable pillow lavas, but the flanking hyaloclastite deposits can serve as aquitards. Subglacial eruptions are remarkable in that they are able to create both the reservoir and caprock in one volcano (Wohltz and Heiken, 1992). Commonly, hyaloclastite formations in Iceland are created by the effect of volcanism under glaciers. The sequence of formation is shown in Figure 3. Most recent volcanism of this type was in Bárdarbunga 1996 in the glacier Vatnajökull, but the most famous episode was formed at the seafloor south of Iceland from 1963-1967, and formed the island Surtsey which belongs to the Vestmannaeyjar archipelago. The morphological structure is named móberg (in Icelandic) or hyaloclastite, and the formation, table mountain (Figure 3). Hyaloclastite formations characterize the environment in the Hengill region and form mountains like Mt Skardsmýrarfjall, Mt. Reykjafell and Mt. Hengill.

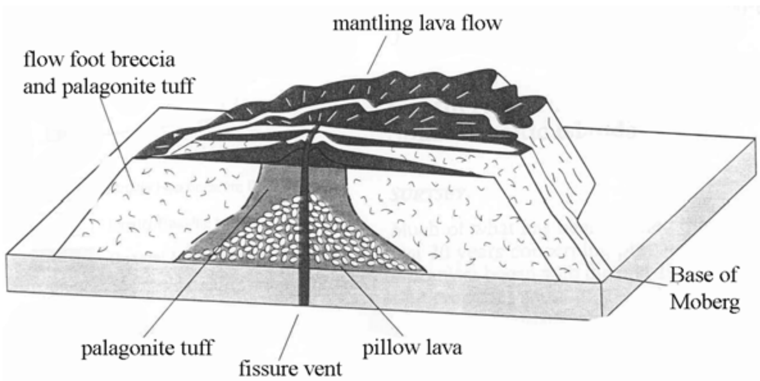

FIGURE 3: Hyaloclastite formations (móberg or table mountain) form during eruption of basalt along a fissure under a glacier (Jones, 1969)

The fissure swarm: There are two main volcanic fissures trending NE-SW in the Hengill area of Holocene age that have fed the last volcanic eruptions in the area, extending from the Lake Thingvallavatn in the northeast part of the Hengill area (Nesjavellir high-temperature field) about 20 km, toward southwest of the Hengill mountain (Hellisheidi). The age of the older one is about 5500 years and the younger one is about 2000 years old (Saemundsson, 1967). The lava flows are widespread and cover a large part of Hellisheidi (Figure 4). Well HE-9 is located between these two fissure swarms. These eruptive fissures and parallel faults control up- and outflow of hot water and steam from the centre of the Hengill system. Tectonic activity is episodic and accompanied by rifting and major faulting along the fissure swarm that intersects the Hengill central volcano and magma is injected into the fissure swarm. A row of small craters is marked along both older and younger eruptive fissures.

The primary heat source for Nesjavellir is probably partially molten rocks beneath the central volcano causing a major upflow of geothermal fluids (Fridleifsson et al., 2003). Hydrothermal activity in the Hengill area could be pictured as follows: cold groundwater leaks down into the crust, mainly within the fissure swarm, intersects hot intrusions associated with the magma pockets of the Hengill volcanic system, and the solidifying magma chambers beneath the Hengill volcano. The cooling rocks contract and fracture, causing microearthquake activity, thus allowing the hot water to convect towards the surface, where vertical permeability is high, especially along the fractures and faults of the three volcanic systems. A part of the hot water reaches the surface mainly as boiled steam in the geothermal area (Hersir et al., 1990). It can be concluded that Nesjavellir and Hellisheidi have a mutual heat source.

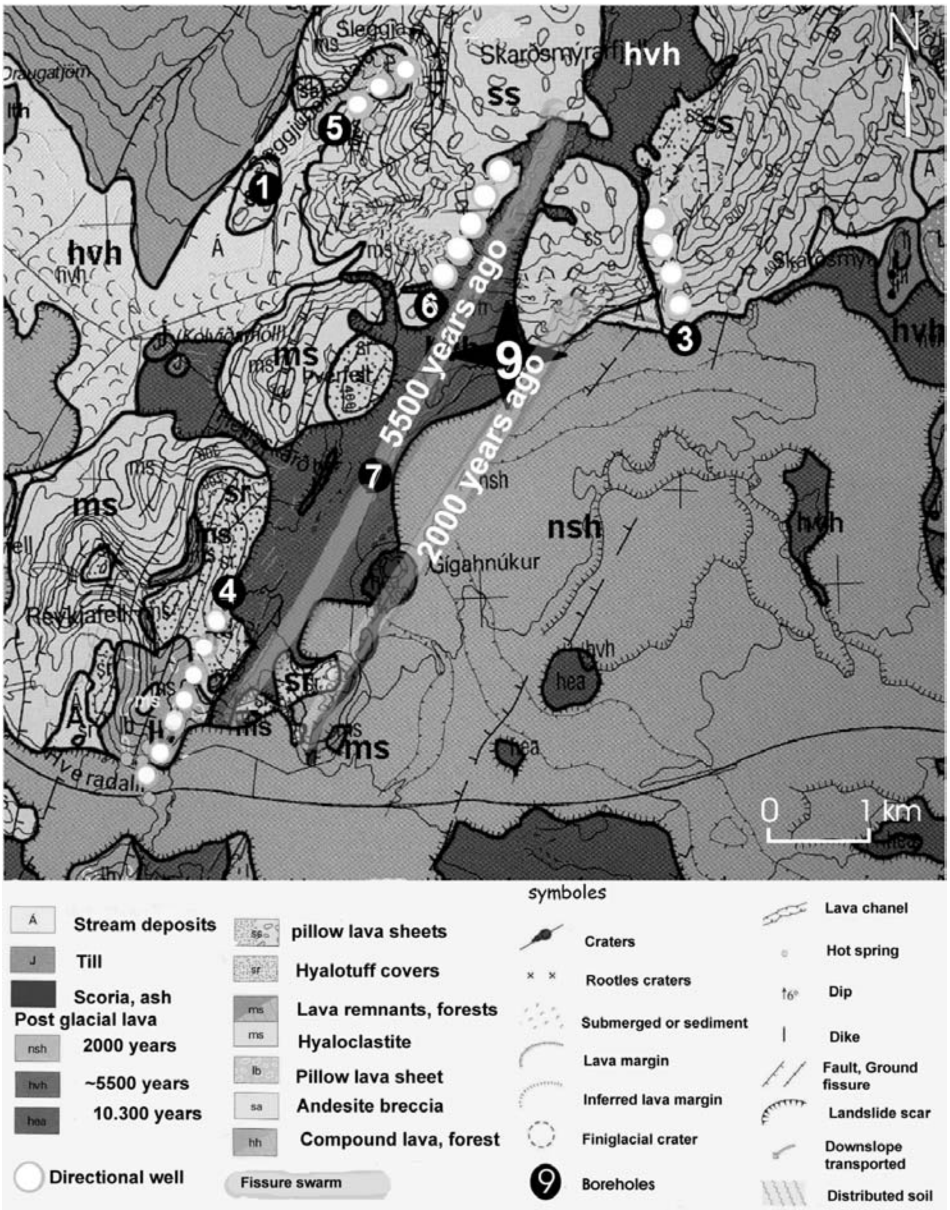

FIGURE 4: Geological map of Hellisheidi geothermal field showing boreholes (modified after Saemundsson, 1995)

3.2 Geophysical exploration

Extensive resistivity surveys have been done in the Hellisheidi geothermal field including Schlumberger and TEM resistivity measurements (Björnsson et al., 1986). The electrical resistivity provides information on the degree of alteration and therefore hydrothermal activity, including both ancient and recent alteration. A low-resistivity area covering 110 km^2 measured at the depth of 400 m b.s.l., indicates roughly the extent of the high-temperature fields. All surface manifestations like fumaroles and altered grounds are within this area (Hersir et al., 1990). The main feature is a high-resistivity zone (50-500 Ωm) which is observed beneath the low-resistivity layer. A correlation between resistivity, rock temperature and alteration at Nesjavellir (northeast of Hellisheidi) shows high-resistivity values close to surface can be attributed to fresh unaltered rocks. The low-resistivity values (1-5 Ωm) are connected with the smectite-zeolite belt at temperatures between 50-200°C. But below the low resistivity there is a high resistivity core associated with a high-temperature alteration zone. This high-resistivity zone is related to the chlorite–epidote zone that is located under a chlorite zone, indicating temperatures of more than 240˚C (Árnason et al., 2000).

