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BOREHOLE GEOLOGY AND HYDROTHERMAL MINERALISATION OF WELL HE-22, ÖLKELDUHÁLS FIELD, HENGILL AREA, SW-ICELAND

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ABSTRACT

Well HE-22 is the third exploratory well drilled in the Ölkelduháls area, situated at the eastern flank of the Hengill volcanic and geothermal complex. The intercepted rock succession consists of hyaloclastite formations and lava flows of basaltic composition as well as minor intrusive rocks. The formations host a wide variety of secondary hydrothermal assemblages from low- to high-temperature minerals. Five main alteration zones have been identified: smectite-zeolite (<200°C) at <170 m, mixed-layer clay (200-230°C) from 170 to 206 m, chlorite (230-240°C) from 206 to 364 m, chlorite-epidote (>240°C) between 364 and 740 m, and the upper boundary of epidote-actinolite (>280°C) at 740 m. The relationship of time and mineral crystallisation indicate formation from low-temperature at shallower levels to high-temperature in deeper portions of the well. However, the wide deposition of calcite as the end member of the assemblage may indicate cooling of the geothermal system. Seven feed zones were encountered and categorized into weak and moderate aquifers. These aquifers can be correlated to lithological formations, intensity of alteration, abundance of veins and vesicles, stratigraphic boundaries, and the presence of intrusive bodies. The comparison of hydrothermal mineralisation with other wells drilled in Ölkelduháls geothermal field indicates progressive crystallisation from low-temperature minerals at shallow depth to high-temperature minerals at deeper levels; there are, however, indications of overprinting of these minerals. The current geothermal formation temperature is in disequilibrium with the hydrothermal alteration temperatures.

1. INTRODUCTION

The Hengill high-temperature geothermal field rates as one of the largest in Iceland. It is geographically located in southwest Iceland, approximately 30 km east of Reykjavik. Well HE-22 is the twenty-second geothermal drillhole in the southern and eastern part of the Hengill central volcanic complex; and the third well drilled in the Ölkelduháls sector. Ölkelduháls is situated on the eastern fringe of the Hengill central volcanic system. The well is a directional hole, reaching a depth of 2104 m. This geological research is based on the upper 800 m of the well, and involves a characterisation of the lithology, hydrothermal mineralisation, sequences of mineral deposition, and aquifers. The results of this study are compared with the previous wells drilled in the Ölkelduháls sector and a conceptual model of the system is produced. This report is a completion to the six-month training course of the United Nations University - Geothermal Training Programme (UNU-GTP) in 2006.

1.1 Regional tectonic and geological settings of Iceland

Iceland is a product of a unique tectonic and geologic combination of divergent oceanic plate boundary tectonic regimes and a hot spot. The island is geologically located on the sea floor spreading boundary of the Mid-Atlantic Oceanic Ridge, where the tectonic plates of the North American and Eurasian plates are diverging at an average rate of 2 cm per year. It is a site where a mid-oceanic ridge is exposed above sea level. The exposure lies between the Kolbeinsey Ridge to the north and the Reykjanes Ridge to the south. The west-northwest motion of the mid-oceanic ridge relative to the hot spot has resulted in a repeated southeastwards ridge jump since ~23 Ma and the formation of overlapping spreading centres (Garcia et al., 2003; Hardarson et al., 1997). Iceland is divided into various volcanic rift zones namely: northern, middle, western and eastern zones (Figure 1). The magmatism is currently represented on land by the volcanic zones (Hardarson et al., 1997). The western and eastern volcanic zones are being offset by a "leaky transform fault" of the mid-Iceland volcanic zone, also known as the south Iceland seismic zone (LaFemina et al., 2005). The location of the mantle plume or hot spot is thought to be located underneath the southeastern portion of the island. It represents the broadest hot spot on the planet**.** The volcanic zones are the primary settings for intense tectonism, frequent earthquake epicentres, active volcanism, and widespread geothermal activity.

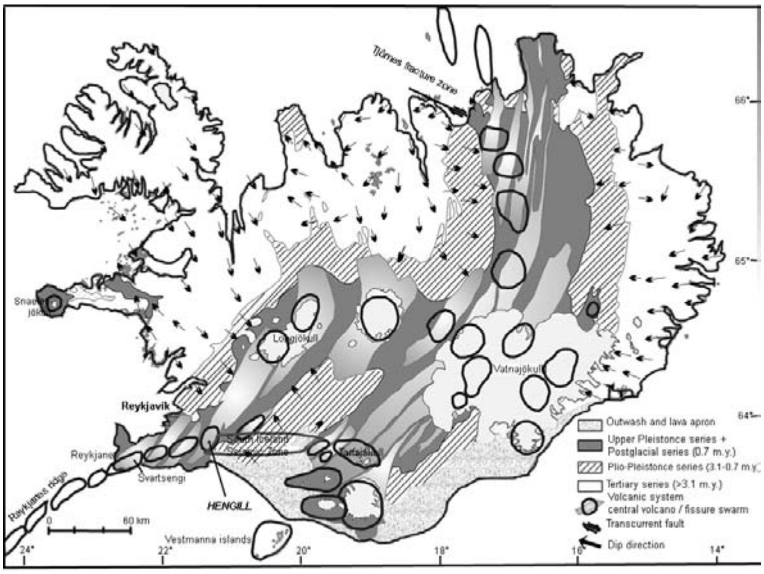

FIGURE 1: Map showing the main geological features of Iceland (Saemundsson, 1979)

The geological history of Iceland is relatively young, undergoing continuous tectonic activity and changes. The oldest rock formations date back to Tertiary basaltic lavas, which are predominantly exposed in the eastern and northwest quadrants of the island. A rock outcrop is dated approximately 16 Ma in the extreme northwest region (Hardarson et al., 1997). The Quaternary rocks are composed of sequences of basalt lavas and hyaloclastites that are exposed in the central, southwest, and east sectors. The volcanic episodes during this period were strongly controlled by climatic conditions. The volcanism is divided into: ice free volcanism and glacial time volcanism (Vargas, 1992). The ice free volcanism is categorized into Inter- and Post-glacial volcanism, and the rock types erupted under this climatic condition are represented by subaerial eruptions forming lava flows, pyroclastic scorias, and welded lavas. The glacial volcanism is divided into sub- and supra-glacial volcanism, and eruptions characterised by phreato-magmatic deposits and the formation of hyaloclastites.

The most prominent tectonic feature is the active NE-SW fractures of the axial rift zones that transect the Quaternary neo-volcanics. The rift zone is characterised by the presence of en echelon arrays of volcanic fissure swarms, which are made up of well developed extensional structures such as normal faulting, tensions, fractures, and the formations of grabens. The swarms are from 5 to 15 km wide and sometimes exceed more than 100 km in length. The swarms are also the locus for the formation of the central volcanic complexes or systems. Based on petrological and volcano-tectonic data, some 30 volcanic systems have been defined within the volcanic zones (Saemundsson, 1979). The western volcanic zone can be traced from the Reykjanes Peninsula in the southwest, to the Langjökull icecap in the western central portion of Iceland. Geological data show that it has been active for the past ~7-9 Ma, due to shifting tectonic movement of the eastward propagation of the ridge systems from the Snaefellsnes Peninsula towards the Reykjanes Peninsula (Saemundsson, 1992). The most recent seismic movements of the Hengill volcano occurred in 1993-1998 (LaFemina et al., 2005). The dominant normal faults, fissures, and dikes in this zone trend ~N30°E (Gudmundsson, 1987). The eastern volcanic zone is younger than the western volcanic zone, and has only been active for the last ~2-3 Ma, during the eastward shift of the spreading ridge from the western volcanic zone. The N45°E direction is the most prominent direction of the fissure swarms and dikes in the eastern zone. The zone hosts a number of very active central volcanoes such as: Bárdarbunga, Hekla, Grimsvötn, Torfajökull, Katla and a few others. The northern volcanic zone extends from Vatnajökull glacier to the northern coast, and continues to the seafloor where it is offset to the west by the Tjörnes fracture zone that connects to the Kolbeinsey ridge. The zone hosts the Krafla volcanic system, the site of fissure volcanic eruptions from 1975 to 1984.

The high- and low-temperature geothermal activity in Iceland is widespread and abundant, and the geothermal energy is extensively utilized (Figure 2). The high-temperature fields are concentrated along the present active volcanic and rifting zones, manifested by the presence of steaming vents, mud pools, fumaroles, and highly altered grounds. The reservoir system is characterised by temperatures >200°C at 1 km depth. The low-temperature geothermal fields are confined in Quaternary and Tertiary areas, along the flank or outside the active volcanic zones. This type of field has a reservoir temperature of <150°C in the uppermost kilometre, and is characterised by the presence of hot/boiling and/or warm springs.

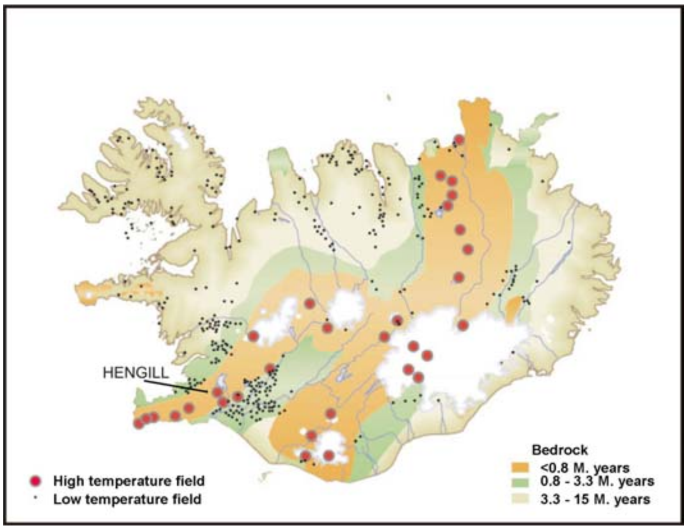

FIGURE 2: Locations of high- and low-temperature geothermal fields in Iceland

1.2 Geological materials and analytical methods

During the drilling of HE-22, approximately 400 samples of drill cuttings were collected at 2 m intervals, starting from -8 m down to -800 m; and these samples were properly labelled and stored. The drill cuttings serve as the primary and essential base for the geological information regarding the subsurface lithology, the distribution of hydrothermal minerals, and the alteration zones of the geothermal well. These samples were washed and cleaned thoroughly with tap water to remove unwanted mud/clay and other contaminants during the drilling activity. Then, representative samples from the washed cuttings were placed into a rectangular plastic box (56 x 38 x 15 mm) for analyses and interpretation under the binocular microscope.

The cuttings were studied using an Olympus SZ12 binocular microscope with a magnification range of 7x to 90x. Various geological data could be extracted in this investigation, such as: the determination of the rock types, stratigraphic sequences, grain texture, hydrothermal alteration minerals, the intensity of the alteration, the degree of porosity and permeability, types and intensities of vein and void systems, and evidence of structural controls such as faulting and jointing.

In addition, thin sections were prepared from a number of representative samples for in-depth petrographic analysis and further confirmation on the results of the cuttings interpretations. One of the important aspects of this study is to determine the minerals and alteration time sequences. A total of 30 thin sections were investigated using a Leitz Wetzlar petrographic microscope.

Furthermore, 25 samples were also carefully selected and subjected to X-ray diffraction (XRD) analysis instrumentation, following the standard operating procedures with an interaction of Diffract and EVA software packages (Appendix I). XRD is used for the identification of clay minerals, which were not identified or were impossible to identify under the binocular and petrographic microscopes. Minerals are identified based on peak location and height in the XRD spectra. Fluid inclusion was also conducted at depths of 364 and 380 m using a Leitz Laborlux microscope with a Doric Trendicator 410A °C for measurement of homogenisation temperature.

The results of the geological information and the geophysical logging data were combined and assessed, in order to further determine the characteristics of the geothermal system of the well, and if possible, to correlate it to the other well(s) drilled in the area in order to understand the overall behaviour of the geothermal field system.

2. THE HENGILL HIGH - TEMPERATURE AREA AND THE ÖLKELDUHÁLS FIELD

2.1 An overview of Hengill high-temperature area

The Reykjanes peninsula is the southwesternmost part of Iceland. Geologically, on the surface the Reykjanes Peninsula consists primarily of hyaloclastites of the last glacial periods, and of Postglacial basaltic lava flows. The peninsula hosts several high-temperature geothermal areas such as the Reykjanes, Eldvörp, and Svartsengi fields in the western part; the Krýsuvík area (Krýsuvík, Trölladyngja, and Sandfell fields) in the middle; and the Brennisteinsfjöll area and the Hengill area situated in the easternmost sector (Figure 3).

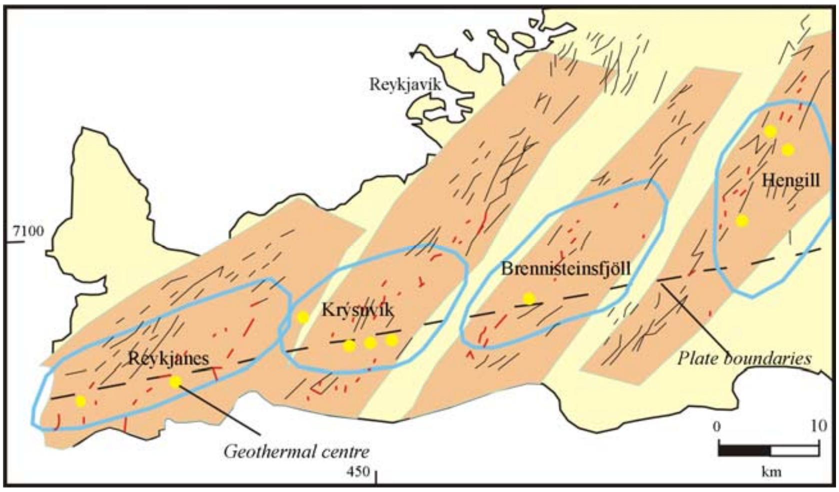

FIGURE 3: Distribution of high-temperature geothermal and volcanic systems in Reykanes Peninsula,

The greater Hengill volcanic complex and its geothermal activity are related to three distinct volcanic systems (Figure 4). The oldest system is the extinct and eroded Pleistocene Hveragerdi - Grensdalur (Grændalur) volcanic system. The volcanic system supplies geothermal heat to the Reykjadalur and Hveragerdi sites. Situated northwest of Hveragerdi - Grensdalur is the volcanic complex of the Hrómundartindur system in which the latest recorded eruption dates back to 10,000 years ago. The presence of thermal manifestations in the Ölkelduháls area is related to the geothermal activity in this volcanic system. The Hrómundartindur geothermal area is the smallest. Situated west of these volcanic systems and complexes is the Hengill volcanic system. Hengill is the youngest and most active of the three volcanic and geothermal complexes. The Hengill central volcano has an elevation of over 500 m above sea level. The volcanic and structural features of the Hengill geothermal system extend from the southwest through Innstidalur, Kolvidarhóll and Hverdalur to the northeast through Nesjavellir and Lake Thingvallavatn.