4. BOREHOLE GEOLOGY

4.1 Materials and methods

About 400 samples of drill cuttings were picked at 2 m intervals during the drilling of the well, HE-9, down to 800 m. The samples were analysed and are the foundation of the subsurface geology, distribution of alteration zones and the alteration history of the well. The cuttings that are drilled and crushed by a drilling bit in the bottom of a well are carried to the surface by mud, water (or air) and poured out on a shaker. The samples are labelled by the drilling company with depth, date and name of the well, at 2 m intervals and put in 125 ml plastic containers. After thorough washing, the samples are studied under a binocular microscope. The binocular microscope used for analysing the cuttings was an Olympus SZX12 type. The petrographic polarising microscope that was used for studying thin-sections was a Leitz-Wetzlar model. Philips XRD equipment was used to run the X-ray analyses and special software used to solve the XRD-diagrams. Appendix I describes how samples for XRD were prepared, processed and identified. It also shows examples of XRD runs and the results. The software Logplot 2001 from RockWare, Inc. was used to manipulate all the borehole, geology and drilling data. It was used for drawing alteration mineral zonations, and different borehole geology data, showing lithology, distribution of alteration minerals, alteration zones, possible intrusions and possible aquifers with geophysical logs. Comparing data from geophysical logs with cutting analysis, thin-section analysis and XRD analysis is valuable especially for finding possible aquifers and possible intrusions.

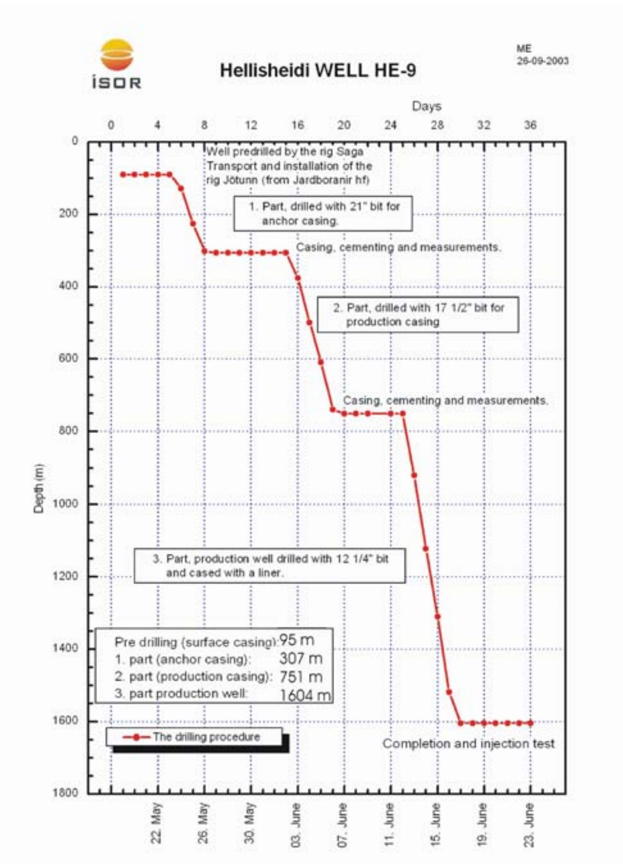

FIGURE 5: Drilling time schedule of well HE-9

4.2 Drilling

Well HE-9 was the eighth exploration well drilled in the Hellisheidi high-temperature geothermal field. This well is located between two fissure swarms in the southern flanks of Mt. Skardsmýrarfjall at coordinates (Lambert system): X = 385089.89 and Y = 394914.32 and at the elevation 395 m a.s.l. The drilling was performed in three stages that are illustrated in Figure 5. The first section of the well (pre-drilling phase) was drilled by the rig Saga. This part of the well was drilled with a 26" bit and cased to 95 m depth by a 22½" casing. After the pre-drilling, the rig Jötunn was installed. The owner of both rigs is Jardboranir Ltd., an Icelandic drilling company. Jötunn is a conventional rotary drill-rig, and was set up to drill the other parts of the well to final depth. Drilling bits and casing sizes that were used for the well are shown in Table 1. Well HE-9 was drilled with a wider programme than ordinary wells in Iceland (Table 1). The schematic design of the well is shown in Figure 6. The main reason for the different programme was that previous exploration wells established a low enthalpy fluid with maximum temperature of 280°C at the bottom or below 2000 m depth. Reverse temperature was seen in temperature profiles at the depth interval 1100 - 1700 m, but this cooling was not observed in well HE-9. Drilling started on the 18th of May 2003, and the rig had left the area after a completed injection test 36 days later.

Air-foam was used as fluid circulation material in the pre-drilling part of the well. In this method, samples are also picked from the shaker. Fast drilling, saving time and money is the reason for using air drilling with portable rigs in Iceland but drilling with air can cause problems if aquifers or big cavities are struck. After pre-drilling, mud was used as circulation fluid until the production casing was installed. Water was used as circulation fluid in the production part between 751 and 1604 m to keep it clean and cool and to protect the well's aquifers against sealing.

The purpose of the exploration drilling is gathering all available data about the geothermal reservoir. At the drill site, borehole geologists focus on analysing the cuttings and cores and make a lithological section through the stratigraphy, which is drilled, as well as identifying the alteration minerals and mapping their distribution.

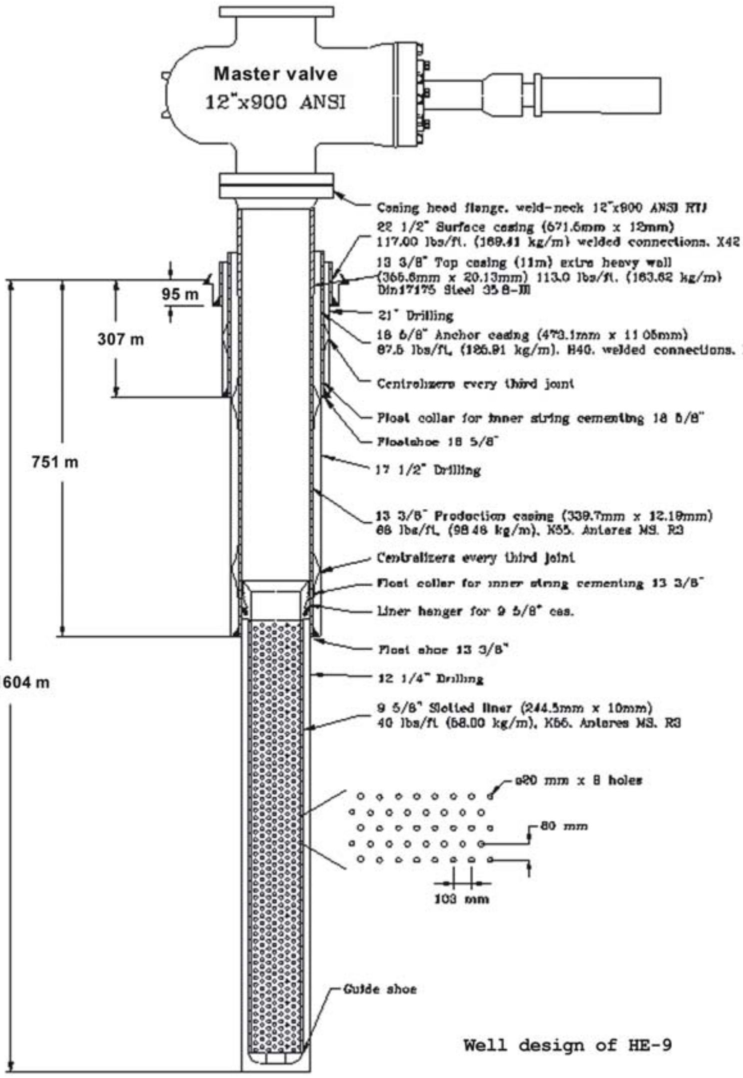

FIGURE 6: Schematic well design of well HE-9 (Thórhallsson, 2003)

TABLE 1: Drilling characteristics of well HE-9

Well HE-9			Ordinary wells in Iceland		
Drill bit (")	Depth (m)	Casing size (")	Drill bit (")	Depth (m)	Casing size (")
26	95	22½	22	75	18⅝
21	307	18⅝	17½	300	13⅜
17½	751	13⅜	12¼	800	9⅝
12¼	1604	9⅝	8½	2000	7

Coring in Icelandic drilling is rather rare mostly due to the cost and therefore emphasises on analysing the cuttings. Concurrently, all other available data from the drilling concerning the drilling fluid, i.e. temperature down and up and circulation losses are collected. In addition, the borehole geologists and geophysicists do the first interpretation of all the loggings that are performed at the drillsite. Recently, there have been increasing demands of daily news and reports from the drill site geologist.

Deduced work like further interpretation was based on study of thin-sections, and running XRD for clay and fracture fillings. Furthermore, different parameters of the geophysical logs were analysed with special attention to the lithology. Generally, it is common procedure while high-temperature wells are drilled to measure the following geophysical logs: Caliper, neutron-neutron, natural-gamma, and 16" and 64" resistivity. Each of them is measuring certain parameters in situ, whereas much more detailed analysis can be done on the core and cuttings (Stefánsson and Steingrímsson, 1990). Temperature logs were performed every time it was required during the drilling procedure. And pressure and temperature logs were used during the injection test during the drilling completion procedure.

A caliper log is a record produced by a spring-loaded caliper that continually adjusts itself to the size of a borehole as it is pulled to the surface, and the log is a direct measurement of the diameter of the borehole as a function of depth (Allaby and Allaby, 1990). Several types of measuring sounds exist with three-arm caliper the ordinary type, but upto 60 arms are available (Stefánsson and Steingrímsson, 1990).

A natural gamma log measures the radioactivity in the volcanic rock and the sensor is combined to the neutron-neutron tool. Correlation between radioactivity and SiO_2 content in volcanic rock has been established (Stefánsson et al., 2000). In a geological environment like in Iceland, where rock is mainly of tholeiitic basalt composition, the natural gamma ray log will generally show low values (low gamma intensity) with a few peaks due to more acid units in formation pile (Stefánsson and Steingrímsson, 1990). High peaks in natural gamma logs indicate more evolved rock richer in silica like andesite and rhyolite.

A neutron-neutron (N-N) log measures the amount of hydrogen ion present within the rocks surrounding a borehole. Water content of the formation is usually a major source of hydrogen, and the log is therefore frequently referred to as a porosity log (Stefánsson and Steingrímsson, 1990). High measured values indicate low content of water in the formation like in intrusions that generally have low porosity and therefore low water content. On the contrary, hyaloclastites are highly porous and rich in water, but not necessarily with high permeability. It should be pointed out, however, that the neutrons do not distinguish between protons belonging to formation water and water bound in minerals. This is of particular interest in geothermal logging, as hydrothermal alteration is a process of forming minerals with bound water. Furthermore, the water content of secondary minerals which form frequently in fissures in geothermal rock is often high.

Resistivity logs are measuring the conductivity due to Ohms-law in the formation with two different diameters. The specific resistivity of the reservoir rock is the result of two different contributions, the resistivity of the rock matrix and the formation fluid (Stefánsson and Steingrímsson, 1990). Technical problems in running the resistivity tools are the reason no measurements do exist in the upper part of the well. Also one should pay attention to the fact that no geophysical measurements exist in the uppermost 95 m, because of the large diameter of the well in the pre-drilled part; and no geophysical measurements exist for the last 50 m (750-806 m) dealt with in this report, because of problems in running the geophysical tools in the final parts of that stage. Geophysical logs are shown in Figure 7 parallel with the lithology.

4.3 Stratigraphy

The description of the stratigraphic columns is mainly based on the binocular stereoscope observations, and aided by petrographic analysis of thin-sections. The succession is mainly divided into hyaloclastite formations formed under sub-glacial conditions and some apparent lava series which are described below; intrusive rocks that the well dissects are dealt with in Section 4.4.

Basaltic lava flow I (0-20 m)
This lava flow is very oxidized and scoriaceous from the top down to about 12 m depth, and is underlain by a fine- to medium-grained basalt. This flow has been dated at 2000 yrs and was erupted from a fissure

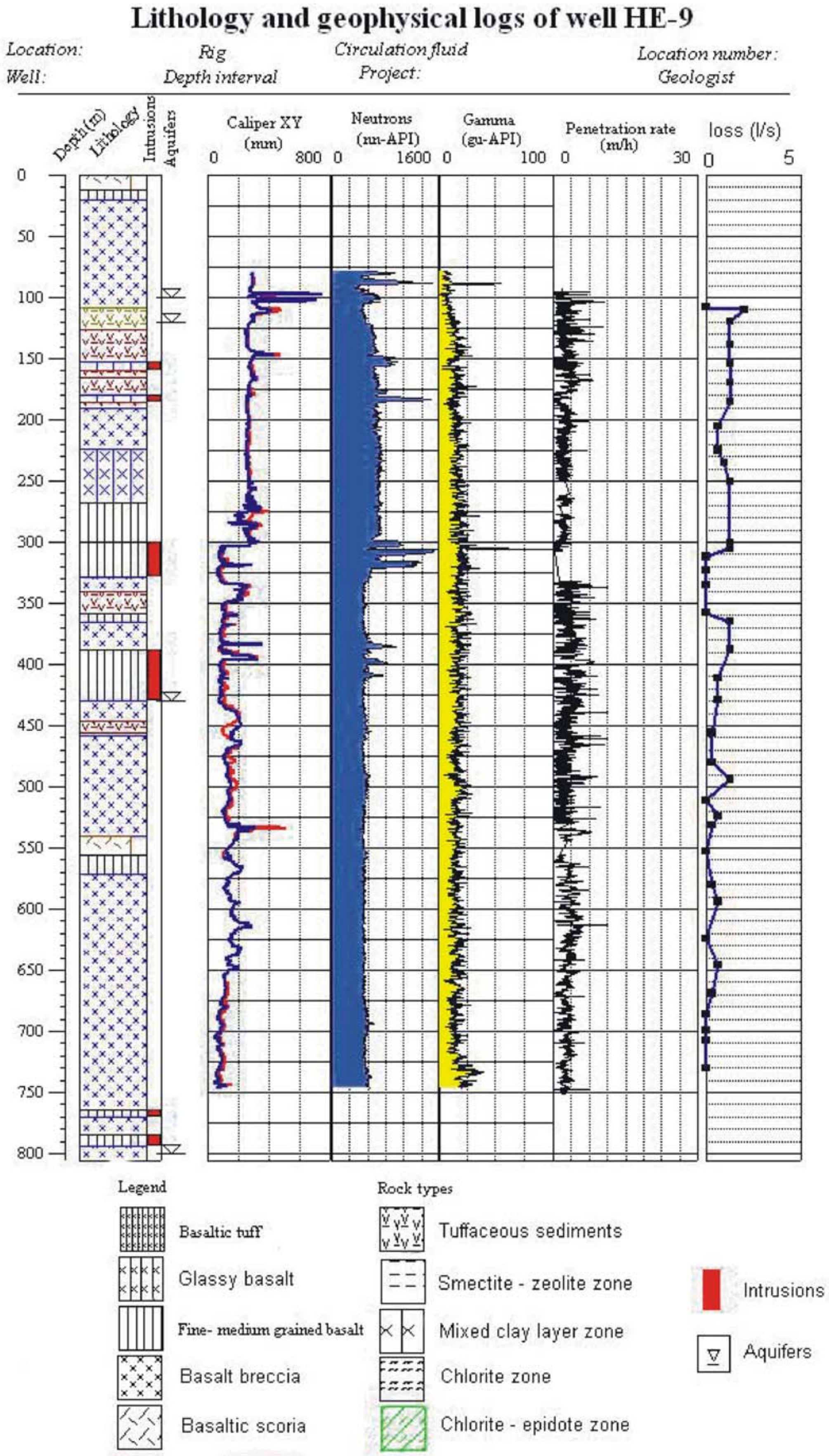

FIGURE 7: Geophysical logs of well HE-9

a few tens of metres from the well. Some calcite is found in the pores of the lava along with some pyrite. The high oxidation found associated with the lava is probably due to the interaction with surface groundwater.

Hyaloclastite I (20-224 m)
This formation can be broken down into six parts:
Basaltic breccia 20-108 m. This breccia is a mixture of pillow basalt, pillow breccia and tuffs. It is porphyritic plagioclase and pyroxene. The tuff grains are bluish to grey in colour. Calcite deposition and oxidation is observed along with some pyrite.
Tuffaceous sediment 108-126 m. This tuff shows fine layering indicating deposition in a water environment. Opal deposition is observed along with some calcite.
Basaltic tuff 126-166 m. The tuff is porphyritic plagioclase and olivine, highly porous but has minor fillings of calcite.
An *intrusion* is penetrated between 152 and 160 m depth as described later.
Basaltic tuff 166-190 m. This tuff is greenish in colour. Chalcedony alteration is found below 174 m depth. The tuff is cut by an intrusion between 180 and 186 m depth.
Basaltic breccia 190-224 m. This breccia is brown to green in colour. Calcite is found both in groundmass and as large individual grains, especially at 194 m depth.