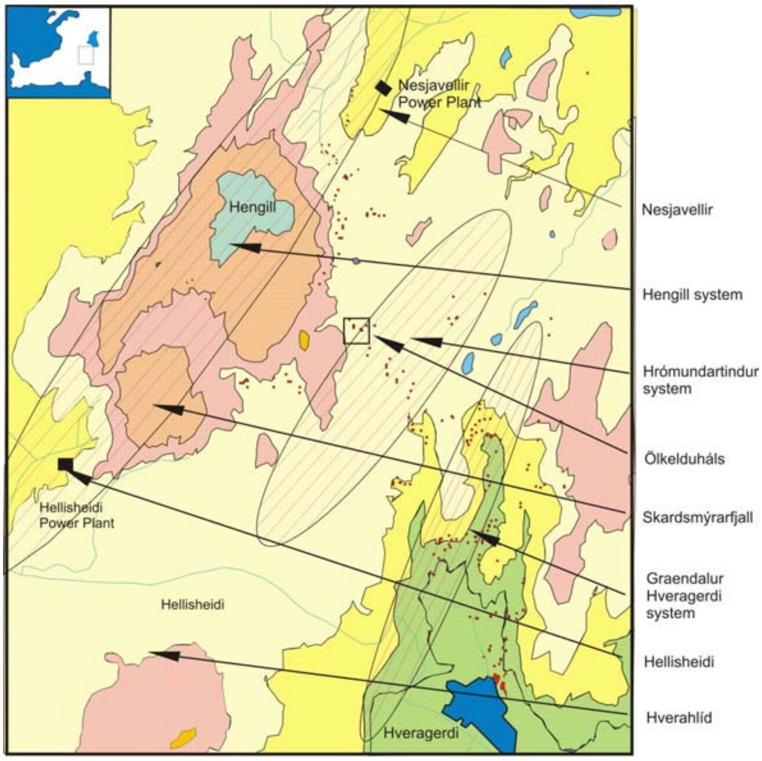

FIGURE 4: The Greater Hengill geothermal-volcanic system

The general geology of the Hengill volcanic complex comprises sub-glacially formed hyaloclastites and pillow basalts, inter glacial lava flows, and post glacial lava flows (Saemundsson, 1979; Figure 5). These volcanic rocks are of tholeiitic and olivine tholeiitic composition with aphyric or porphyritic texture. The Hengill central volcano covers an area of about 40 km^2.

The overall morphological landscape of the area is dominated by NE-SW trending hyaloclastite ridges forming the highlands, whereas the inter-glacial and post-glacial lava flows cover and dominate the low and flat-lying elevations. These deposits are highly porous but have low permeability due to the high intensity of hydrothermal alteration.

The Interglacial and Post-glacial eruptions consist of lava flows. Post-glacial volcanism is characterised by three fissure eruptions, approximately 9,000, 5,000, and 2,000 years in age. The fissures, especially the last two eruptions are believed to form the major outflow zones in the Hengill geothermal system. The sub-surface geological data from the borehole cuttings indicate two distinct types of intrusions in the geothermal field: fine-grained basalt and fine-grained andesite - rhyolite (Franzson et al., 2005).

2.2 Production fields and potential of the Hengill high-temperature geothermal complex

The Hengill geothermal - volcanic system is considered one of the largest high-temperature geothermal fields in Iceland (Reykjavik Energy, 2005). Currently, there are two producing fields, the Nesjavellir field that started operation in 1990, and the Hveragerdi field, which uses geothermal water and steam for space heating, industrial, and greenhouse farming for the town of Hveragerdi. A new geothermal power plant in the Hellisheidi field will start operation in October 2006. The Hengill geothermal fields and power plants are being operated by the Reykjavík Energy Co., a company almost fully controlled and owned by the city of Reykjavík. It is the largest developer of geothermal energy in Iceland. The company produces a total combined output of 750 MWt coming from four low-temperature fields within the vicinity of Reykjavik. The Nesjavellir geothermal area is located on the northern flanks of the Hengill central volcano. The field is a co-generation geothermal plant with

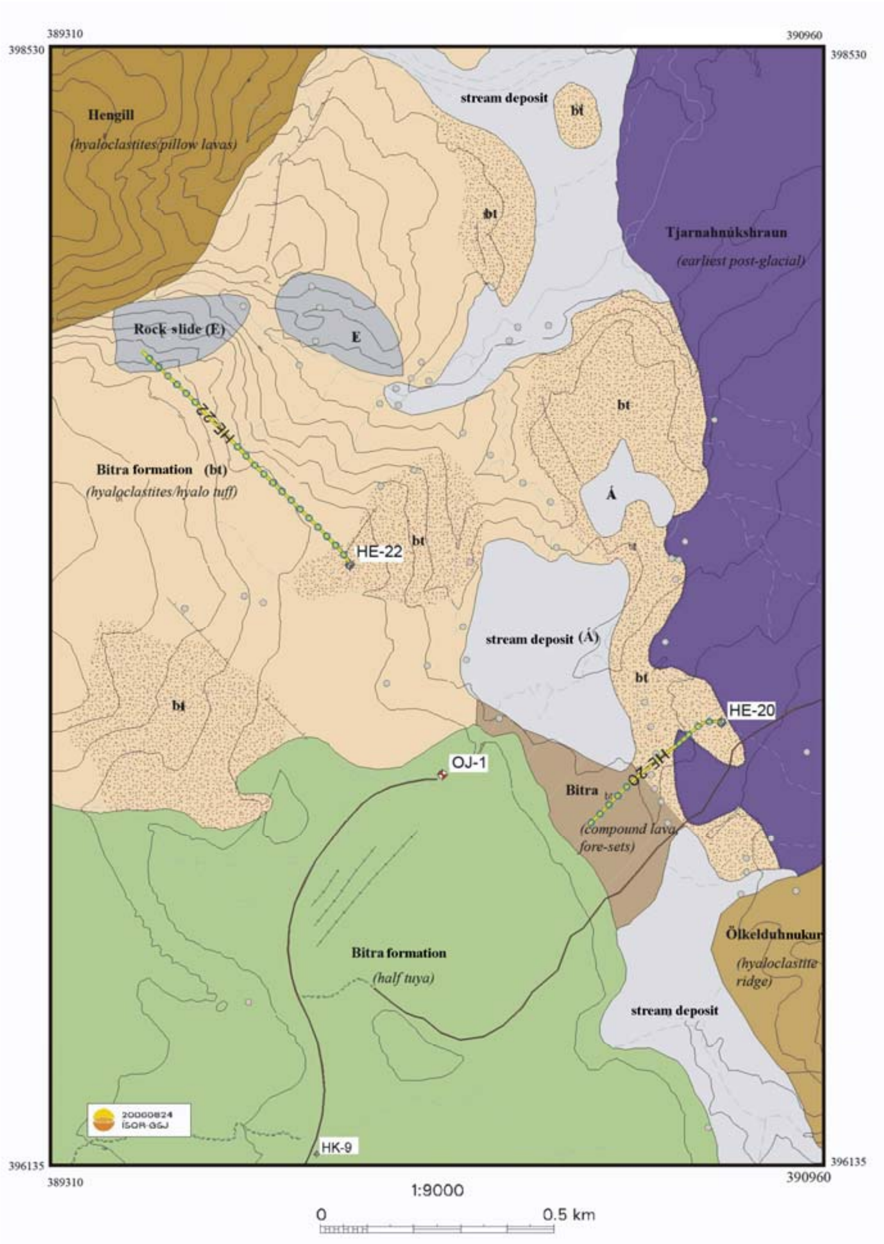

FIGURE 5: Geology of Ölkelduháls area and the locations of the wells (slightly modified from Saemundsson, 1995; and Gebrehiwot, 2005)

an operating capacity of 120 MWe and 300 MWt for direct utilization, providing electricity and heating to the city of Reykjavik and its surrounding areas. To date, 22 holes have been drilled in Hellisheidi, but 5 of them are not producing. The depth of the wells ranges between 1000 and 2000 m, with a maximum measured temperature of 280°C. The Reykjavik Energy is currently constructing a new geothermal power plant in the southern portion of Hengill, the Hellisheidi geothermal field. The initial installed capacity is 80-90 MWe. The drilling started in 2001. Preliminary results indicate that the geothermal fluid is dilute, as is common in high-temperature fields in Iceland, with low gas content. The power plant is intended to meet the increasing demand for electricity and space heating for domestic and industrial consumers of Reykjavik and neighbouring areas. The power plant extracts geothermal energy from the production wells within the Hellisheidi area. The exploration drilling activity in Ölkelduháls will assess the potential for a new geothermal power plant in that area.

2.2 Geology and structures of Ölkelduháls area

The Ölkelduháls field straddles and lies between the Hrómundartindur and Hengill systems. The detailed geology of the area is well mapped and discussed by Saemundsson (1995) and Gebrehiwot (2005). It is composed mainly of the Bitra formation, Hengill formation, Ölkelduhnúkur, and Tjarnarhnúkshraun (Figure 5).

The Bitra formation is the dominant rock in the area; it is made-up of hyaloclastites, hyalo-tuffs, compound lavas flows and foreset breccias. The eruption dates back to the late glacial period when the ice was retreating and thinning. During the early volcanic phase, Bitra erupted under sub-glacial conditions but, during later and final stages, it transformed and developed into lava shield volcanism.

The Hengill formation is a semi-circular table mountain consisting of pillow basalt, hyaloclastites with glomeroporphyritic texture and capped with subaerial lava flows.

The Ölkelduhnúkur formation can be found in the southeast portion of the area. It has an aphyric texture of mostly hyaloclastite tuff but with occasional pillow lavas. The formation erupted in a sub-glacial environment. The age of volcanism is probably older than the Hengill formation.

The Tjarnarhnúkshraun lava erupted along the Tjarnarhnúkur fissure during Holocene. The lava flow is situated in the eastern section of the area. The erupted material contains porphyritic basalt with crystals of plagioclase, pyroxene, olivine, and pyroxene.

Rock slides, terraces and stream deposits are also widely found in Ölkelduháls. The rocks were obviously deposited at the end of the last glacial period. Earthquakes and avalanches also played an important role in the emplacement of these alluvial deposits.

The NE-SW trending lineation is the predominant structural control in the Ölkelduháls geothermal area, as well as for the Hengill volcano. However, detailed mapping conducted by Gebrehiwot (2005) indicates that N-S and NW-SE trending fault/fracture zones are also present.

2.3 Surface thermal manifestations

Thermal activity in the Ölkelduháls area includes fumaroles, steam vents, boiling mud pots, water pools, hot and warm springs, steaming grounds, and extensive areas of hydrothermal alteration (Saemundsson, 1995b; Gebrehiwot, 2005). These manifestations are structurally controlled by NW-SE and N-S oriented faults and fissures, and are confined within the elevation from 230 to 430 m. The surface hydrothermal alteration is classified into slight and moderate clay alteration.

2.4 Geophysics

Various geophysical exploration surveys such as resistivity, magnetic, and gravity measurements were extensively undertaken in the Hengill geothermal area, including the Ölkelduháls field. The results of the Schlumberger and TEM resistivity surveys by Björnsson et al. (1986), Árnason (1993), and Árnason and Magnússon (2001) indicate an extensive resistivity anomaly corresponding to the presence of an active high-temperature geothermal system (Figure 6).

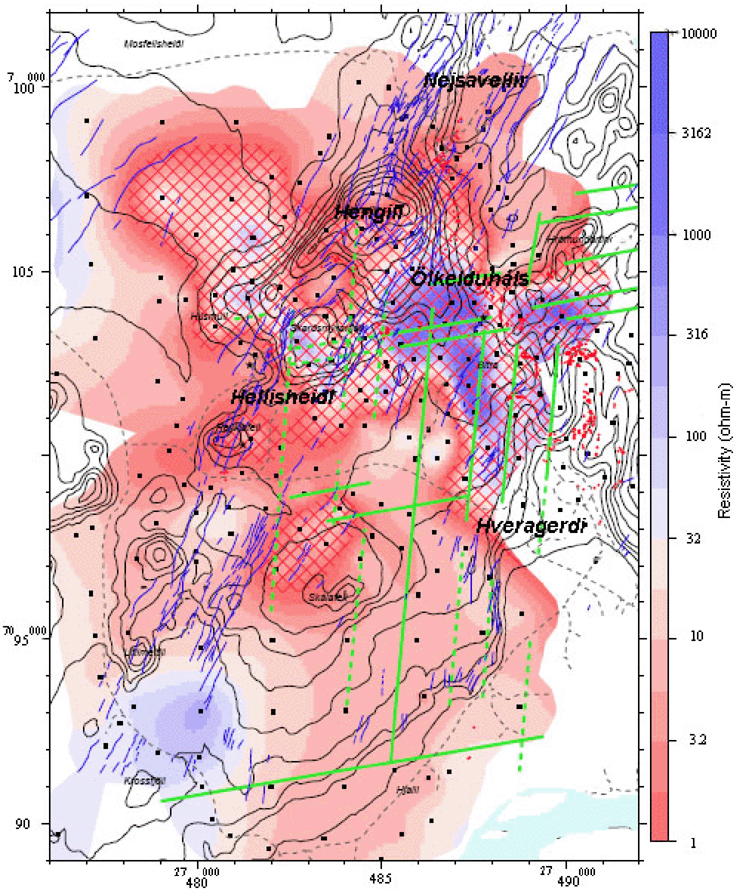

FIGURE 6: Resistivity map at 600 m b.s.l. based on TEM measurements in the Hengill geothermal area with major structural zones (Árnason and Magnússon, 2001)