Basaltic lava series II (224-300 m)
This lava series is divided into two parts on grounds of crystal structure.
Glassy basalt 224-268 m. Most of the pores in the glassy texture are filled by calcite and siderite especially in upper parts. Calcite is obvious as big crystals that fill vugs.
Fine- to medium-grained basalt 268-300 m. Big plagioclase crystals found as phenocrysts in fine- grained basaltic lava that is similar to the upper formation; most of the pores are filled by calcite and siderite.

Hyaloclastite II (300-358 m)
This formation is dominated by a *breccia* down to 340 m and is underlain by a tuff layer down to 358 m depth. Siderite seems to be the dominant deposition mineral. Pores in the rock are mostly empty.

Basaltic lava series III (358-366 m)
This is a single fine- to medium-grained basaltic lava. Siderite is the only deposition mineral in the pores of the lava.

Hyaloclastite III (366-540 m)
This formation is mostly of pillow breccia, underlain by basaltic tuff down to 540 m and lastly by another basaltic pillow basalt and breccia to 540 m depth. Hydrothermal alteration is dominated by some pyrite and siderite and then calcite appearing below about 440 m. Quartz was first encountered below 450 m depth.

Basaltic lava series IV (540-572 m)
This series consists of a scoriaceous layer down to about 556 m depth succeeded by a fine- to medium-grained basalt down to 572 m. Alteration deposition includes quartz, calcite and pyrite.

Hyaloclastite IV (572-806 m)
The formation is dominated by pillow basalt and breccia along with some minor tuff layers. Hydrothermal alteration is rapidly increasing within this formation, with mixed layer clay appearing at about 600 m depth, and well formed quartz below 620 m. Wollastonite appears below 770 m along with wairakite and chlorite. Calcite continues to appear in the vesicles and veins.

4.4 Intrusions

Intrusions are younger than the host rocks and are much less porous, hence they are much less altered than the surrounding rocks. Geophysical logs can also help to locate possible intrusions, e.g. high peaks in neutron-neutron logs, and low rate of penetration. According to this information, six possible intrusions were distinguished in the well:

Medium-grained basalt (152-160 m)
A thin-section at 156 m depth shows plagioclase-olivine porphyritic texture in medium-grained basalt. Grains are totally fresh and unaltered indicating an intrusion at this depth. Existence of a lot of magnetite characterizes this formation. There is a small peak in the neutron-neutron log that emphasizes this.

Medium-grained basalt (180-186 m)
This medium-grained basalt is totally fresh. Deposition of siderite is starting in 182 m depth as a yellow radial aggregate. A high peak in the neutron-neutron log also confirms the very low porosity in the formation.

Fine- to medium-grained basalt: (300-328 m)
Three high peaks in the neutron-neutron (N-N) log, very low rate of penetration (less than 2 m/hour), and low porosity implies three thin intrusions at these depths.

Fine- to medium-grained basalt (388-430 m)
Three small peaks in the neutron-neutron log, and low porosity indicate three thin intrusions.

Fine- to medium-grained basalt (764-770 m)
The relatively fresh and low porosity basalt indicates an intrusion.

Fine- to medium-grained basalt (784-794 m)
Alteration is lower than in the host rock (basaltic breccia), and just calcite and pyrite were observed, hence the possibility that it is an intrusion. No geophysical logs are available for comparison.

5. HYDROTHERMAL ALTERATION

Hydrothermal alteration is a general term embracing the mineralogical, textural, and chemical response of rocks to a changing thermal and chemical environment in the presence of hot water, steam, or gas (Henley and Ellis, 1983). Due to water-rock interaction and chemical transport by the geothermal fluids, the primary minerals in the host rock matrix are transformed, or altered, into different minerals. The alteration process and the resulting type of alteration minerals are dependent on the type of primary minerals, chemical composition of the geothermal fluid and temperature. On the other hand, intensity of alteration is dependent on the temperature, but also on time and the texture of the host rocks. Overall, hydrothermal alteration is affected by temperature, permeability (related to gas contents and hydrology of a system), fluid composition (pH value, gas concentration, vapour- or water-dominated, magmatic, meteoric), initial composition of rocks, duration of activity (immature, mature), number of superimposed hydrothermal regimes (overprinting of alteration), and hydrology (variable) (Reyes, 2000). In basaltic formations in Icelandic high-temperature systems, the alteration intensity temperatures lower than 200˚C, and low-temperature zeolites and smectite (clay) are formed. The range where low-temperature zeolites and smectite are abundant is called the smectite-zeolite zone. In the temperature range above 200˚C, the low-temperature zeolites disappear and the smectite is transformed towards chlorite in a transition zone, the so-called mixed layered clay zone where smectite and chlorite coexist in a mixture. The chlorite zone is characterized by disappearance of smectite at temperatures around 230˚C and the dominance of chlorite. At higher temperatures of about 240-270˚C, epidote becomes abundant in the so-called chlorite-epidote zone. This zoning is found in both fresh water and saline systems. The zoning is the same but the mixed layered clay zone extends over a wider temperature range in saline systems.

Comparison of estimated formation temperatures deduced from temperature logs, and the alteration mineralogy can be used to tell about present cooling or heating or if it has occurred recently (Árnason et al., 2000).

5.1 Rock alteration

Alteration reflects the interaction of fluid and rock at temperatures that range from warm (< 100˚C) to hot (> 300˚C). Alteration mineralogy, however, documents the post-formation history of the rock, information that has practical implications. The distribution and mineralogy of the alteration relates to the hydrothermal environment, and hence, the type of mineral deposit and study of this provides information on reservoir and fluid characteristics, and the evolution of the geothermal system. These data are used in conjunction with other information to evaluate potential geothermal resources. During the study of hydrothermal systems, it is important to evaluate the extent of equilibrium in the alteration assemblage. It is common to find in vugs or veins, minerals that are not necessarily in equilibrium with the minerals that formed by reactions between the hydrothermal fluid and minerals in the rock wall. Similarly, different alteration mineral assemblages may occur with distance from the vein, thus demonstrating the progress of reactions and modification of the fluid as it moves into the rock away from the vein or fluid pathway. This observation demonstrates the dynamics and complex nature of hydrothermal systems, but they also provide important information which aids in interpreting the physical and chemical history of the geothermal system (Goff and Janik, 2000). Geothermal systems within Hengill central volcano contain dilute fluids (Fridleifsson et al., 2003). The basaltic rocks in well HE-9 contain plagioclase, clinopyroxene, olivine and opaque minerals (generally magnetite). Where the rock is quenched, glass is the main component. Table 2 shows the results of alteration in well HE-9.

TABLE 2: Main rock alteration minerals in well HE-9

Fresh	Altered
Glass (tuff)	Clays, calcite, zeolites, quartz, sphene, epidote
Olivine	Iddingsite, clay, calcite, sulfides, sphene
Plagioclase	Clay, albite, calcite, sphene, chlorite, epidote, adularia, wairakite
Magnetite	Sphene, pyrite, pyrrohtite

5.2 Distribution of hydrothermal alteration minerals

In Icelandic geothermal systems, glass and olivine are the first minerals that are altering at temperatures about 50˚C; and at temperatures above 200˚C both of them are completely altered (Figure 8). The results from cuttings, petrography and XRD analyses show that clay, calcite and pyrite are the most common secondary alteration minerals down to 800 m depth in well HE-9. Siderite is also the most common secondary mineral at depths between 182 and 480 m indicating relatively cold ground water, with temperatures less than 50˚C (Hjalti Franzson pers. com.). A sharp change to high-temperature alteration occurs at about 520 m depth in the well indicating a temperature increase to above 200˚C.