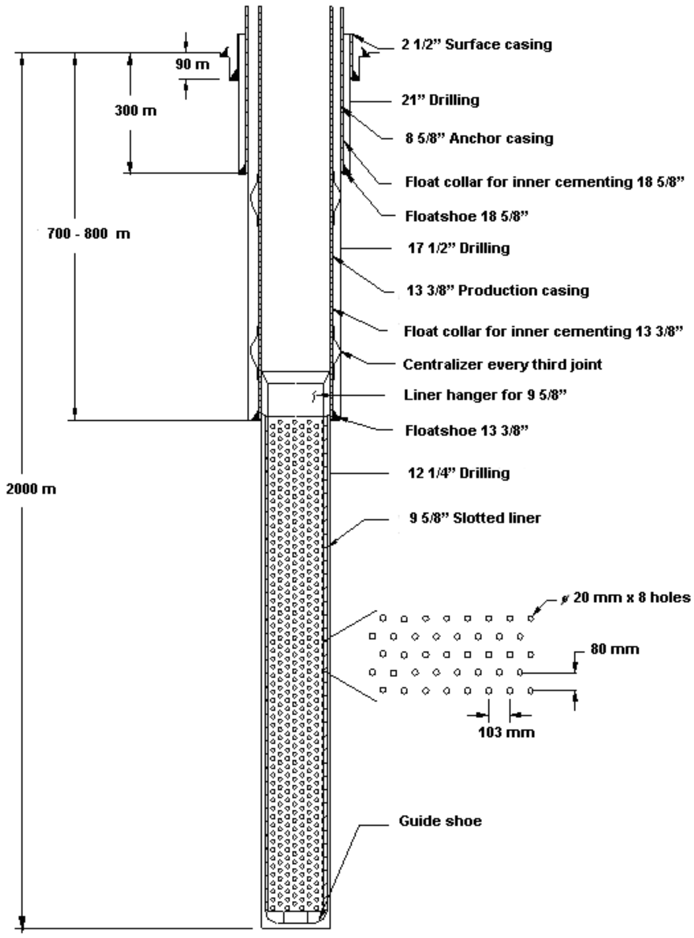

FIGURE 7: The well design of HE-22 (Mortensen et al., 2006)

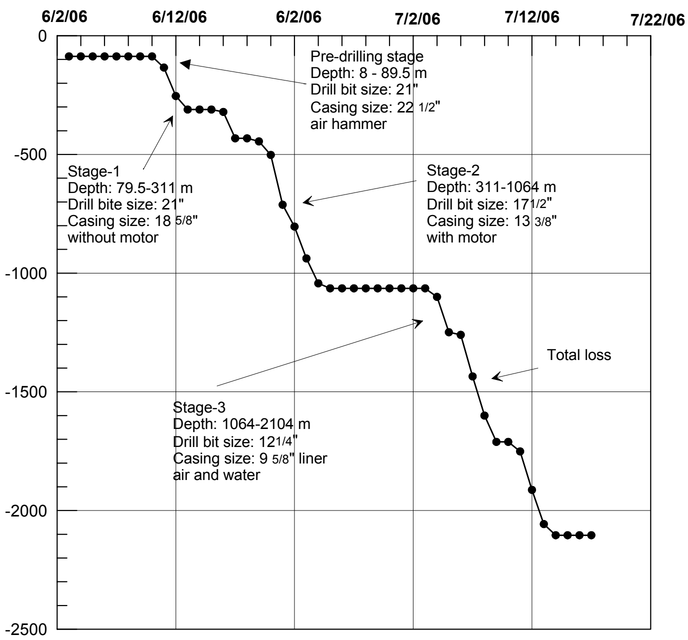

FIGURE 8: Drilling progress of well HE-22

2.5 Previous drilling activities

Besides well HE-22, two previous exploratory wells were drilled in the Ölkelduháls geothermal area. The first was ÖJ-1, drilled to a depth of 1035 m almost 12 years ago, from November 21, 1994 to January 22, 1995. This was followed by HE-20, drilled in October 2005, to a depth of 2002 m. ÖJ-1 has a measured bottom-hole temperature of about 200°C but has a relatively low wellhead pressure. HE-20 has a much higher temperature, just over 250°C, but is below the expected >300°C temperature. ÖJ-1 has high permeability, compared to the medium characteristics of HE-20.

3. BOREHOLE GEOLOGY

3.1 Drilling of well HE-22

Well HE-22 is a deep directional exploratory drillhole with a total depth of 2104 m. The well pad has the coordinates X 389945.47, Y 397419.80, Z 370.8 m. It was drilled in a north-northwest direction for the purpose of intercepting the major northeast trending faults of probable high permeability and temperature.

The Icelandic drilling company, Jardboranir Ltd., drilled from June 4 to July 12, 2006, a total of 45 days. The well design and the drilling stages are illustrated in Figures 7 and 8, respectively. The pre-drilling stage involved drilling the uppermost 9.5 m using an air hammer drill, and then a 26" drill bit and a casing size of 22 ½" down to 86.3 m. After the completion of pre-stage drilling and cementing, a larger and more powerful rig took over the rest of the program. The first stage involved drilling from 79.5 to 311 m without a motor, using a 21" drill bit and an anchor casing size of 18 5/8" down to 310 m, which was then cemented. In the second stage, a motor was used to drill from 311 m down to 1064 m. A drill bit size of 17½" was used for a production casing of 13 3/8" from the top to 1062 m. Finally, the last stage was drilling the production part to 2104 m with a 12 ¼" drill bit, using air and water as circulation fluids. The production section was lined with a 9 5/8" slotted liner down to 2084 m. The kick-off point for inclination drilling was at 320 m. The degree of inclination and well direction during stage 2 were monitored and controlled by taking measurements while drilling (MWD) and taking gyro surveys.

3.2 Stratigraphy of well HE-22

The stratigraphic column of well HE-22 is shown in Figure 9 and consists primarily of alternating sequences of hyaloclastite units and layers of lava with basaltic intrusive bodies. The series or units are further subdivided into various sub-series: the hyaloclastite lithology into pillow lavas (glassy basalts), basaltic breccia, and basaltic tuff; the lava flows are classified into fine- to medium- and medium- to coarse-grained texture. Overall, four hyaloclastite units, four lava flow series, and six intrusions were recognized. The hyaloclastites and pillow lavas have glassy texture. The outer rim of the pillow lava has a black glassy surface known as tachylite (Saemundsson and Gunnlaugsson, 2002). However, the interior parts of the pillow lavas have crystallised textures of tholeiite and are sometimes porphyritic. Volcanic breccia is characterised by abundant lithic fragments. The lava flows are tholeiitic and olivine tholeiitic in composition. Tholeiitic basalt is fine-grained and slightly richer in silica but poorer in sodium. It constitutes crystals of calcium-rich plagioclase, pyroxene of augite, and magnetite. It also contains minor olivine. Olivine tholeiite is coarser grained with crystals of plagioclase, augite, and some olivine. Intrusive rocks are of more massive and fine to coarse-grained texture. They are relatively unaltered compared to the surrounding rocks. The intrusive bodies are intercepted at various depths of the upper 800 m of the well.

The lithological descriptions are based mostly on binocular microscopic analysis with additional information from petrographic identifications. The descriptions and characteristics of these series/units are as follows:

Hyaloclastite series I (above 118 m): This unit is considered the upper part of the Bitra formation. It is divided into three (3) sub-units: the upper part is a thin layer of scoria (<10 m); the middle-unit is glassy basalt or pillow basalt (10-58 m); and the lower sub-unit is basaltic breccia (58-118 m). The first sub-layer has sub-aerial deposition while the latter two are formed in a sub-aqueous environment. No cuttings were collected between 0 and 8 m depth.

The first cutting sample is relatively fresh scoriaceous plagioclase porphyritic basalt without any hydrothermal alteration. This rock type probably extends up to the surface.

Just below the scoria is the formation of vesicular glassy pillow basalts. The pillow lavas are plagioclase porphyritic. Some fragments are composed entirely of glass while some rock cuttings have a thin glassy coating rim composition. Binocular microscope study shows crystal fragments of plagioclase, calcite, pyrite, limonite, and clay. Pyrite and calcite start to appear at a depth of 24 and 46 m, respectively. Limonite starts to form in the upper depth level. The rock sequence is fresh in the upper part but becomes slightly altered at the bottom. The vesicles are also without secondary minerals except near its contact with the lower basaltic breccia sub-layer . The filling material is mainly calcite. Likewise, calcite veins are common along the contact with the basaltic breccias.

This sub-unit of the Bitra formation is generally characterised by brecciated texture of phenocrysts of subhedral plagioclase and pyroxene in a microcrystalline groundmass/matrix of mostly the same minerals along with opaque and $\pm$ olivine, or in a glassy matrix. Brecciation is very intense in the entire sub-unit column but less in the upper segment. The unit is porphyritic in texture and shows a sub-ophitic pattern. It has an alteration intensity of a slight to moderately greenish colour. Low-temperature hydrothermal minerals such as zeolite, chalcedony, and limonite are also present. Zeolite

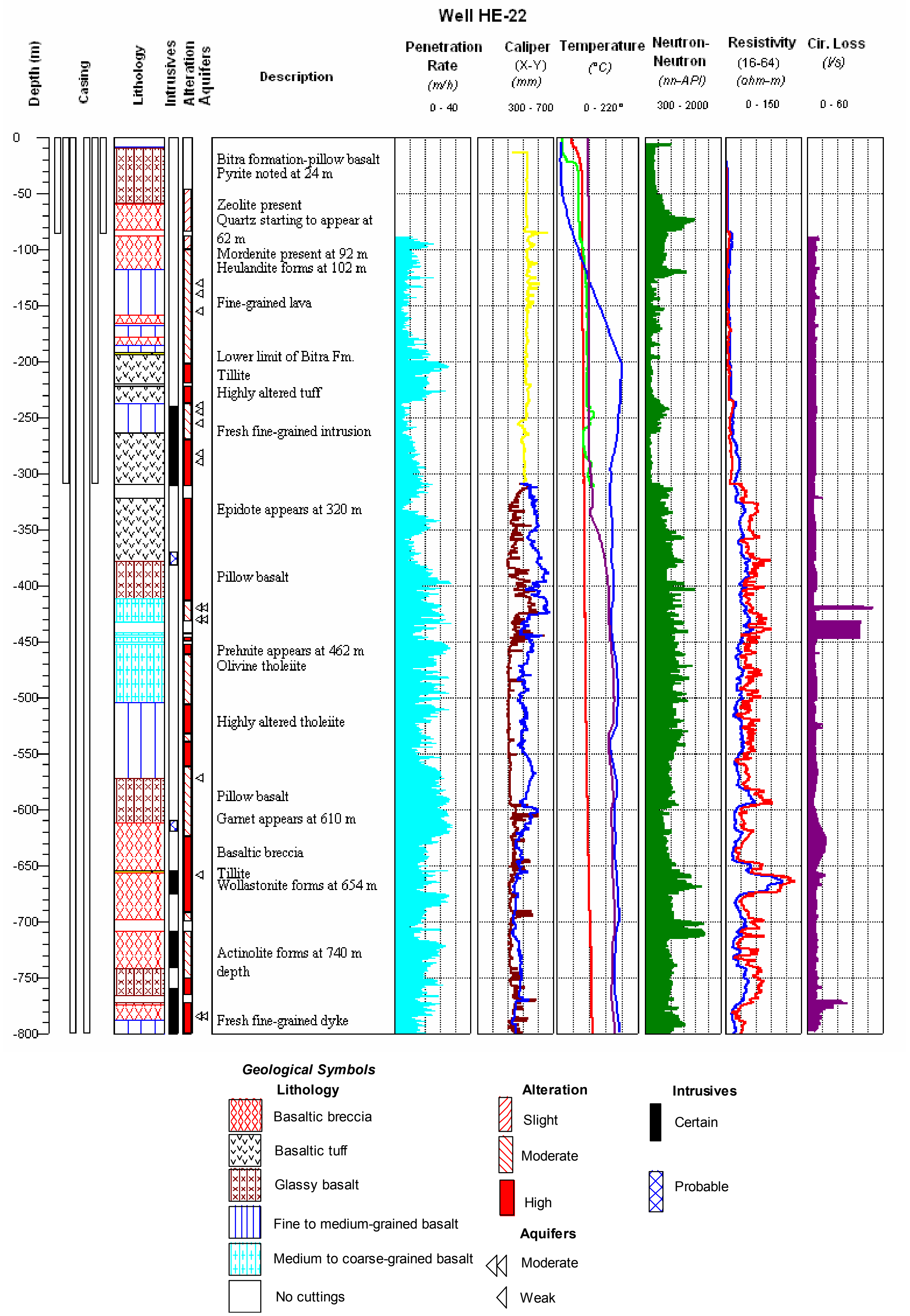

FIGURE 9: Lithology and geophysical logs of well HE-22

members are thomsonite at 56 m, analcime at 62 m, and mesolite at 94 m. Quartz was observed in the petrographic microscope at 64 m but is rare. Angular fragments of glass shard have been replaced by either calcite or clay. Phenocrysts of plagioclases have skeletal texture due to the replacement by platys or patches of calcite alteration. The mineral sequence is characterised by simple assemblages from clay (smectite) to calcite, zeolite → calcite, and chalcedony → calcite.

Basalt lava series I (118-192 m): This series is the sub-aerial member and the lower part of the Bitra formation. It consists principally of thick fine and medium-grained basaltic lava flows with thin intercalated layers of basaltic breccias. The entire unit is 72 m thick.

The flow unit consists of porphyritic olivine tholeiite lavas with phenocrysts of plagioclase and pyroxene, with olivine and opaque. Textural variation also varies to intersertal - subophitic. Skeletal pattern is seen in a few phenocrysts of plagioclase and microcrystals of olivine. The basalt lava flows are moderately altered from top to bottom. The lava unit has alteration colours of bleached cream to greenish. Precipitation of low-temperature minerals such as heulandite, stilbite, and chalcedony is observed. Calcite, pyrite, and limonite are likewise common. Vesicles are filled partially or wholly by calcite, chalcedony, or clay showing simple to complex combinations or assemblages of the two or three minerals. There are relatively few voids that are completely unfilled. Simple or complex zonation of vein fillings of calcite, chalcedony, and pyrite are observed. Olivine is transformed into iddingsite, while some opaques are altered partially to sphenes/titanites. The common mineral assemblages are clay (smectite) → calcite and zeolite → calcite. The oxidation has a low intensity.

Thin interlayer basaltic breccias were intercepted at levels 160-164 m and 180-186 m. Under the binocular microscope, the basaltic breccia is made-up of plagioclase, calcite, and clay. The two layers have greenish to dark green alteration. The brecciated clasts are replaced by secondary minerals of the same components as in the fine to medium grained lava flows. A veining system, specifically calcite, is common. Oxidation is not intense in this intercalated sub-unit.

Tillite deposit (192-194 m): Tillite deposit was identified in a thin-section at 192 m, and probably represents the boundary between the Bitra formation and the underlying older hyaloclastite formation. The clasts of the tillite fragments are more rounded indicating its sedimentary origin compared to the very sharp angular fragments of the hyaloclastites.