The following alteration minerals were found in the upper 800 m of the well (Figure 9):

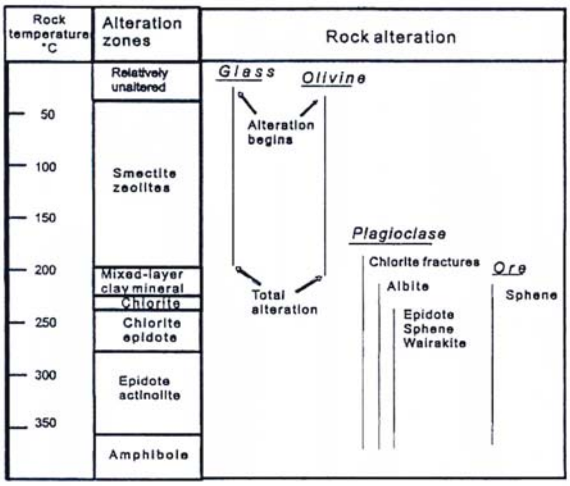

FIGURE 8: Temperature-related alteration zones and rock alteration in Icelandic geothermal systems (Franzson, 1998)

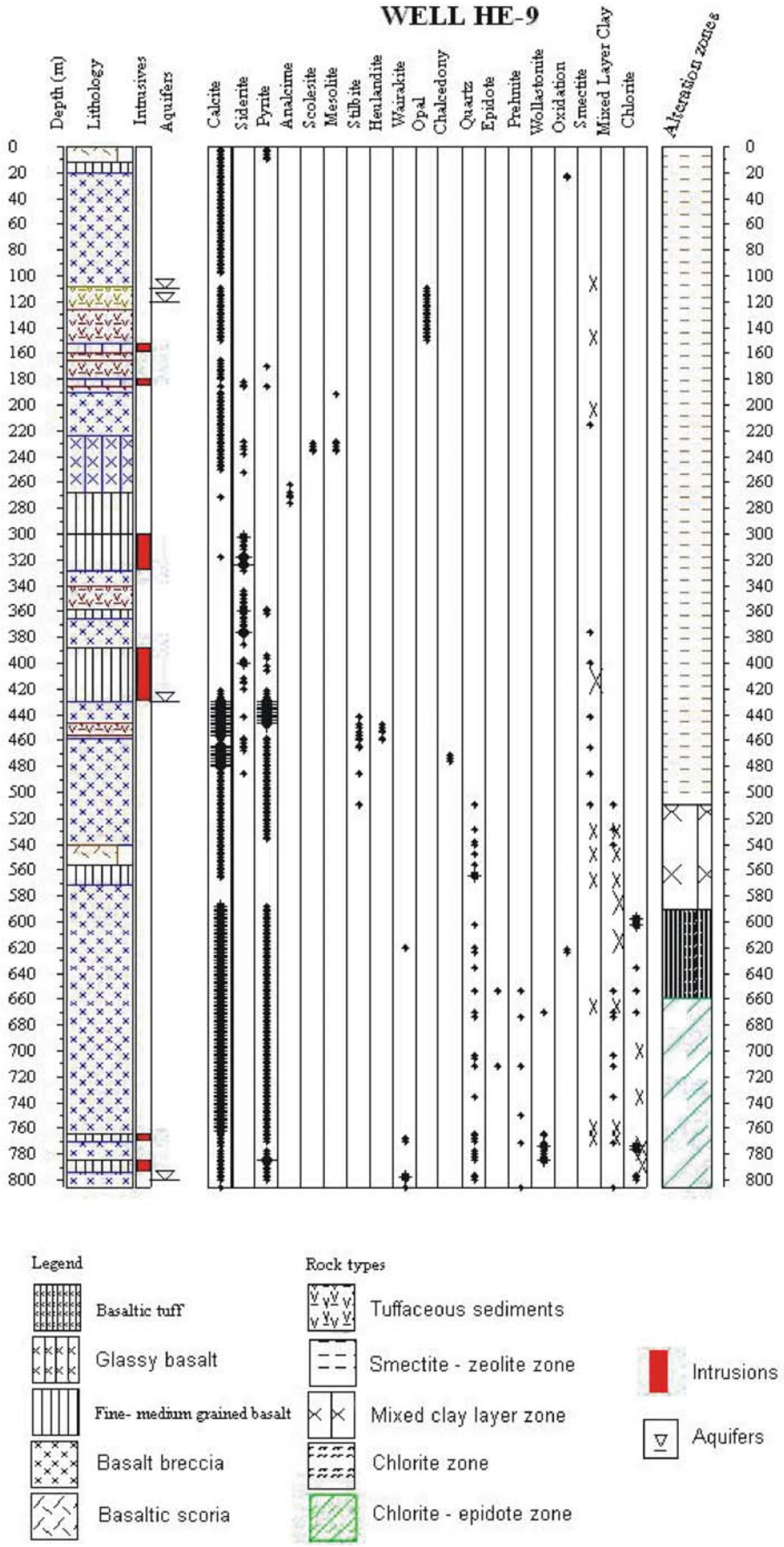

FIGURE 9: Distribution of hydrothermal alteration minerals with hydrothermal alteration zones in well HE-9

Calcite occurs as replacement of calcium-bearing minerals and volcanic glass, and as open space fill. It is easily determined by dilute HCl acid (1-2 normal), and in thin-section it is distinct because of its relief, which changes from very high to very low as the stage is rotated along with very high birefringence, which gives it a light pink colour under crossed nicols. Its cleavage at 120˚C and uniaxial optical figure distinguishes it from anhydrite. Calcite forms over a wide temperature range, replaces calcium-bearing minerals (e.g. Ca-plagioclase, zeolites) and volcanic glass in the presence of CO_2-rich fluids in rocks with low porosity and low permeability. In open spaces, calcite deposits in response to boiling (Thompson and Thompson, 1996).

Siderite is another carbonate in the well that is indicating cold aquifers with temperatures less than 50˚C. Siderite is very common down to 490 m but disappears below that. In cuttings, it seems like a yellow rounded aggregate that is filling vugs and veins. In thin-section it shows zonal texture and carbonate optical character.

Pyrite is a common mineral in the well and shows a good correlation with calcite. Pyrite implies high H_2S content in the formation and also indicates good permeability in the formation, but is not an indicator of temperature. Pyrite is abundant especially in basaltic breccia, filling vugs and veins, and is also found scattered.

Zeolites are hydrous sodium calcium aluminium silicates that commonly occur as secondary minerals in cavities of basaltic rocks (Kerr, 1959). The formation of zeolites is strongly temperature-dependent and because of this their identity is a useful guide to their deposition temperature (Kristmannsdóttir and Tómasson, 1978). The following were found in the well:

Analcime occurs as white or yellow isotropic trapzohedron or modified cube crystals similar to wairakite. Its occurrence indicates low temperature between 40 and 60˚C. It was found at depths between 260 and 280 m.

Scolecite is characterized by a radial texture that is obvious both in cuttings and thin-sections at depths between 210 and 230 m, indicating temperatures around 90˚C.

Mesolite is similar to scolecite and is formed at the same temperature (about 90˚C). It was found at 180-230 m depth.

Stilbite is a transparent framework zeolite and was found at depths between 430 and 500 m. It indicates temperatures between 90–120˚C.

Heulandite. In thin-section it shows parallel extinction with a fan-like aggregate; in cuttings it has generally tabular and sometimes radial form with lustre reflection. Its presence indicates temperature between 90 and 150˚C. It was found at depths between 440 and 460 m.

Wairakite. Deposition of wairakite (Figure 10) is starting at 610 m depth and is abundant especially in the lowest parts of studied depth (806 m) and indicates a temperature greater than 200˚C. Wairakite is white to colourless, forms euhedral pseudo-dodecahedral crystals and fills vugs and veins. In thin-section, it has a very low relief and typically displays in cross-polar light two perpendicular polysynthetic sets of twin lamella, a distinctive feature giving an appearance similar to microcline with poor cleavage (Thompson and Thompson, 1996).

FIGURE 10: Wairakite found at 806 m depth in well HE-9

Opal. In cuttings, it is pale yellow-brown coloured, transparent to subtranslucent with a hardness close to quartz and in thin-section it is often found in collourform crusts, in veinlets, and as a cavity filling or lining. More often it is massive without any particular structure or cleavage. It was found between 100 and 140 m depth, indicating a temperature below 100˚C.

Chalcedony. A low-temperature silica mineral that indicates temperature between 100 and 150˚C is found at lower temperatures than quartz and at depths of 460-470 m.

Quartz was found below 490 m down to 806 m depth. It deposits in vugs and veins. Vuggy quartz alteration is characterized by fine-grained quartz with numerous open spaces that may be partly filled by a variety of minerals. Quartz is a hexagonal mineral, stable in geothermal systems above 180˚C.

Epidote has a yellow-green colour and that makes it easy to identify in the cuttings. In thin-section it is pale yellow, green, and greenish brown with weak to moderately strong pleochroism. It is often forming along with quartz (Thompson, and Thompson, 1996). It was found in the well associated with prehnite indicating temperatures greater than 240˚C below 610 m depth.

Prehnite is a common mineral in this well below 650 m depth associated with chlorite at temperatures more than 250˚C. In thin-section, it is characterized by bowtie texture, strong interference colours and relatively high relief.