Hyaloclastite series II (194-238 m): The hyaloclastite unit - II is a predominantly basaltic 46 m thick tuff. The tuff is plagioclase porphyritic with glassy textured microcrystalline crystals. The primary minerals are plagioclase, pyroxene, and accessory $\pm$olivine. The unit is moderately altered in the upper segment but becomes highly altered in the lowest segment where it has a bleached colour, greenish and creamy. Micro-laths of plagioclase are relatively fresh in comparison to the uncommon but larger plagioclase phenocrysts, which are partially to near completely altered into calcite and clay, forming skeletal and resorbed patterns. Olivine micro-crystals are also altered into clay. Calcite, pyrite, and limonite are common but chalcedony and zeolites are less abundant. Quartz is starting to be re-deposited and becoming abundant. Vesicle intensity ranges from poor to moderate and increases with depth. Veins are common, particularly near the contact with the underlying lava, and filled by calcite, clay, or chalcedony. Mineral successions are typically of clay, followed by calcite or zeolites, with calcite as the end-member. Melt and fluid inclusions are also present in the phenocrysts of plagioclase and calcite deposition.

Basalt lava series II (238 - 264 m): The lava series II consists of a 28 m sequence of basaltic lava flows of fine-grained plagioclase porphyritic texture with pyroxene and opaque. The basalts are moderate, altered to greenish and brownish colours. Pyrite and calcite are moderately abundant but decrease with depth. Wairakite starts to appear at 248 m. Quartz is relatively uncommon in the lava flows, whereas limonite is common. Calcite and pyrite veins are abundant in this series but the vesicles are rare or absent. The vesicles are partially or totally filled with chalcedony, calcite, or clay. This lava series is intruded by fine-grained fresh and massive basaltic dykes, which probably caused the intense veining network. Subsequently, the vein system has been filled by secondary minerals due to the presence of weak but active aquifers along the fractures formed by the dykes.

Hyaloclastite series III (264-412 m): This series of hyaloclastites is divided into two (2) sub-units: the first unit is a basaltic tuff from 264 to 378 m; the second unit is glassy basalt ranging from 378 to 412 m. The entire thickness is 148 m.

The basaltic tuff is about 114 m thick. It has a texture of porphyritic angular fragmented clasts set in an altered glassy matrix. The tuff is composed of glass with microcrystalline plagioclase, pyroxene, quartz, and opaque minerals. It is highly altered with greenish and light cream discolouration. The glass matrix is transformed almost completely into clay. Plagioclase phenocrysts are fragmented and partially altered to calcite and/or clay, leading to a skeletal texture while some crystals are also transformed into albite. Opaques have been altered into sphene, but pyroxenes are relatively unaltered. Vesicle fillings are common, mostly calcite, quartz, clay, and wairakite. In the thin section (294 m) are found simple to complex filling structures of alternating sequences of thin layer clay with calcite. The representative alteration sequence is clay → calcite, quartz → calcite, and wairakite → calcite.

The second sub-unit is glassy basalt, possibly pillow basalt, with a thickness of about 34 m. The primary minerals are very fine-grained plagioclase, pyroxene, and opaque, set in glassy mesostasis. The entire sub-unit is highly altered into greenish and brownish colours. The secondary mineralisation includes clay, quartz, epidote, calcite and wairakite. The glassy matrix has been slightly to moderately altered into clay. The plagioclase has been replaced mainly by calcite and clay, with or without epidote or quartz. Crystals of pyroxene and opaque are relatively resistant to alteration. Epidote appears at 324 m depth but is not abundant. Quartz is also rare. Amygdules are moderately to highly abundant with partial to complete filling of calcite, clay, pyrite, quartz, and epidote. Complex combinations of these hydrothermal minerals are common, for example: epidote → quartz → calcite → clay. The sub-unit has low oxidation intensity.

Basalt lava series III (412-572 m): This lava series has a thickness of approximately 158 m, and the lava series varies with medium- to coarse- and fine- to medium-grained porphyritic olivine tholeiite lava flows. The latter is much thicker and occupies the upper portion, from the depth of 412-504 m; while the former was intercepted at 504-570 m. Occurrences of fine-grained sediments are very prominent in this interval, which can signify various deposition events of lava flows.

The medium- and coarse-grained lava flows have porphyritic and intersertal textures with a subophitic pattern of primary minerals of plagioclase, pyroxene, opaque, and accessory olivine. Minor textural patterns also appear, such as embayment of plagioclase and pyroxene, and some phenocrysts of plagioclase form a skeletal pattern. Micro-crystals of plagioclase and pyroxene are showing branch-like texture. The formation of magnetite started at a depth of 452 m.

Most of the cuttings in the medium- to coarse-grained rock are moderately altered, but a few cuttings had a high degree of alteration with greenish-brownish colours. The alteration mineralisation is typically calcite, clay, epidote, wairakite, and quartz. Large plagioclase phenocrysts are replaced mostly by platy calcite and clay, resulting in the appearance of a skeletal-like pattern. The micro-cracks within the plagioclase are filled by calcite, epidote, wairakite, and epidote-quartz. In the entire sub-unit, pyroxenes are very resistant to alteration, while opaques are altered to sphene. Epidote sometimes forms a radial-acicular habit but is not as common as quartz. Amygdules are not common in the upper and middle parts of the sequence but increase with depth, near the contact with the subsequent lava flows. The voids are partially or completely filled by quartz, epidote, calcite, or clay. Calcite, pyrite, and open veins appear sporadically. The mineral assemblages consist of simple sequences of epidote → quartz, epidote → clay, and epidote → wairakite.

The second series consists of fine- to medium-grained porphyritic basaltic lava flows with intersertal texture. Glomeroporphyritic, sub-ophitic, and trachytic-like textures are also present. This basaltic lava has primary mineral components of plagioclase, pyroxene, and magnetite. The secondary mineralisation is composed of quartz, prehnite, epidote, clay, calcite and wairakite. The presence of quartz, pyrite, and epidote is not abundant. Pyrite is crystallised in finer grains. Prehnite appears at around 512 and 548 m depths, showing a bow-tie like texture. The alteration is characterised by a greenish-brownish colour and moderate to high intensity. Amygdules and vein formations are more common, and are filled by calcite and pyrite. The typical assemblages of minerals are epidote → clay, quartz → calcite, and epidote → quartz.

Hyaloclastite series IV (572-788 m): This series consists of alternating layers of glassy basalt and basaltic breccia. The entire sequence has a total thickness of about 210 m. The sequence of pillow basalts is 72 m thick, while the two layers of breccias are 134 m thick in total. Fine to medium-grained sediments were observed in a thin section (654 m) which would separate these into two hyaloclastite formations.

The two layers of glassy or pillow basalts were encountered at depths of 572-612 m and 742-774 m. Petrographic interpretation of these layers indicates glassy to hypocrystalline and cryptocrystalline nature. It is made up of plagioclase, pyroxene, and opaque. The sequence is moderately altered with greenish - creamy and brownish colours. The secondary assemblage consists of clay, pyrite, epidote, magnetite, wairakite, quartz and garnet. Plagioclase crystals are slightly and moderately affected by calcite and clay alteration. Pyroxenes are relatively fresh but opaques were altered to sphene. Garnet starts to appear at 610 m and persists down to the bottom of the series. The glass was transformed into clay with a flow and lamination pattern. The alteration sequences in the upper portion are quartz → wairakite and fine grained clay → quartz → coarse-grained clay → calcite; in the lower segment, the assemblages are prehnite → epidote → quartz → wairakite. The rock fragments are fairly vesicular, particularly where they approach contact with the breccias.

The two layers of basaltic breccias were intercepted at 612-742 m and 774-778 m depth. In the thin sections (654, 710 and 732 m), the upper one has a general texture of porphyritic fine-grained fragmented crystals set in a glassy matrix. The primary and secondary mineralisation is similar to that found in the pillow basalts, except for the appearances of wollastonite and actinolite at 654 and 740 m depth, respectively. However, it is not impossible that these minerals were also present in the pillow basalts. The first layer has a moderate to high alteration intensity, while the second has a moderate intensity. Plagioclase is partially replaced by calcite and clay, pyroxene is unaffected by the alteration, and opaque is transformed into sphene. Wollastonite precipitates first before the epidote, as observed in the thin sections. Vesicles are irregular and have sometimes complex vug fillings of combinations of more than two secondary minerals for example: quartz → prehnite→ wairakite → calcite.

Basalt lava series IV (788-800 m): The series has porphyritic fine- to medium-grained texture basaltic lava flows. Various patterns were observed in the thin sections (788 and 796 m) such as branching, embayment, and intersertal. The primary minerals are plagioclase, pyroxene, and opaque with alteration mineralisation of calcite, clay, albite, wairakite, garnet, wollastonite, quartz, actinolite, pyrite and prehnite. The rock is moderately altered. Plagioclases have been replaced by various combinations of the mentioned secondary minerals. Pyroxenes are slightly altered into clay and calcite. Amphibolization of pyroxenes was observed forming a thin reaction rim of actinolite (796 m). Opaques are transformed into sphene. Voids and veins appear moderately in the lavas with fillings of wairakite, clay, calcite, epidote, quartz and prehnite. The lava flow is intruded by a fresh fine-grained dyke, which coincides with the presence of an aquifer.

3.3 Intrusive rocks

Generally, the intrusive rocks are identified as being massive, relatively low in alteration, and with coarser - grained texture than the surrounding wall rocks. Geophysical logs show intrusions in association with high neutron-neutron peaks and resistive anomalies. As mentioned earlier, the intrusions encountered in the Hengill-Hellisheidi geothermal field are made up of two types: fine-grained basaltic or andesitic-rhyolitic dykes/sills.

In the first 800 m of well HE-22, 4 positive and 2 probable basaltic intrusions were intercepted and identified, described as follows:

Intrusion 1: This first positive basaltic intrusion was encountered at a depth interval between 240 and 312 m. It has a fine to medium-grained porphyritic texture with phenocrysts of plagioclase, pyroxene, and with accessory micro-crystals of olivine and opaque, set in a glassy matrix. The intrusive dyke is fresh to slightly altered. The intrusive body also hosts numerous mineralised veins.

Intrusion 2: This probable intrusive body is approximately 12 m thick from 370-382 m, and was recognised under the petrographic microscope at 380 m depth. It is characterised by the presence of massive and fresh rock fragments of porphyritic plagioclase, olivine, and pyroxene.

Intrusion 3: This is another probable 10 m thick basaltic dyke intrusion, encountered from 610 to 620 m. The rock fragments and thin sections indicate that the fragments are massive, coarser-grained, and unaltered in comparison to the enclosing rock. This intrusion has a high presence of veins.

Intrusion 4: This positive intrusive body was drilled through at a depth of 654- 676 m. It is massive and fine-grained porphyritic plagioclase with pyroxene and opaque. The dyke is moderately altered. The geophysical logging signature shows positive high peaks from the neutron-neutron and resistivity measurements.

Intrusion 5: This 34 m thick basaltic dyke was drilled between the depths of 708 and 742 m. It is characterised by massive fine-grained porphyritic plagioclase with pyroxene and accessory of olivine and opaque. It is slightly to moderately altered.

Intrusion 6: The sixth intrusive body was observed at 760-800 m and probably extended beyond 800 m. However, the drilling underwent blind penetration beyond this level and no available data was gathered. The dyke has transcended from fresh, fine- to medium-, to medium- to coarse-grained porphyritic plagioclase with phenocrysts and pyroxene and accessories of micro-crystal sizes of altered olivine and opaque. Veins are also prevalent at this depth.

4. HYDROTHERMAL MINERALS AND ALTERATIONS

Hydrothermal alteration is a change in the textural, mineralogical, and chemical composition of the host rocks brought about by the action of hydrothermal fluids, steam and/or gas (Henley and Ellis, 1983; Hochstein and Browne, 2000). The hydrothermal fluids carry dissolved solids, either from a nearby igneous source or from leaching out of some nearby country rocks. The primary minerals are replaced by secondary minerals due to changes in the environmental conditions. Secondary minerals precipitate along open cavities, vesicular structures, and fracture zones in the wall rock formations. The mineralogical alteration suites provide in-depth information on past and present characteristics, and an assessment of the characteristics of the geothermal system.

The intensity or degree of alteration depends on several factors such as: permeability (related to gas content and hydrology of a system), temperature, duration of activity (immature or mature), rock composition, pressure, hydrothermal fluid composition (pH value, gas concentration, vapour- or water dominated, magmatic, meteoric), number of superimposed hydrothermal regimes (overprinting of alteration), and hydrology (Browne, 1978; Reyes, 2000; Franzson, 2006). Permeability and temperature play an important role in the stability of most hydrothermal minerals. Temperatures vary from <100 to >300°C. The degree of permeability is directly related to the intensity of the rock. The source of permeability may be faults and fractures zones, lithological contacts, formation permeability (clasts and breccia fragments), and paleosols (Reyes, 2000). The composition of fluids and gasses are extremely variable. These factors are comparatively interconnected to one another. The mineralogical and alteration signatures may vary from one geothermal system to another. The temperature - rock - mineral scale relationships of Icelandic geothermal systems are illustrated in Figure 10. The principal components, glass and olivine, are the first to alter at low temperature, followed by plagioclase and pyroxene at much higher degrees, and, finally, the ore and high-temperature minerals above 200°C.

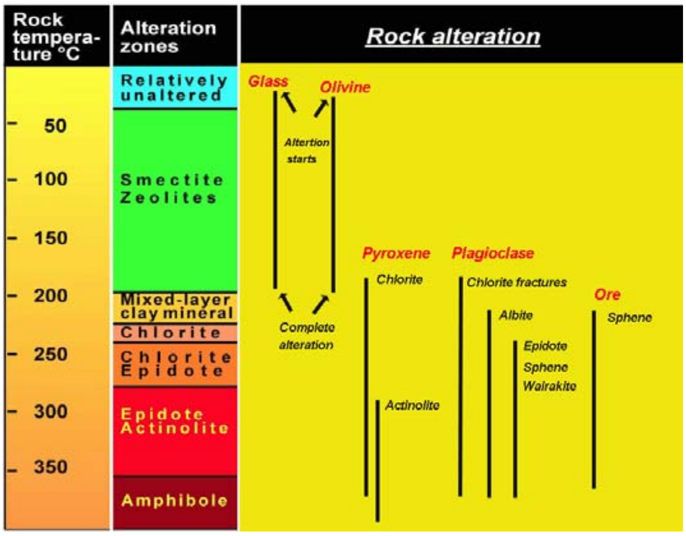

FIGURE 10: Mineral alteration-temperature diagram (sligthly modified from Franzson, 2006)

4.1 Primary rock minerals

The primary minerals of basaltic rocks in HE-22 consist of the following minerals in order of decreasing abundance: plagioclase, pyroxene, opaque (magnetite and ilemenite), and with or without accessory of olivine. The range is from fine- to coarse-grained crystals. The matrix/groundmass is aphanitic to fine-grained and comprises plagioclase micro-lath, pyroxene $\pm$ olivine, glassy and cryptocrystalline. The basaltic lavas are often porphyritic and equigranular to sub-ophitic in texture. Occasionally, textural patterns like trachytic, branching, embayment, and flow-lamination in glass and clay are also present, especially where the rock is partially crystallised. These minerals have been exposed to variable alteration and their alteration minerals are summarized in Table 1. An overview of the petrographic descriptions is given below.