Wollastonite. In this well it was associated with calcite as a tiny, hairy aggregate. In thin-section it has a fairly high relief and weak birefringence, with colours up to first-order range, and shows parallel extinction (Thompson, and Thompson, 1996). Below 660 m depth it is obvious as a hairy aggregate that is growing on calcite surfaces indicating temperatures around 270˚C.

Fe-oxides. Iron-oxides were found in the upper parts of the basaltic lava that erupted about 2000 years ago probably due to groundwater oxidation. At 778-780 m depth, iron oxide was again formed in basaltic breccia that is in the chlorite zone, and is possibly affected by an intrusion at 780 m depth.

The sheet silicates (clay minerals).
Smectite is formed in a low-temperature environment and associated with zeolite minerals indicating temperatures less than 200˚C. Smectite is widespread to 574 m depth and scattered down to 670 m. XRD analysis showed typical smectite at 424 m depth (Figure 1 in Appendix I).

Mixed-layer clays (MLC) are a complex of smectite and chlorite clay minerals indicating temperatures between 200 and 230˚C. In thin-section, it appears as a coarse-grained clay mineral, coarser than smectite and finer than chlorite. XRD analysis showed typical mixed-layer clay at 774 m depth (Figure 1 in Appendix I).

Chlorite in cuttings is commonly light green. Chlorite represents a temperature >230˚C and is associated with high-temperature alteration minerals like epidote, prehnite and wollastonite. In thin- sections, it is coarse grained and light green coloured in plane polarized light and grey in polarized light. Its texture shows tiny green needles, and sometimes radial forms. XRD analysis showed typical chlorite at 784 m depth (Figure 1 in Appendix I).

5.3 Alteration mineral zonation

With a few exceptions the minerals that provide information on their formation temperatures are those that contain in their structure either (OH) or nH_20. They include clays, zeolites, prehnite and amphiboles (Browne, 1984). The results of the distribution of alteration minerals give information about formation temperature at the time of deposition. These temperatures relate to Icelandic geothermal systems, as is known by empirical work, and are shown in Figure 11.

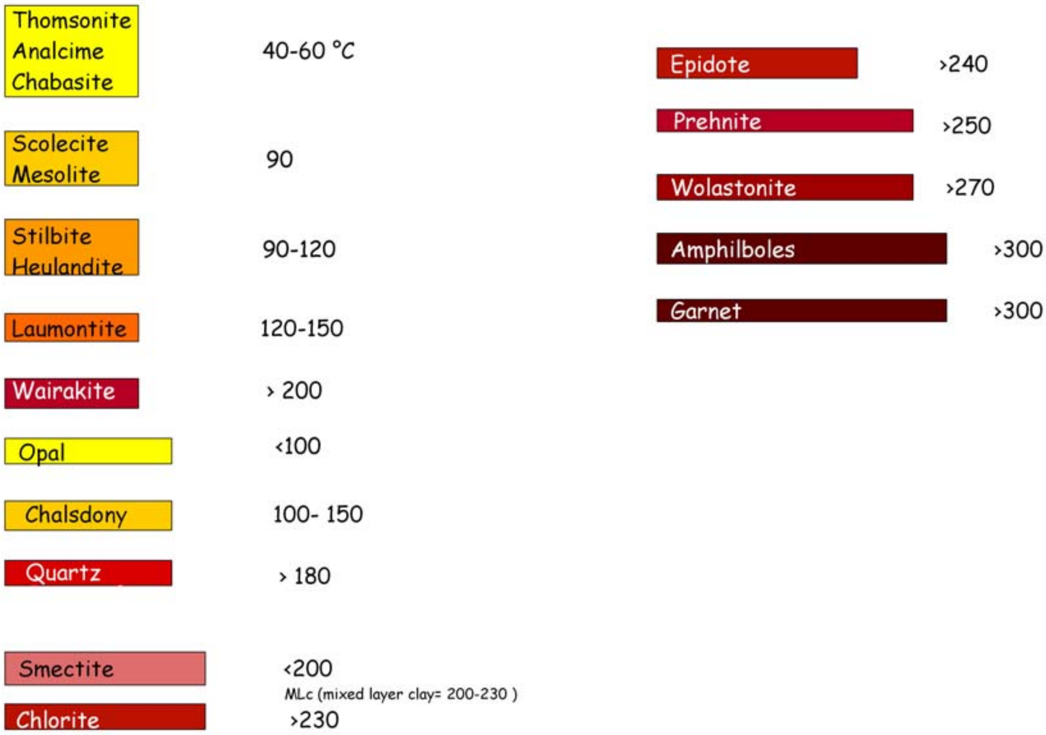

FIGURE 11: Schematic temperature of alteration mineral deposition in Icelandic geothermal systems (Franzson 2003)

Smectite-zeolite zone. Characterized by the presence of smectite and zeolites indicating temperatures less than 200˚C and covers the interval 20-510 m in the well.

Mixed-layer clay zone (MLC). This zone extends between the smectite–zeolite zone and the chlorite zone, indicating temperatures between 200 and 230˚C, and extends from 510 to 590 m depth in the well.

Chlorite zone. The upper limit of this zone correlates with the first signs of chlorite at 590 m depth and extends down to 660 m depth. The upper boundary indicates a temperature of about 230˚C.

Chlorite-epidote zone. Marked by the first appearance of epidote at about 660 m depth indicating temperatures greater than 240˚C. This zone is also characterized by significant amounts of prehnite in this well.

5.4 Mineral time sequence

By studying the deposition sequence of secondary minerals in pore spaces like vugs (vesicles) and veins in 36 thin-sections of different depths of the well to 806 m, one can get an idea of the thermal evolution of the geothermal system (Table 3).

Table 3 shows that the first mineral to deposit is clay, especially smectite. At the low temperatures that are above 486 m, calcite is deposited after clay. Where the temperature starts to increase, below 486 m, wollastonite is deposited after mixed-layer clay at 772 m depth, and at 806 m depth prehnite and wollastonite are deposited after mixed-layer clay indicating that the system is heating up. The relationship with wairakite and wollastonite is not clear and needs more studying.

TABLE 3: Time sequence of alteration mineral deposition in the uppermost 806 m of well HE-9

Depth (m)	**Older to younger**
102	Clay → Pyrite and calcite
122	Glass → Clay → Calcite
142	Glass → Clay → Calcite
156	Pyroxene and olivine → Clay
170	Glass → Smectite → Calcite
186	Not obvious, not vug or vein
216	Glass → Smectite → Calcite
238	Quartz → Pyrite and siderite
272	Calcite filling
302	Glass and olivine → Clay
310	Not obvious, not vug or vein
318	Glass → Calcite and siderite
332	Glass → Calcite and siderite
360	Siderite → Clay
376	Glass → Clay and siderite
400	Clay → Siderite
420	Clay → Siderite
442	Smectite → Calcite, siderite and limonite
466	Smectite → Calcite and siderite
486	Smectite → Siderite → Stilbite → Calcite (siderite → MLC)
510	Glass → Smectite → MLC (smectite → Calcite and siderite)
528	MCL → Quartz → Calcite (starting alteration in plagioclase)
540	Quartz → Calcite
598	Chlorite → Calcite and siderite
602	Calcite → Quartz → Pyrite (chlorite → Quartz)
620	Clay → Quartz → Wairakite (quartz → Platy calcite → Wairakite)
636	Platy calcite → Quartz (and inverse) (smectite → Chlorite)
654	Clay → Quartz → Prehnite
670	Quartz → Calcite → Chlorite → Wollastonite
674	Quartz → Prehnite
712	Prehnite & MCL → Quartz and calcite
736	Quartz → Calcite
750	Calcite → Prehnite
772	MLC → Wollastonite
782	Calcite → Quartz
782	Quartz → Calcite
806	MLC → Prehnite and wollastonite

MLC: Mixed-layer clay

6. AQUIFERS

The aim of deep geothermal drilling is to penetrate into a permeable high-temperature zone. The cause of permeability in rock formations can be faults, joints, intrusions and lithological contacts. Pillows have higher effective permeability than any other rock type encountered by drilling in Icelandic geothermal areas (Fridleifsson, 1978). Meteoric water penetrates down along faults or joints, heats up and rises as steam or hot water towards the surface. Some cold aquifers cut into geothermal wells, especially in upper parts of the well, and have to be cased off and cemented. Sometimes, hot aquifers may also have to be cased off and cemented because of safety reasons. Possible aquifers in a well can be detected by: Temperature logs, circulation loss, hydrothermal alteration, and lithological conditions. Temperature logs may show some peaks during drilling and after drilling in production tests with well discharge and warm–up indicating possible aquifers. When the well encounters aquifers, a loss of circulation will often occur. Some alteration minerals indicate good permeability. In Philippine geothermal wells for example, quartz, adularia, anhydrite, wairakite, illite, hyalophane, abundant pyrite, abundant calcite (often drusy minerals) are indicative of good permeability. Some minerals like prehnite, pumpellyite, pyrrhotite, abundant laumontite and titanite, persistence of smectite and illite-smectite at temperatures greater than 230˚C, and low alteration intensity are poor permeability indicators (Reyes, 2000).

In well HE-9 a total of 4 possible aquifers have been indicated down to 800 m depth. Figure 12 shows three possible aquifers at depths of 100 m, 120 m and 800 m. Graphs A and B are temperature logs during drilling, and graph C is a temperature log during the warming up period, 45 days after drilling completion. It is worth pointing out even though it is beyond the scope of this work that the main aquifer of the well is at 1100-1200 m depth and can been seen as a cooling point in graph C.

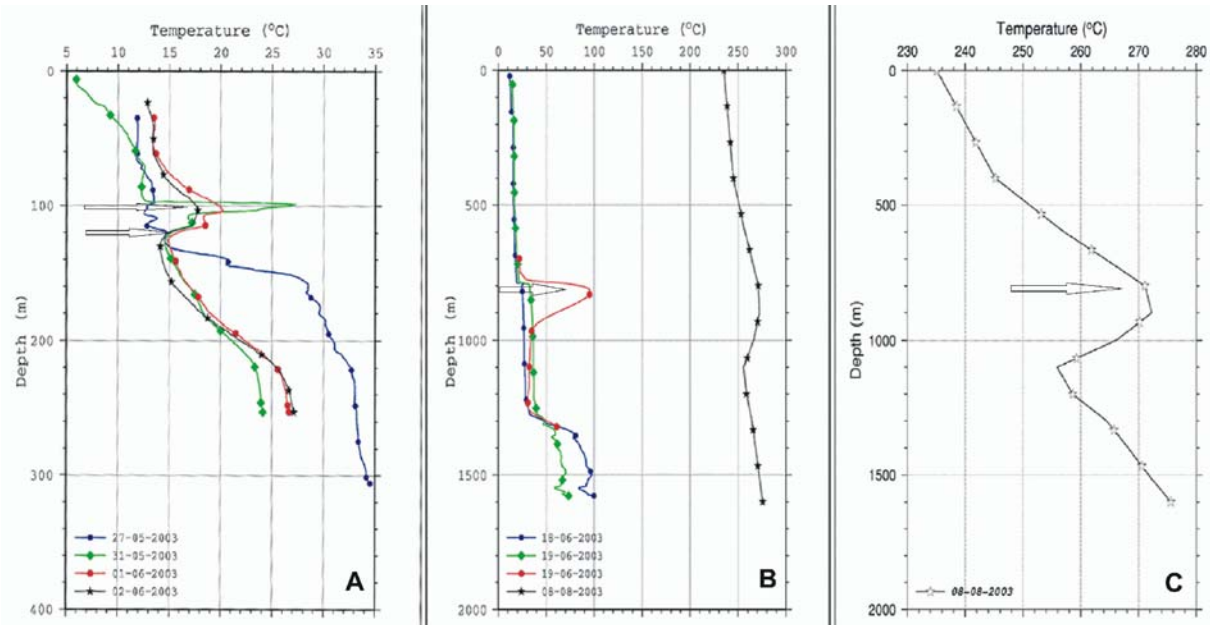

FIGURE 12: Temperature logs indicating 3 possible aquifers in the well HE-9

The alteration mineralogy log in Figure 9 also indicates another aquifer at 430 m depth, where high deposition of pyrite and calcite at the bottom of a fine- to medium-grained basalt indicates a possible aquifer. Loss of circulation further confirms aquifers at depths of 100 and 120 m with about 2 l/s loss. Drilling with mud is an effective way to seal permeable formations and narrow fractures, so the relatively few aquifers found above 500 m depth must be attributed to the mud drilling. All these aquifers are located above the production casing part of the well. Exploration in the well HE-3, at a distance of about 1 km to well HE-9, showed that aquifers are generally small and confined to the upper 180-500 m depth interval, and that they are related to lithological boundaries and intrusion contacts (Getaneh, 2001). Correlation between lithology, stratigraphy and aquifers shows that most of the aquifers are small and located at formation contacts and some at the contact with intrusions.

The aquifer at 800 m depth is in the production part of the well just below the production casing. It is located at boundaries of basalt intrusion and basaltic breccia. It is obvious in temperature profiles in Figure 11. It appears as a heat anomaly on the graphs, and is seen because the water table in the well was lowered during the injection test. Therefore, the pressure of the aquifer was higher than the pressure in the well and so the aquifer started to flow into the well.

7. DISCUSSION

In each geothermal system, one of the most important questions is whether the system is cooling down or heating up. Study of the mineral deposition time sequence reveals which alteration minerals are deposited earlier and which ones deposited later. Results of this study showed that there is a heating up in the high-temperature system deduced from prehnite and wollastonite deposition after mixed-layer clay in vugs. However, clear rapid heating like deposition of quartz after low-temperature zeolites was not seen.

In order to compare temperature of alteration minerals to measured temperatures, Figure 13 was drawn. It shows relevant direct temperature measurements above 500 m depth, while the well was heating up. Below 500 m depth, good correlation is seen between calculated temperature and alteration minerals. Mixed-layer clay indicates heating up where the temperature in the well is increasing. The aquifer at 800 m affected the upper part during the warming up period, therefore the alteration is more reliable here for formation temperature (Figure 13).

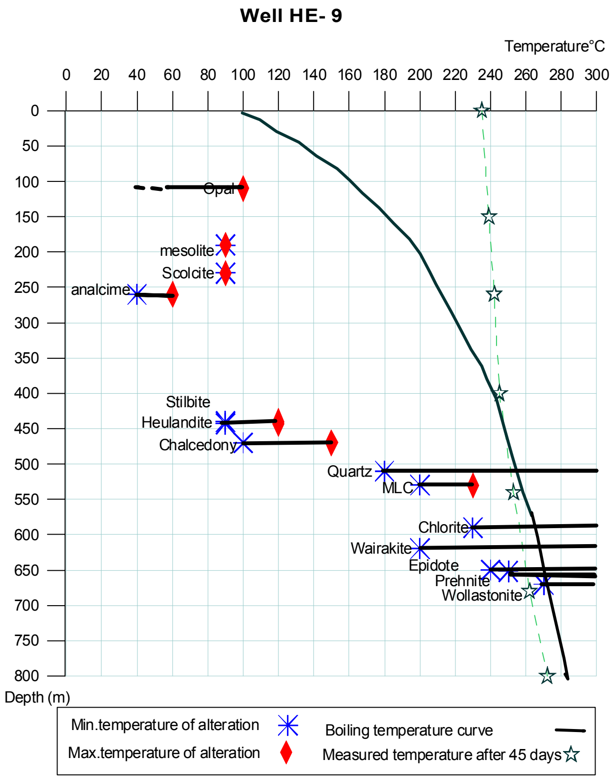

FIGURE 13: Correlation between hydrothermal alteration and measured temperature after 45 days in well HE-9

It is worth considering the sharp change in the distribution of the alteration minerals below the basalt intrusion at 430 m depth. From that point of view, one should look at the lithology and seek explanations. There is a major change at this depth in stratigraphy where basalt lavas, basalt breccia, and intrusions characterise the section above. Below, basaltic breccia is dominant. According to the geophysical logs, one can see higher (on average) porosity in the breccia part than above. If the intrusions are horizontal, they act as a cap rock.

8. CONCLUSIONS

The following conclusions can be deduced:

- Stratigraphy of the first 800 m of the well consists of hyaloclastite formations that were deposited during glacial times, and basaltic lava flows during interglacial periods. A few intrusions were also encountered.
- The alteration mineral distribution indicates four alteration zones above 800 m depth: Smectite-zeolite zone (T< 200˚C) extending to 510 m depth; mixed-layer clay zone (200 < T < 230˚C) at the depth interval 510-590 m; chlorite zone (230<T<240˚C) at the depth interval 590-660 m and chlorite-epidote zone (T> 240˚C) from 660 m depth.
- The time sequence of alteration deposition shows a heating up in the high-temperature system but there are no clear indications in alteration minerals for rapid heating or cooling in the system.
- Correlation between lithology, stratigraphy and aquifers shows that aquifers are located at formation contacts and also at contacts with intrusions. Deposition of calcite and pyrite also imply an additional aquifer at 430 m depth in the well.
- All aquifers above 800 m were cased of and cemented due to their cold nature and for safety reasons.