TABLE 1: Primary mineral alteration in well HE-22

Fresh/unaltered	Alteration products
Olivine	Clay, iddingsite
Plagioclase	calcite, clay, quartz, epidote, albite, wairakite
Pyroxene	clay, sphene, actinolite
Opaques	sphene
Glass (matrix/tuff)	clay, calcite, quartz,

Olivine: Olivine appears as an accessory and is the least common ferro-magnesian mineral observed in the thin sections. It occurs as part of the matrix in microcrystalline size and rarely as phenocrysts. Fresh subhedral phenocryst olivine was well recognised in the intrusive at 380 m. This mineral is very susceptible to alteration, and is commonly altered to clays (150 m) and at times to iddingsite (212 m).

Plagioclase: The primary composition of plagioclase in the basaltic rocks of Iceland is as calcium rich. Plagioclase is common and appears in the entire section of the well. It has subhedral to anhedral forms. It is present as phenocrysts and as part of the groundmass. Fragments of fresh plagioclase were observed in the first few cutting samples under the binocular microscope. However, under the petrographic microscope, it sometimes showed medium to very high degrees of alteration. Plagioclase in hyaloclastites showed more intense alteration compared to lava flows, and was relatively fresh in the intrusive rocks. Phenocrysts and crystal fragments are very much susceptible to alteration, replaced by diverse direct alteration products such as calcite, clay minerals, epidote, quartz, zeolites, and albite. Plagioclase started to alter to albite at a depth of ~230 m. Alteration to quartz, epidote, wairakite, and sphene was also frequent.

Pyroxene: Pyroxene is the second most abundant primary mineral in basalt. It may appear as a phenocryst and a part of the groundmass. It forms subhedral to anhedral crystals but euhedral is also present. In the thin section at 796 m, the rim of the pyroxene altered to actinolite. Generally, pyroxene is very resistant to alteration, and is rarely completely altered. Pyroxene generally starts to alter at temperatures >180°C (Franzson, pers. com.).

Opaque minerals: These minerals comprise mainly magnetite and ilmenite. These minerals are generally crystallised as part of the primary rock constituents. However, in places, especially near the intrusive margins, opaque minerals form as part of the contact aureole.

4.2 Distribution of hydrothermal minerals

The distribution of hydrothermal alteration minerals of well HE-22 is shown in Figure 11. The presence of a wide array of secondary mineralisations in the lithological successions is similar to other areas in the Hengill geothermal system. The minerals are calcite, pyrite, quartz, zeolites, garnet, epidote, and other rare minerals. Below is a summary of the alteration products:

Calcite: It is one of the most abundant and widely distributed secondary minerals. It occurs almost continuously in the entire upper 800 m starting at 26 m. It is very common in the pores of hyaloclastites and lava flows but less in the more compact intrusions.

Calcite either occurs as a replacement of primary minerals or as a direct deposition mineral. The former type is commonly associated with plagioclase and glass with the presence or absence of other secondary minerals. An early generation of dog-tooth shaped calcite was observed underlying thin linings of clay and chalcedony in a thin section (572 m). Calcite formation can be linked to boiling, dilution, and condensation of carbon dioxide in the geothermal system. It can also form during the heating of cooler peripheral fluids (Simmons and Christenson, 1994).

Chalcedony: Chalcedony is one of the varieties of silica polymorph that have temperature equilibrium of less than 180°C (Fournier, 1985). It occurs in an interval depth from above 150 to about 340 m but below this depth chalcedony was replaced by quartz. In thin sections, it can be seen as a thin-layered lining in veins or an outer-rim halo in voids.

Quartz: In well HE-22, quartz was first seen at a depth of about 62 m. It reappeared at about 200 m, and continued to 800 m. Quartz has a temperature stability of >180°C. Quartz appears as euhedral to anhederal crystals, and crystallised in the form of mineral replacement and open space fillings. Patchy, pervasive to total replacement of the glass matrix, and large plagioclase minerals are widespread. Short prismatic euhedral faces are very typical in amygdule, crystallising either in the outer rim or nucleus, as mono-mineral or with complex amalgamation of other secondary mineralisation. These associations of crystals consist usually of epidote, calcite, wairakite, and clay.

Zeolites: Zeolites are a group of hydrated aluminosilicate minerals that have framework structures enclosing interconnected cavities occupied by large positively charged ions, generally of sodium, potassium, magnesium, calcium, barium and water molecules. It commonly and naturally forms in cavities of porous rocks during the alteration processes (Saemundsson and Gunnlaugsson, 2002).

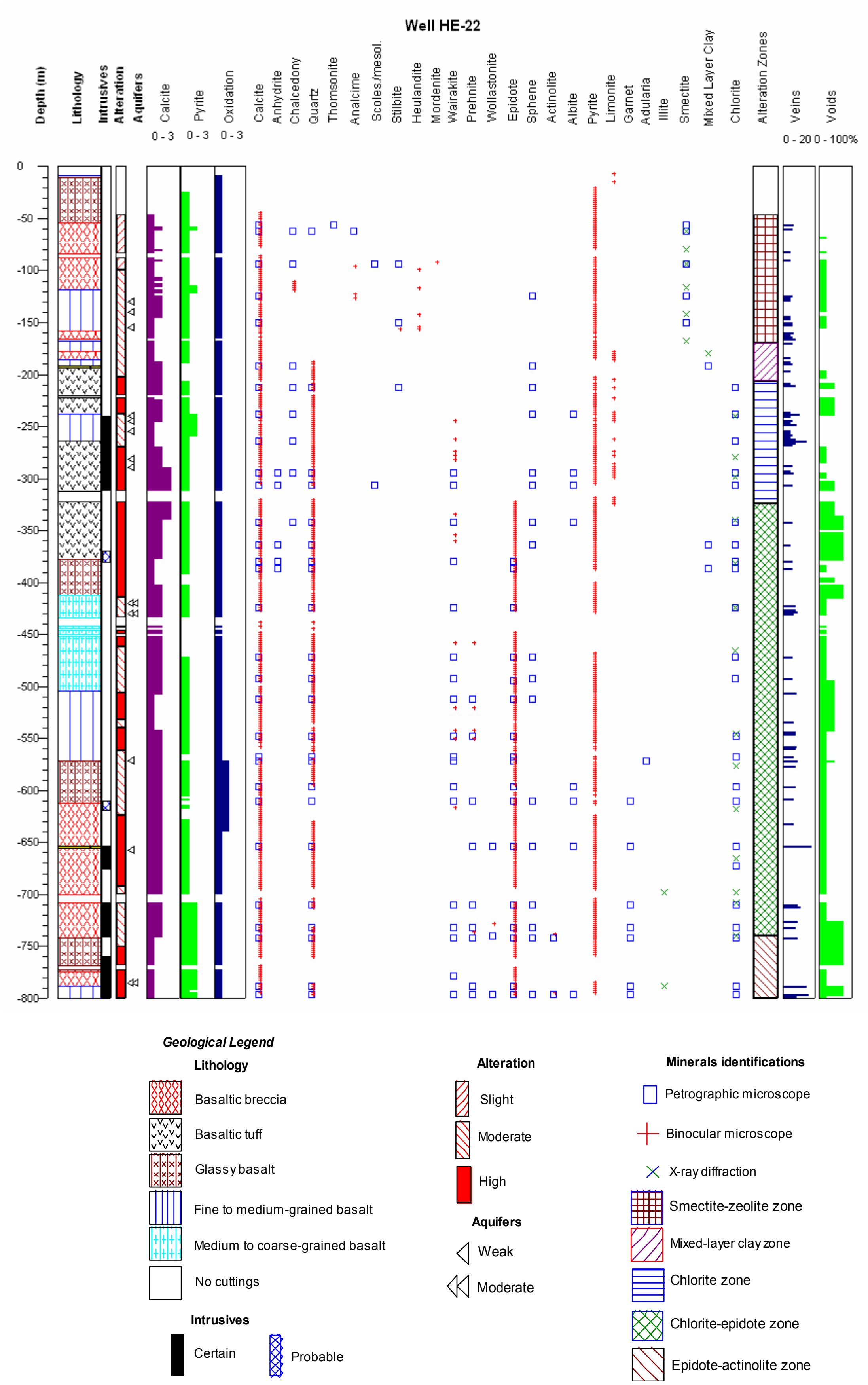

FIGURE 11: Distribution of hydrothermal alteration minerals in the top 800 m of well HE-22

This group is temperature dependent and is used as geothermometer indicators of geothermal formations at temperatures below 200°C. The highest-temperature zeolites are laumontite (120-200°C) and wairakite (200-300°C). In well HE-22, quartz is widely seen as a pseudomorph from zeolites, indicating a temperature increase of the geothermal system. The following zeolites have been identified under the binocular and petrographic microscopes in well HE-22:

Thomsonite: This member of the zeolite family was observed in the thin section at 56 m. It has radiating, elongated and slightly flattening crystal habits. Thomsonite crystallises at around 50°C.

Analcime: This mineral has a whitish-grey colour and is characterised by trapezohedron-sided crystal faces. It was observed at the depth between 100 and 130 m. In the petrographic microscope it was found at 62 m, colourless, and isotropic (cubic system). Analcime has a temperature formation of about 50-70°C.

Scolecite: It was found in the thin section at 306 m, being partially replaced by quartz but the crystal figure/habit could still be recognised. Scolecite precipitates between ~80-120°C.

Mesolite: It was found in the thin section at a depth of 94 m. It is characterised by fibrous radiating clusters. Mesolite is finer and fainter in colour compared to scolecite in a petrographic microscope. It forms at approximately 60°C.

Heulandite: This mineral was recognised in the binocular at the depth between ~100 and ~150 m; it has a platy tabular sheets-like and whitish-colour appearance. It has a crystallisation temperature 90-120°C (Franzson, 1998).

Stilbite/epistilbite: Under the microscope, stilbite is characteristically radial and with fan-like aggregates, and shows good cleavage. Stilbite has been found at the depth interval 94-160 m, and is indicative of the temperate range 90-120°C.

Mordenite: This mineral was identified in the binocular and was encountered only at the depth of 96 m. It has a characteristic delicate hairy white texture. Mordenite is found at temperatures above 90°C (Saemundsson and Gunnlaugsson, 2002).

Wairakite: Wairakite is the most common of the zeolite members observed in well HE-22. This mineral was found from the depth of ~250 m to the base of the analysed section at 800 m. It has the petrographic distinguishing features of being colourless, low-birefringence, with recognisable perpendicular polysynthetic sets of twin lamella, comparable to the characteristics of microcline (Thomson and Thomson, 1996). It precipitated in veins or in the core of vesicles usually succeeding the higher temperature minerals of epidote, quartz and prehnite but sometimes prior to the appearances of platy calcite. It commonly replaces plagioclase. The occurrence of wairakite represents a high-temperature environment of 200-300°C (Saemundsson, and Gunnlaugsson, 2002).

Epidote: Epidote is a common mineral in hydrothermal processes. It is a high-temperature mineral that has a lower temperature stability formation between 230-260°C in volcanic rocks (Browne, 1978), but in Iceland it forms at temperatures >240° (Franzson, 1998). In well HE-22, it appeared continuously from ~320 m and down to 800 m, showing as euhedral to subhedral minute prismatic and radiating needle-liked crystals. It normally precipitates as open space fillings in vugs and voids, and along the vein structures. It is also found as a partial replacement to plagioclase phenocrysts along rims and edges. It is frequently observed associated with other alteration mineral assemblages such as quartz, calcite, clay or wairakite.

Prehnite: Prehnite begins to crystallise at temperatures above 200°C. Commonly, it is found in veins or vesicles, as seen in HE-22. The first appearance of prehnite was observed at 462 m but it became more persistent below 610 m. Normally, prehnite occurs along with epidote and other high-temperature minerals and as a part of simple to complex mineral assemblages.

Wollastonite: This mineral is a hairy-like high-temperature mineral, first seen at 654 m and continued to 796 m. In the thin sections, wollastonite seemed to crystallise after epidote. The upper boundary of wollastonite indicates a temperature of around 270°C.

Anhydrite: This mineral was encountered in thin sections at depths of 306, 364, and 380 m. At 306 m, it occurred in a sequence of calcite - anhydrite - wairakite. The presence of anhydrite in the system, together with drusy quartz and wairakite, signifies boiling in the wells (Reyes, 2000). Anydrite can also be found in some of the geothermal wells in the Nesjavellir field, particularly where temperatures are high at shallow levels. It is a common mineral in the saline geothermal areas of Reykjanes Peninsula (Franzson, pers. com.).

Albite: Albite is produced by the alteration process known as albitization, where the calcic plagioclase labradorite is transformed into albite or sodic rich plagioclase. Albitization was first observed at ~238 m. Commonly, it altered and replaced more of the lath-like shaped plagioclase phenocrysts than the larger stubby crystals. In the Philippine geothermal settings, albite has two ranges of temperature deposition, at ~120-270°C and at ~190-270°C, the former appearing as vein fillings, as replacement of plagioclase and part of the groundmass, whereas, the latter only precipitates as vein fillings (Reyes, 2000).

Adularia: It was observed in a thin section at a depth of 572 m. It has a clear sharp-pointed diamond crystal shape being surrounded by quartz and plagioclase crystals. Adularia formed as a replacement of plagioclase. It is considered an indication of boiling of the hydrothermal fluids (Gemmell et al., 2006), and one of the indicator minerals of permeable zones (Reyes, 2000).

Pyrite: Pyrite is one of the abundant and widely distributed minerals in HE-22. It is found below ~24 m and all the way to the bottom except at a narrow interval at 442-468 m. The crystal textures vary from fine-grained disseminated to a euhedral cubic form. The former appeared in the upper portion of the lithologic units above 50 m, and the latter was prominent in the remaining segment. The abundance of pyrite deposition is an indicator of formation permeability, but in well HE-22 it is difficult to correlate the abundant presence of pyrite with the size of the aquifers. Pyrite has a wide range of temperature stability, from ~120 to 260°C (Reyes, 2000).