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APPENDIX I: Preparation of mineral samples for analysis by the XRD technique and results

Procedure I: Zeolites and other hydrothermal minerals
Pick the mineral grains under the binocular microscope that there is doubt about distinguishing, trying to avoid feldspars in the samples as much as possible. Feldspars cause difficulty in later interpretation of results as they have much refraction that interferes with almost anything requiring analysis. Crush the sample in an agate bowl to attain a powder of 5-10 microns grain size. Keep the sample wet by adding acetone to prevent loss of sample while powdering. Fill the sample window slot with an appropriate amount of powdered sample, and then press a glass slide against the sample in a slot to make it firm, flat and level.

Run the sample from 4-60° on the XRD.

Procedure II: Clay minerals
Place approximately two teaspoons of drill cuttings into a test tube, labelling the well and sample number. Wash out dust with distilled water. Fill the tubes 2/3 full with distilled water and plug with rubber stoppers. Place the tube in a mechanical shaker for 4-8 hours, depending on alteration grade of samples. Remove the test tubes from the shaker and allow settling for 1-2 hours, until particles finer than approximately 4 microns are left in suspension. Pour away a few ml from the top of each tube with a pipette, and place about ten drops on a glass slide labelled with a permanent marker. Avoid having the samples thick. Make a duplicate for each sample and let it dry at room temperature overnight. Place one set of the samples in a desiccator containing glycol ($C_2H_6O_2$) solution and set the other in another desiccator containing $CaCl_2H_2O$. Store the samples at room temperature for at least 24 hours. Thick samples will need longer time in the desiccator or at least 48 hours.

Run both sets of samples from 2 to 14˚ on the XRD.

Place one set of the samples (normally the glycolated one) on an asbestos plate and heat in a pre-heated oven at a temperature between 500 and 550˚C. The oven temperature must not exceed 550˚C. The exact location of individual samples on the asbestos plate must be known (by drawing a schematic shape) before heating because labelling will disappear during the heating process. Cool the samples sufficiently before further treatment.

Run the samples from 2 to 14˚C on the XRD.

TABLE 1: Results of the XRD analysis of clay minerals in well HE-9
(OMH = untreated; GLY = glycolated; HIT = heated)

No.	Depth (m)	d(001) OMH	d(001) GLY	d(001) HIT	D(002)	Mineral	Type	Remarks
1	112	15.2 broad	16.69 broad	15 broad / 10 low	none	Sm: sm	Sm	Vague clay min.
2	154	14.9 broad	17.1 broad	15 broad / 10 low	none	Sm: sm	Sm	Vague clay min.
3	210	14.9 broad	17.1 broad	15 broad / 10 low	none	Sm: sm	Sm	Traces clay min.
4	224	nd	nd	Nd	nd	nd	nd	No detection clay
5	312	nd	nd	Nd	nd	nd	nd	No detection clay
6	424	13.8 asym	16.5 asym	15 broad / 10 low	none	Sm: sm	Sm	Good smectite
7	536	12.6/14.2	14.2/16.4	9.8	~7 HIT=0	Sm+MLC	Sm+MLC	7.2 OMH/GLY
8	554	12.6/14.6	14.6/16.6	10	~7 HIT=0	Sm+MLC	Sm+MLC	7.2 OMH/GLY
9	574	12.7/14.4	15.1/16.5	10	~7 HIT=0	Sm+MLC	Sm+MLC	7.2 OMH/GLY
10	596	14.4	14.1	12.4	~7 HIT=0	MLC:ill/ sm/chl	MLC	
11	624	14.5	14.5	12.6	~7 HIT=0	MLC:ill/ sm/chl	MLC	
12	672	12.7/14.7	12.7/13.7	9.8	~7 HIT=0	Sm+MLC	Sm+MLC	7.2 OMH/GLY
13	706	12.8/14.3	12.9/14.3	14.3/9.8	~7 HIT=0	Chl. unst.	Chl	7.2 OMH/GLY
14	742	14.2	14.2	14.8/9.9	~7 HIT=0	Chl. unst	Chl. unst	7.1 OMH/GLY
15	766	14.8/16.1	17	10.2	~7 HIT=0	MLC	MLC	7.2 OMH/GLY
16	774	14.6	15.5/16.9	14 broad / 10.2	~7 HIT=0	MLC	MLC	7.2 OMH/GLY
17	784	14.5	14.5	14.5	7.1 HIT=7.4 str.	Chl	Chl	
18	798	14.4	14.4	14.4	7.1 HIT=7.4 low	Chl	Chl	

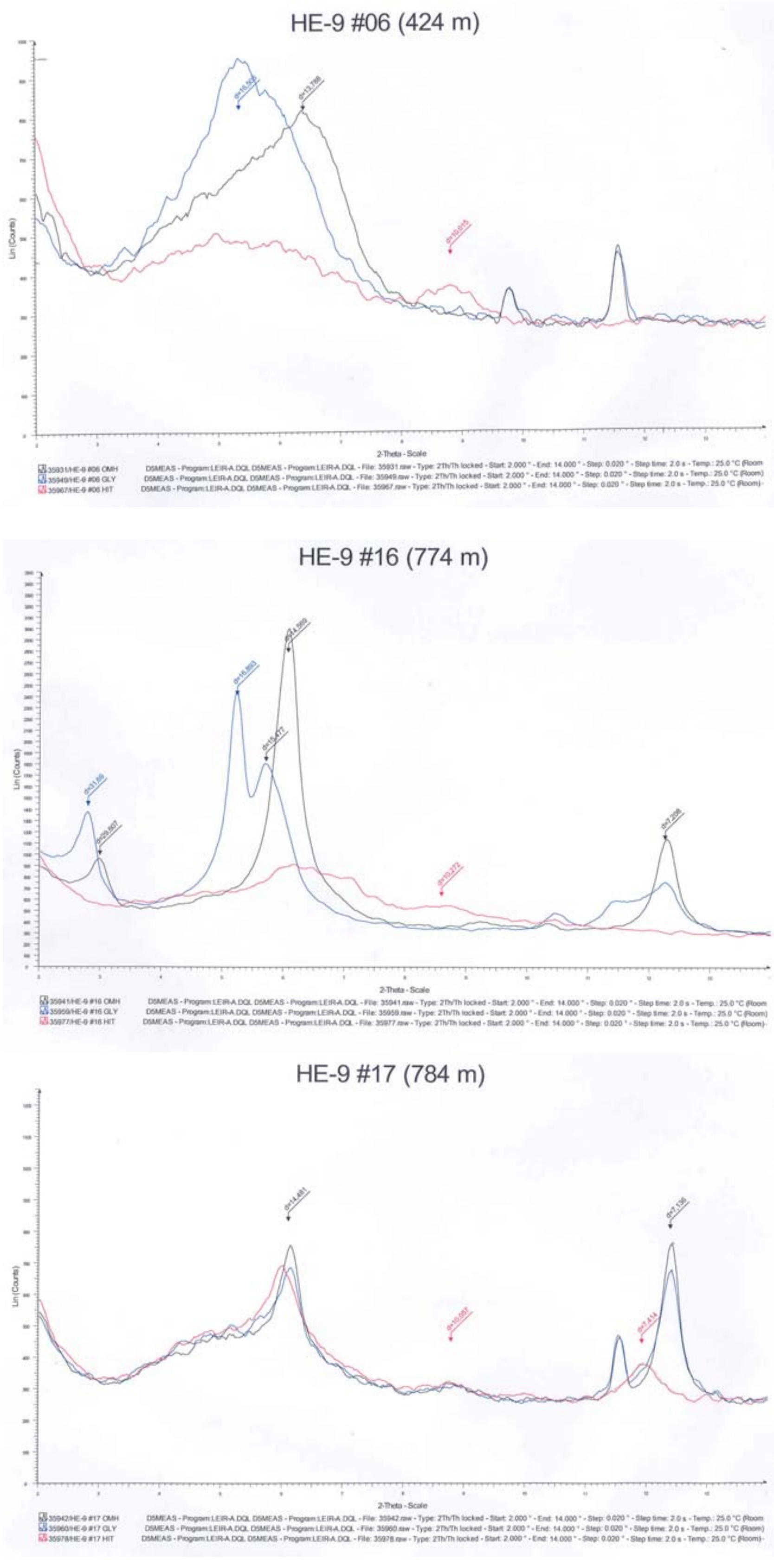

FIGURE 1: Graphs showing results of XRD analyses indicating typical smectite at 424 m depth, mixed-layer clay at 774 m depth and chlorite at 784 m depth