Limonite: This hydrated iron oxide mineral forms mostly due to the oxidation of iron and other metal minerals to cold meteoric water-rock interaction at a shallow depth, and with temperatures usually <80°C. In well HE-22, it started to appear near the surface (~6 m). It has a physical habit showing oolitic, spheroidal, and concentric patterns, which were deposited along the surface of the fragments, inside the vugs, and along the fracture zones.

Sphene/Titanite: Sphene or titanite was occasionally identified petrographically. It has a brownish to dark brown dusty-cloudy discoloration that formed due to partial to complete alteration of opaque minerals. It formed sporadically in the rock below 124 m. In the Philippine geothermal settings, the occurrence of sphene indicates weak permeability and porosity (Reyes, 2000).

Garnet: This mineral was found petrographically from 610 to 796 m, forming clusters of fine-grained subhedral to anhedral crystals. The crystallisation of garnet indicates temperatures of more than 280°C.

Actinolite: Actinolite was found during the binocular examination of the rock cuttings at depths of 740 and 796 m, with a pale green colour with a prismatic habit; in the thin section at 796 m, pyroxenes showed a thin surrounding alteration rim of actinolite. Actinolite starts to form at a temperature of 280°C.

Clay minerals: Clay minerals are common and abundant alteration products in the hydrothermal system. It is the dominant mineral in both high- and low-temperature fields in Iceland (Kristmannsdóttir, 1977). These crystals are finely crystalline or meta-colloidal and occur in flake-like or dense aggregates of varying types. Primary minerals like olivine, plagioclase, and rarely pyroxene, are altered to different types of clay, greatly depending on permeability and temperature. Volcanic glass is also very susceptible to the reactions of hot fluids and transforms directly to clay. Clays precipitate as a direct replacement of earlier crystallised minerals, as infillings in vesicles in the nucleus, form thin rims, or fracture linings. The typical clay alteration products in Iceland consist of three types: smectite, mixed layered clays, and chlorite. However, the XRD analysis of the samples in well HE-22 showed only smectite and chlorite (stable and unstable); the mixed-layer clays could only be inferred from petrographic examination.

Smectite: Smectite in well HE-22 has a thin layer zone at about ~170 m depth. Under the microscope, smectite is fine-grained with a greenish-brown colour. It is deposited as a thin lining layer in vesicles and as a mineral replacement. In XRD it has a peak between 14-15 Å for untreated, 14-16 Å for glycolated, and 9-10 Å for a heated sample. Smectite forms at temperatures below 200°C (Franzson, 1998)

Mixed-layer clays: Mixed layer clay minerals are intermediate products of pure end-members of clays (Sradon, 1999). This type of clay was identified through the analysis of the thin sections and appeared at depths of 192, 364, and 386 m, characterised by a vibrant brownish-green colour. Under plane polarized light the clay showed strong pleochroism. In the thin section at 264 m depth, it was observed that mixed layer clays were strongly in contact with chlorite. In the XRD analysis at 180 m depth, the clay sample was characterised by a strong component of smectite rather than of chlorite.

Chlorite: Chlorite is the most extensive alteration product in HE-22. It appears immediately after the disintegration of mixed-layer clays at around 206 m, and all the way down to 800 m. Based on XRD analysis, chlorite is divided into a stable and an unstable type. In the upper layer, the first to crystallise is the unstable chlorite (~200-500 m). This chlorite has re-appearing reflection peaks at 7 Å for air-dried, 7 Å for ethylene glycolated, and collapses after heating to 550°C. The collapse may be caused by the absence of Fe and Mg contents. Stable chlorite had re-appearing peak values of ~7 Å in all treatments. Chlorite is characterised by fine- to coarse-grained textures, and petrographically with dull light green-greyish non-pleochroic colour. In the thin sections, it was observed that some of the unstable type had more dynamic pleochroic colours which resembled mixed-layer clays. The presence of chlorite is usually associated with other hydrothermal minerals in veins and vesicles. Chlorite has a crystallisation temperature above 230°C (Franzson, 1998).

Illite: This mineral was detected only through the XRD, at depths of 698 and 788 m. It had a persistent peak of ~10 Å for the three stages of analyses.

4.3 Veins and vesicles

Hydrothermal mineral deposition is mostly found in vesicles and vein fillings. The abundance depends on lithology and tectonic fracturing. These voids form much of the porosity and permeability of the geothermal system. Hyaloclastites, for instance, are highly porous compared to lava flows, while intrusions have a low porosity. The identification and description of the voids and veins in HE-22 were carried out with the aid of binocular and petrological microscopes.

Vesicularity was high in some intervals of the sequence. The vesicles were unfilled, lined, or filled by secondary minerals. In general, they were unfilled in the top of the sequence but were gradually filled towards and into the geothermal system. In the first 800 m of the stratigraphy, the highest concentrations of voids are confined to depth intervals of ~340-380, ~400-420, ~740-760, and ~800 m.

The first cluster of voids is confined within a highly altered basaltic tuff. The second is situated along and near contact with moderately altered glassy basalt and a highly altered medium-grained lava flow. This zone is characterised by weak to moderate aquifers. The third group is within the range of a basaltic breccia and glassy basalt of moderate to strong alteration. The deepest cluster is also within contact with basaltic breccia and lava flows which are cut by a dyke. The site is a passageway for a moderate-quality feed zone.

Most of the variability in veins is correlated with basaltic lava flows, intrusions of dykes and the occurrence of feed zones. The nature of vein formations indicates mostly closed or mineralized veins, with very few open or unfilled. Similarly, the veinlets showed clustering or grouping. The first vein system is situated at ~120-170 m, mostly in lava flows and along the thin contact with breccia. The second vein group is also confined to the fine-grained basaltic lava flows that are found with the units of basaltic tuff (~240-260 m). The third and the fourth vein networks were observed in the upper and lower sections of basaltic lava series III, respectively. The final clustering is hosted by lava flows and can be found at the bottom (~800 m). Table 2 is a summary of the vein descriptions in HE-22.

TABLE 2: Distribution and characteristics of veins in well HE-22

Depth (m)	Quantity	Mineralisation	Host rocks	Remarks
~120 - 170	22	cc, chal, pyr, clay, lim	Fine-grained lava flows + basaltic breccia	Moderate alteration, weak aquifers
~240 - 260	36	cc, qtz, pyr, clay, wai, lim	Fine-grained lava + basaltic tuff +basaltic intrusive	Moderate to strong alteration, weak aquifers
~420 - 430	17	cc, pyr, clay, ep	Medium- to coarse-grained basaltic lava flows	Moderate alteration, weak to moderate aquifers
~530 - 580	33	clay, cc, qtz, ep, preh, mag,	Fine-grained lava flows	Moderate to high alteration
~780 - 800	31	clay, cc, ep, preh, qtz, mag	Fine-grained lava flows + basaltic intrusive	High alteration, a strong aquifer

cc – calcite; pyr – pyrite; mag – magnetite; lim – limonite;
chal – chalcedony; qtz – quartz; ep – epidote; wai – wairakite;
preh – prehnite.

4.4 Alteration mineral zonation

Some of the secondary minerals are good geothermometer indicators, being temperature dependent and crystallising at specific temperature ranges (Reyes, 1992). Minerals like clays, zeolites, prehnite, garnet, and amphiboles contain OH or nx-H_2O in their crystal lattices (Browne, 1978). In the Icelandic geothermal settings, low-temperature zeolites and amorphous silica form below 100°C, chalcedony below 180°C, quartz above 180°C, wairakite above 200°C, epidote above 240°C, and garnet and amphibole above 280°C (Saemundsson and Gunnlaugsson, 2002; Franzson, 1998). The clay minerals crystallise below 200°C for smectite, at 200-230°C for mixed layer clays, and above 230°C for chlorite (Kristmannsdóttir, 1977).

In the top 800 m of HE-22, five mineralisation zones were recognized based on mineral-indices temperatures, crystallinity and abundance (Figure 12). These alteration zones are as follows:

Smectite - zeolite zone (<200°C): This alteration zone is characterised by the presence of smectite coupled by low-temperature silica and some members of the zeolite group. This alteration assemblage covers the interval ~ 46-170 m.

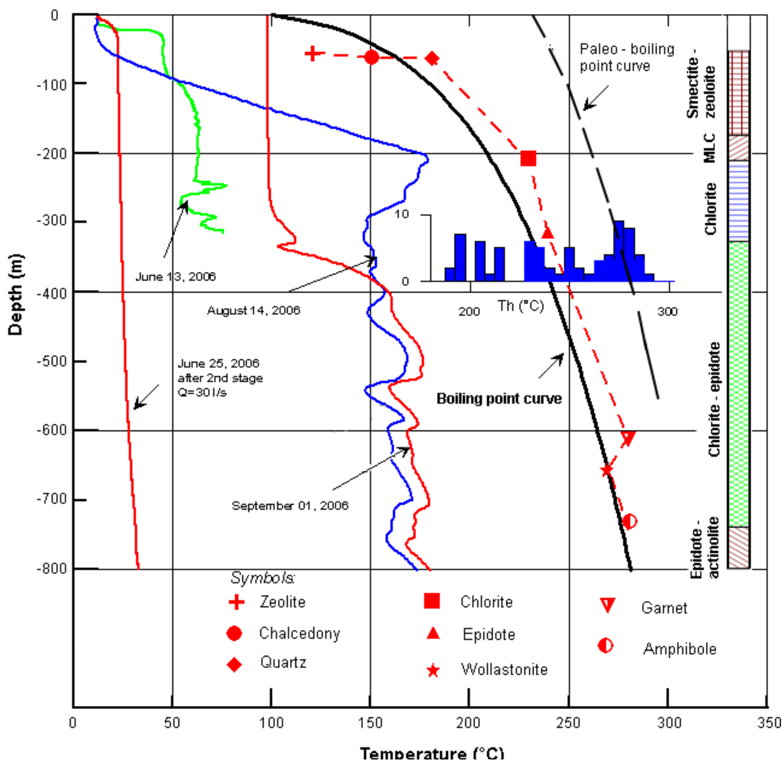

FIGURE 12: Correlation of measured and alteration temperatures, and fluid inclusion histogram in well HE-22

Mixed layer clay zone (200-230°C): The mixed layer clay zone was identified only through the petrographic microscope at a depth of 192 m. The zone interval is probably approximately from 170 to 206 m. Under petrographic microscope, this clay is medium- to coarse-grained and has vibrant greenish-brownish pleochroic colours. The XRD results indicate more smectite type clay characteristics than chlorite (180 m). In this layer, quartz was becoming widespread. The mixed-layer clays have a temperature range between 200 and 230°C.

Chlorite zone (230-240°C): This zone is marked by the appearance of chlorite (unstable) together with abundant quartz and wairakite. This zone extends from ~206 to 324 m. Under the petrographic microscope, some of the unstable chlorite crystals have almost the same characteristics as stable chlorite such as a dull green colour but, in some instances, with a faint pleochroic behaviour resembling the mixed-layer clays.

Chlorite - epidote (>240°C): This zone ranges between 324 and 740 m. It consists of chlorite with the appearance of abundant epidote coupled with wairakite and quartz at the upper level. The XRD analyses and interpretations show that chlorite has an unstable behaviour from 324 to 512 m depth, and then transforms into stable chlorite beyond 512 m.

Epidote - actinolite zone (>280°C): Actinolite was found at ~740 m depth and in pyroxene alteration at 796 m. This probably represents the upper boundary of this zone. The XRD analyses below 1000 m indicate that this zone is prevalent.

4.5 Fluid inclusions

The fluid inclusion homogenisation temperature (Th) was measured in calcite at depths of 360 and 384 m. In all 144 measurements were taken, about 83 primary and 61 secondary inclusions. They ranged from ~190 to 290°C. The higher temperatures generally identified with primary inclusions, while the lower Th was associated with secondary inclusions. The results gave a much higher temperature than the current rock formation temperature, which can be interpreted as being an intense heating reaction of the paleo-hydrothermal system to a boiling point environment, as shown in Figure 12. Indeed, the temperature Th surpasses the boiling point curve for that depth. Th was also drastic in the neighbouring well, ÖJ-1, interpreted as being due to an intense hydrothermal system with a hydrological contact to a watertable within the overlying glacier. However, this situation might be localised. The projection of an above-boiling-point curve indicates that this hydrological surface is approximately 300 m above the present level.

4.6 Mineral deposition sequences and paragenesis

The hydrothermal mineralisation assemblages depend on the specific evolution and reactions with various factors such as temperature, fluid composition, rock types, the interaction between the hydrothermal fluids and the country rock, porosity and permeability of the rock, and duration of the interactions. Successive stages of mineralisation reflect the paleo-geothermal and present hydrothermal activities and environmental situations. The sequences may vary from simple to highly complex. The secondary mineralisation sequences may be reversed, repeated or parts may be missing entirely,, depending on the specific evolution and its reactions to the precedent sealing mineral and/or minerals, and the host rock as a whole. In addition, precipitation of single mineral or mineral assemblages may be sealed at any point in the sequence and remain sealed, until being reactivated at a certain time and event in the geothermal system.

The study of the direct depositions and replacement of secondary mineralisation were analysed under the petrographic microscope. These mineral suites varied from low- to high-temperature environments but overprinting cannot be disregarded. The observed sequences ranged from simple bi-mineral assemblages to more complex minerals associations. It is also common to distinguish a single mineral with precipitation behaviour of multiple layers, particularly clay minerals. The secondary hydrothermal mineralisation sequences observed in well HE-22 are presented in Table 3. Clays are common hydrothermal minerals, forming as thin linings in the walls of the vesicles and veins or thicker and coarser-grained clays, usually with platy calcite as the dominant end-member of the assemblages. Calcite and clays are present in the entire sequence. The appearance of calcite is relatively complicated. It crystallised mostly at the end of the sequence but also appeared in the beginning and middle of the assemblages. The presence of calcite at the end of the high-temperature mineral sequences may imply cooling. In the upper zone at ~170 m, fine-grained smectite prevailed coupled with zeolites and chalcedony. A thin zone of mixed-layer clays appeared from the lower limit of smectite down to ~206 m. Below this zone, fine- and coarse-grained chlorite started to precipitate. Coarse-grained clay commonly succeeded the fine-grained clay. At a depth of 294 m, wairakite and quartz became part of the sequence down to 800 m. They replaced the low-temperature zeolites, while chalcedony became pseudomorphs of quartz. Unexpectedly, at 306 - 364 m anhydrite was observed and included in the assemblages. Epidote became common at 360 m, and at much deeper level it succeeded wollastonite. Garnet crystallised after chlorite below 600 m. Wollastonite precipitated first in the sequence before epidote, as was recognised in the thin section from 796 m.

5. AQUIFERS- FEED ZONES

Aquifers are typically water-saturated regions in the subsurface which produce an economically feasible quantity of water to a well. The movement of sub-surface water is controlled by the type of rock formations, the characteristics of its permeability and porosity, the temperature and pressure of the sub-surface environment, natural recharge, and the hydraulic gradient. The presence of structural formations such as faults, fractures, and joints, lithological contacts, clasts and fragmented matrixes, and paleosols are positive indications of geothermal feed zones (Reyes, 2000). The formation of strong and good aquifers is very important in geothermal systems for the extraction of hydrothermal fluids and steam. The methods for determining the presence of aquifers include direct observation of the circulation loss/gain, sudden change in the rate of drilling penetration, and from geophysical measurements of temperature and caliper loggings. Examination of rock cuttings is an indirect approach in determining aquifers. The presence of numerous shreaded rocks (mylonites), abundant vein networks, drusy and a high concentration of alteration minerals are indications of the presence of strong sub-surface hydrological circulation. Alteration minerals such as the crystallisation of quartz, adularia, anhydrite, wairakite, illite, hyalophane, abundant pyrite and calcite are also positive signs of good permeability. However, the absence of these alteration minerals, a low degree of alteration, the precipitation of prehnite, pumpellyite, pyrrhotite, and large quantities of laumontite and titanite can be attributed to a low-permeability zone (Reyes, 2000). Loss of circulation may vary from minor or weak

TABLE 3: Deposition sequence of secondary minerals in well HE-22

Depth (m)	**Mineral assemblages Early stage → Late stage**								**Degree of alteration**	**Rock types**
56	fg clay							cc	low	breccia
62	fg clay	chal						cc	low	breccia
94	fg clay				zeol			cc	moderate	breccia
124	fg clay							cc	low	breccia
150	fg clay				zeol			cc	low	lava flows
192	fg clay	chal						cc	moderate	breccia
212	fg clay					cg clay		cc	high	basaltic tuff
238	fg clay	chal				cg clay		cc	high	tuff with intrusion
264						cg clay		cc	moderate	tuff, lava, intrusion
294	fg clay	chal	qtz		wai				high	tuff and intrusion
306					wai		anhy		high	tuff
	cc				wai	cg clay	anhy			
342	fg clay		qtz		Wai			cc	high	tuff
364	fg clay		qtz				anhy	cc	high	tuff
380	fg clay	ep	qtz			cg clay		cc	high	tuff and pillow lavas
386			qtz			cg clay				
424	fg clay	ep	qtz			cg clay		cc	moderate	olivine basalt
472	fg clay	ep	qtz						moderate	lava flows
	fg clay	ep			wai					
492	fg clay		qtz			cg clay			moderate	lava flows
512		ep			wai			cc	mod. to high	lava flows
548			qtz					cc	high	lava flows
568			qtz			cg clay				
572	fg clay		cg clay		wai			cc	moderate	lava flows
	fg clay	ep			wai					
	cc		fg clay					chal		
596	fg clay					cg clay			moderate	lava flows
610		ep	qtz	preh	wai				high	breccia and pillow
654	fg clay		qtz			cg clay			high	breccia
	fg clay					cg clay		gar		
710		ep	Qtz		wai				moderate	breccia
732	fg clay	ep		preh		cg clay			moderate	breccia
742		ep	qtz	preh				cc	high	breccia and pillow
788	fg clay	ep		preh					high	breccia and intrusion
796	woll	ep		cc	wai				high	breccia and intrusion
		ep	qtz					cc		

fg clay: fine-grained clay; cg clay: coarse-grained clay; ep: epidote; wai: wairakite; qtz: quartz; preh: prehnite; zeol: zeolites; cc: calcite; woll: wollastonite; cha: chalcedony; gar: garnet

loss, due to tight characteristics of the formation, to the total circulation loss that is characterised by highly permeable formations. In the geothermal settings of Iceland, the highest permeability zones intercepted are associated with dykes and faults (Arnórsson, 1995).

Seven feed zone clusters were encountered in the top 800 m depth of well HE-22. These zones are categorized into weak and moderate aquifers, correlated to the characteristics of the lithological formations, intensity of alteration, abundance of veins and vesicles, the stratigraphic boundary, and the presence of an intrusive body. The majority of the feed zones are confined in the basaltic lava flows or near contact with basaltic tuff. A single aquifer was located in the interior of the basaltic tuff. All the aquifers encountered were within the production casing. All drilling to that depth was with mud, which resulted in minimum circulation loss. The geophysical logging and the location of the aquifer zones in well HE-22 are shown in Figure 9, and the comparative plots of temperature measurement with the rate of penetration are shown in Figure 13. The following are descriptions of the seven aquifer clusters:

Aquifer 1: This feed zone is located at 130, 140, and 155 m depths. The aquifer is located along the horizontal stratification boundary, and is hosted by a fine-grained basaltic lava flow with the lowest feed point near the contact with basaltic tuff. Lithological evidence indicates that the host rock has slight alteration, with immense and moderate abundances of calcite and pyrite. Vein networks are also common at these depths. A minor loss of circulation was observed at these points with measurements of ~1.6, ~4.5, and ~2.0 l/s, respectively. The aquifer has temperature measurements varying from ~90 to 125°C (Figure 13).

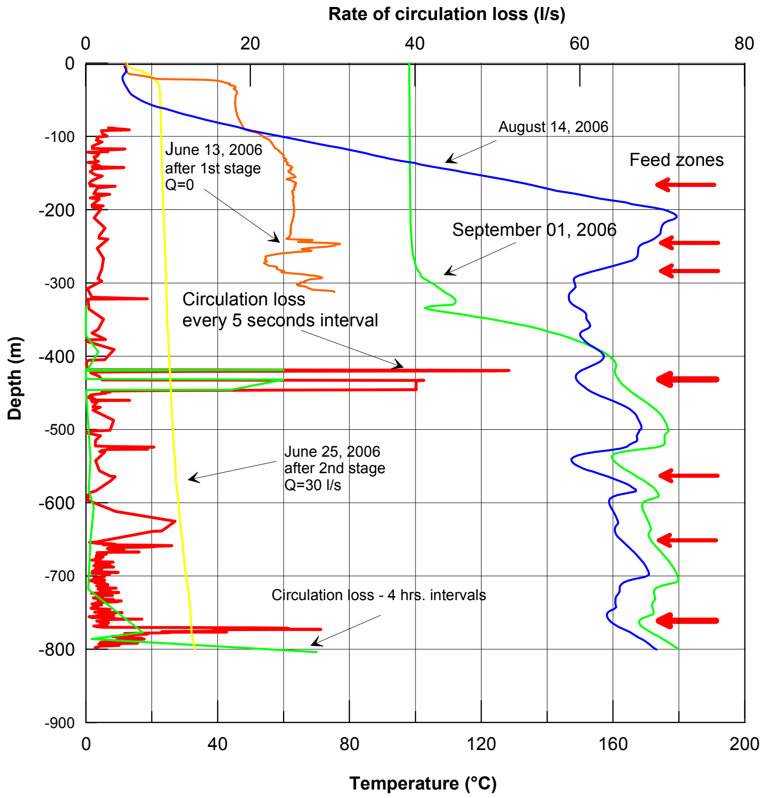

FIGURE 13: Locations of feed zones in well HE-22, in correlation to the temperature logs and rate of penetration

Aquifer 2: This aquifer is located between 240 and 260 m depth with three feed points. The aquifer is probably controlled by a combination of horizontal stratification and a vertical dyke. Aquifer 2 is associated with basaltic lava flows and is located near the contact with the overlying basaltic tuff. The lavas are intruded by a fine-grained basaltic dyke. This depth interval has a moderate degree of alteration and large concentrations of veins. The highest observed loss of circulation in this zone was 11 l/s. Temperature logs indicate a slight decrease of temperature from above 170 to 167°C (Figure 13).

Aquifer 3: This zone is found at 282 and 290 m depth. It is a vertical aquifer with a basaltic dyke cutting across a basaltic tuff. The host rock formation is highly altered with a fair amount of veins, and partially to totally filled vesicles. The penetration rates increased with depth. The temperature ranged from 148 to 155°C (Figure 13).

Aquifer 4: This zone is a moderate capacity feed zone with two feed points situated at 420 and 430 m. It is a horizontal aquifer that is hosted by medium- to coarse-grained basaltic lava flows with moderate alteration. Abundant veinlets were encountered in this sector. A large amount of circulation loss was observed, about 50 and 40 l/s, at depths of 420 and 430 m, respectively. Results of the temperature logging show a relatively constant measurement of ~150°C (Figure 13).

Aquifer 5: This feed is a weak horizontal stratification aquifer situated between the contact of fine-grained basaltic lava flow and glassy basalt. It was encountered at 572 m. Mineralised veinlets are common at this depth. Less than 5 l/s circulation loss occurred when this zone was intercepted, and the measured temperature was ~160°C.

Aquifer 6: This is a combination horizontal and vertical aquifer with a weak single point feed zone intercepted at 658 m. It is situated along the contact between basaltic lava tuff and tillite, cut by a dyke intrusion. The wall rock is characterised by intense alteration and abundant veins but is confined in a narrow distribution around the intrusion. Mineralised vesicles filled in by epidote, quartz, and prehnite are abundant at this depth. Approximately 10 l/s loss occurred when this aquifer was intercepted. The measured temperature log stands at around 168°C (Figure 13).

Aquifer 7: This zone is a combined vertical and horizontal stratification aquifer and has a moderate capacity. It was encountered at 785 m, associated with basaltic tuff near the stratigraphic contact of the underlying fine-grained basaltic lavas, cut by a narrow intrusive body. The wall rock has a high degree of alteration with an intense presence of veins and vesicles. Pyrite, epidote, and quartz are relatively abundant at this depth. The circulation loss measurement pegged at 6 l/s, and the temperature log at ~170°C (Figure 13).

6. DISCUSSION - MINERALOGICAL COMPARISONS OF THE DRILLED WELLS IN THE ÖLKELDUHÁLS AREA

Besides well HE-22, there have been 2 exploratory drillings conducted in the Ölkelduháls field, namely: ÖJ-1 and HE-20 (Figure 5). ÖJ-1 is a vertical well with a total depth of 1035 m. The lithological formations encountered consist, primarily, of altered basaltic hyaloclastic rocks of breccia and tuff with intercalated fresh to altered basaltic lava flows ubiquitous at the lower portion of the column (Steingrímsson et al., 1997). The drilling of ÖJ-1 was followed by HE-20. HE-20 is a directional well that reached a bottom at 2002 m. The rock types intercepted were almost the same sequences as in ÖJ-1. However, the rock formations in HE-22 are composed of alternating series of mostly relatively thin hyaloclastite type rocks with occasional lava flows in between (Mortensen, pers. com.). The formations in these two wells were intruded by a series of basaltic dykes of fine- to coarse-grained olivine tholeiite with a porphyritic texture.

The correlation of the common secondary minerals of the three wells in the Ölkelduháls geothermal sector is shown in the cross-section in Figure 14. The sequence demonstrates increasing progressive mineralisation and alteration with increasing depth. The crystallisation and the abundance of low-temperature zeolite members and chalcedony occur at a shallow level, followed by the presence of higher temperature minerals such as quartz, wairakite, and epidote in deeper series. The first appearance of these minerals seems to be slightly shallower in HE-20 and HE-22 than in ÖJ-1. This may seem to imply that past geothermal activity in both HE-20 and HE-22 was quite extensive compared to ÖJ-1. However, overprinting of low- and high-temperature minerals cannot be ignored, as shown with the crystallisations of chalcedony and quartz at the same depth in ÖJ-1 and HE-22, the presence of wollastonite at much greater depths in HE-20 than in HE-22, and the first appearance of garnet at shallower depths with respect to wollastonite in

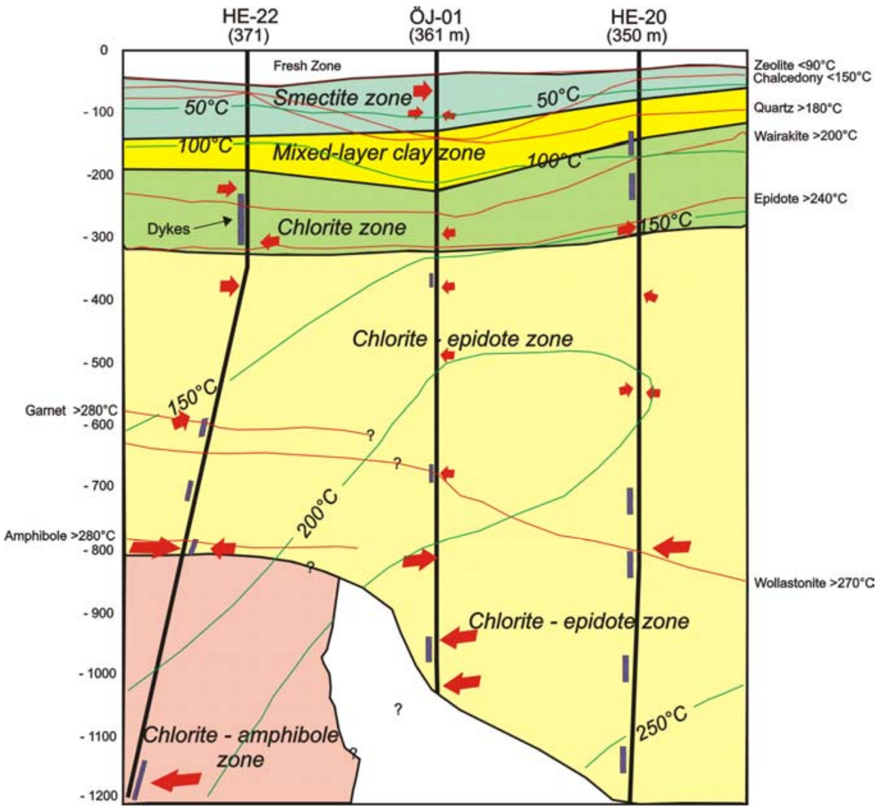

FIGURE 14: Comparison of the hydrothermal mineralisation of the three geothermal wells drilled in the Ölkelduháls area

HE-22. Likewise, higher-temperature crystals like garnet and amphibole are present and abundant in HE-22. The deposition of these minerals in HE-22 can be attributed to its location at the eastern boundary of a graben belonging to the Hengill central volcano, which deviated into the faults that form the eastern boundary. It is speculated that the intense alteration zones at depth in HE-22 may indicate that the graben fault system is more intense than the system seen in ÖJ-1 and HE-22. Another probability is the existence of numerous basaltic dykes and even rhyolitic intrusions at greater depths that might impact higher permeable zones and, subsequently, the deposition of these minerals. Furthermore, as has been previously discussed, precipitation of calcite is dominant in the entire section of HE-22. This characteristic is also prevalent in ÖJ-1 and HE-20, which seems to indicate a slight decrease in temperature or minor cooling of the geothermal system in Ölkelduháls (Franzson, pers. com.). However, the abundant presence of calcite in HE-22 can be related to boiling of the past geothermal system and intrusion of cold groundwater into the geothermal system, shown in the Th measurements in Figure 12. The calcite deposited in HE-22 has a drusy appearance, an indication of a high-temperature environment. In Hellisheidi field, calcite dissolved when the temperature rose above 290°C at about 1000 m, coinciding with the appearance of the epidote-amphibole zone (Franzson et al., 2005). This extreme formation temperature in Hellisheidi was not measured in the Ölkelduháls field. As illustrated in the temperature logs shown in Figure 15, the three wells displayed drastic cooling compared to the hydrothermal alteration.

Similarly, the comparison of clay alteration in the three wells indicates progressive zonation, starting with the smectite layer at a shallow level, then passing to the transitional mixed-layer formation, chlorite, and then to a chlorite-epidote zone (Figure 14). The chlorite-epidote zone is the thickest layer. The chlorite-amphibole zone can only be found in the deeper section of HE-22. This layer is absent in the two previously drilled wells as far as can be seen; XRD samples from HE-20 below 1100 m reveal the presence of chlorite, and the bottom alteration zone of ÖJ-1 also indicates chlorite with epidote (Steingrímsson et al., 1997).

The mineralisation characteristics of HE-22, especially the formation of higher-temperature minerals like garnet, amphibole, wollastonite, and the formation of chlorite-amphibole zone, show that the paleo-hydrothermal activity at the bottom depth of HE-22 was more active than in the other wells. It must be noted that HE-22 was drilled towards the Hengill central volcano, whereas both ÖJ-1 and HE-20 were drilled and straddled between the Hengill and Hrómundartindur geothermal systems. The geothermal activity in Ölkelduháls is assumably directly related to the Hrómundartindur system. The wells drilled in the Ölkelduháls area confirmed a relatively cool convective system at least down to 1 km depth. This is furthermore illustrated in Figures 14 and 15, showing that the measured temperature is highest in HE-20 (~240°C) compared to HE-20 (~210¨C) and ÖJ-1 (<200°C). It must, however, be emphasised that the internal flow within HE-22, where fluids descend from the upper aquifers down into lower areas, may

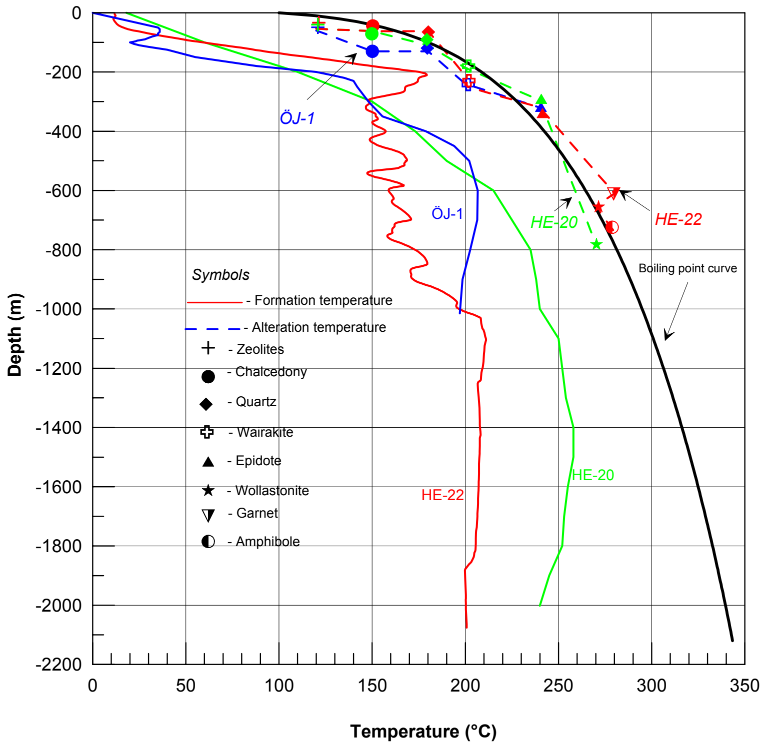

FIGURE 15: Measured and hydrothermal mineralisation temperatures of the three wells at Ölkelduháls

mask the true formation temperatures in the deeper part of the well. The computed gas geothermometers in ÖJ-1 indicate much higher temperature at greater depth (Steingrímsson et al., 1997). The present formation temperatures in the three wells decreased respective to their hydrothermal alteration temperatures, which implies disequilibrium between the measured and crystallisation temperatures (Figure 15). Moreover, it can be roughly concluded that this situation might indicate decreasing thermal activity in HE-22 or, in general, towards the Hengill geothermal system. A reverse situation occurs in HE-20 with increasing temperature towards the east in the Hrómundartindur system. It is most likely that the contributing factor in the lower temperature of the formation in HE-22 is a strong influx of colder sub-surface water flowing along fracture networks toward the geothermal system. This inflow of cold groundwater towards the geothermal system is also prominent in the Nesjavellir and Hellisheidi fields, causing the systems to cool down (Franzson et al., 2005).

When compared with the present boiling point curve, the anomalous high-temperature alteration in Ölkelduháls wells shows intense past geothermal activity, a higher paleo boiling curve, and may also indicate that the hydrological contact between the geothermal system and an overlying glacier is way above the present surface. This is also indicated in the Th measurements of HE-22 (Figure 12) and ÖJ-1 (Steingrímsson et al., 1997). The last glacial period ended about 12,200 years ago.

7. CONCLUSIONS

The following conclusions can be deduced from the geological study of well HE-22:

1. The stratigraphy of the first 800 m depth of well HE-22 consists primarily of altered hyaloclastite rocks intercalated with fine- to coarse-grained basaltic lava flows. These formations are intruded by a series of fine- to coarse-grained basaltic dykes.

2. The formations host a wide variety of secondary hydrothermal mineralisations ranging from low- to high-temperature minerals. The alteration zonation indicates four assemblages: a smectite - zeolite zone (<200°C) at 46-170 m, mixed-layer clays (200-230°C) from 170 to 206 m, chlorite (230-240°C) between 206 and 324m, chlorite-epidote (>240°C) from 324 to 740 m, and the upper boundary of the epidote-actinolite zone (280°C), and may be present below 740 m depth.

3. Seven clusters of feed zones were encountered and categorized into weak and moderate aquifers. These aquifers can be correlated to the characteristics of the lithological formations, intensity of alteration, abundance of veins and vesicles, stratigraphic boundary, and the presence of intrusive bodies.

4. The correlations of the common secondary mineralogical compositions of the three wells drilled in the Ölkelduháls geothermal sector demonstrate progressive alteration with increasing depth; however, overprinting of other minerals cannot be disregarded. The current formation temperatures show disequilibrium with the hydrothermal temperatures.

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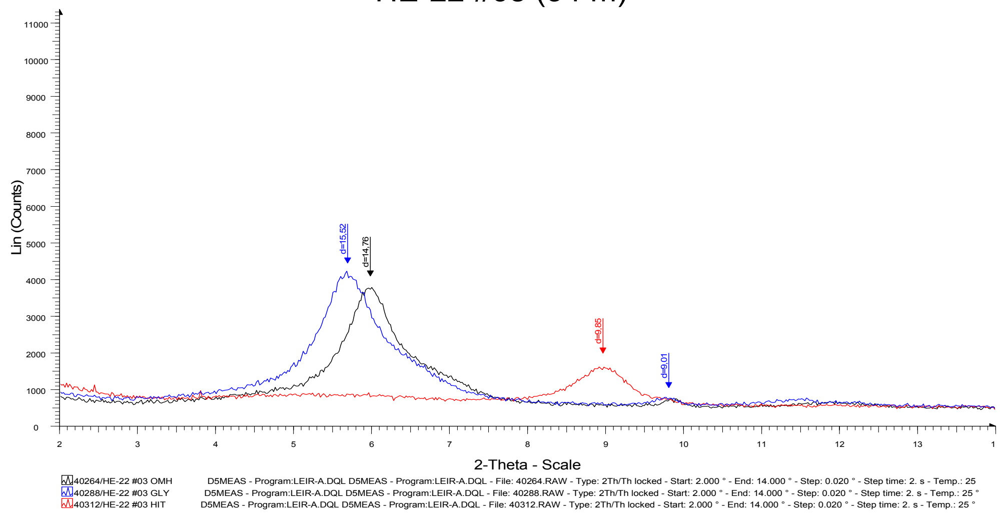
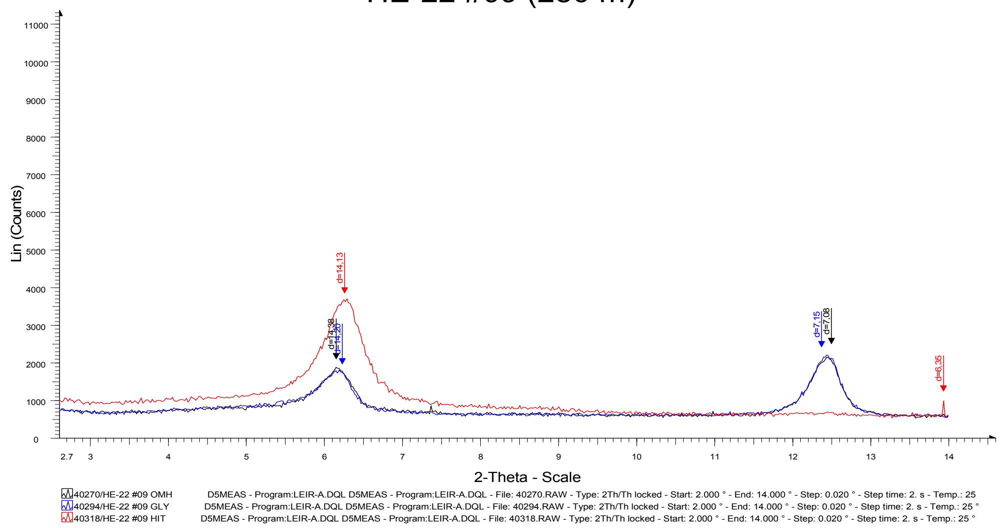
APPENDIX I: X-ray diffraction analysis

Depth (m)	Type of clay	Untreated (Å)	Glycolated (Å)	Heated (Å)	Rock type
62	Smectite	15.26	16.67		Basaltic breccia
80	Smectite	15.06	16.67		Basaltic breccia
94	Smectite	14.76	15.52	9.85	Basaltic breccia
116	Smectite	14.41	14.76	9.5	Basaltic breccia
142	Smectite	14.80	15.43	9.77	Fine-grained lava flows
168	Smectite	14	15	9.52	Fine-grained lava flows
206	Unstable chlorite	14.38	14.63	14.00	Tuff
		7.21	7.131		
240	Unstable chlorite	14.26	14.54	14.09	Fine-grained lava flows
		7.08	7.15		
280	Unstable chlorite	14.38	14.20	14.13	Tuff
		7.08	7.15		
298	Unstable chlorite	14.42	14.20	14.02	Tuff
		7.10	7.11		
340	Unstable chlorite	14.35	14.28	13.72	Tuff
		7.10	7.08		
382	Unstable chlorite	14.13	14.68	14.47	Glassy basalt
		7.07	7.16		
424	Unstable chlorite	14.44	14.19	13.98	Medium-grained lava flows
		7.15	7.10		
466	Unstable chlorite	14.33	14.75	14.0	Medium-grained lava flows
		7.11	7.20		
500	Unstable chlorite	14.26	14.51	13.91	Medium-grained lava flows
		7.15	7.06		
546	Chlorite	14.58	14.33	14.06	Fine-grained lava flows
		7.14	7.07	7.14	
576	Chlorite	14.63	14.35	14.06	Glassy basalt
		7.19	7.11	7.12	
618	Chlorite	14.49	14.26	14.0	Basaltic breccia
		7.15	7.08	7.15	
666	Chlorite	14.53	14.28	14.79	Basaltic breccia
		7.17	7.10	7.0	
698	Chlorite	14.56	14.33	14.11	Basaltic breccia
		7.15	7.08	7.15	
	Illite	10.18	10.10	10.01	
740	Chlorite	14.68	14.24	14.47	Basaltic breccia
788	Chlorite	14.60	14.44	14.28	Basaltic breccia
		7.15	7.10	7.22	
	Illite	10.22	10.02	10.11	Fine-grained lava flows

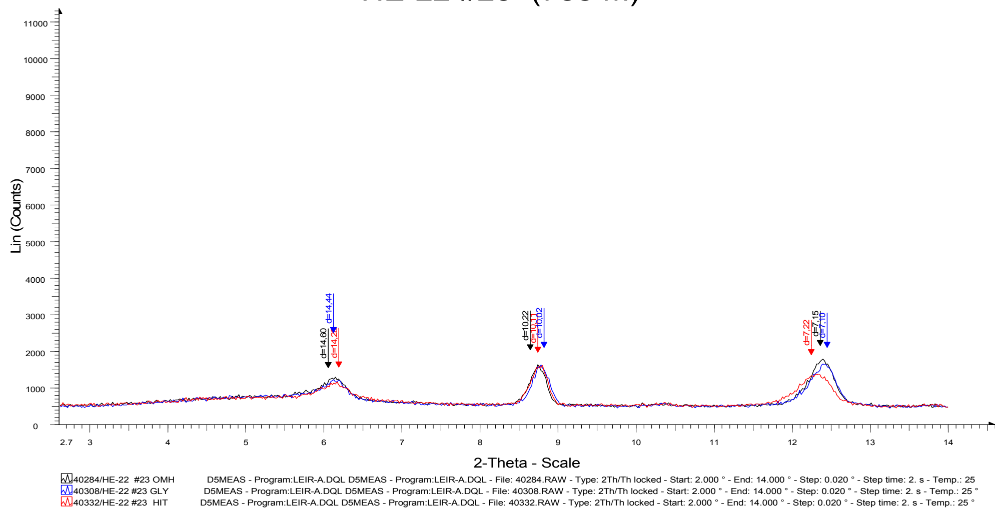
HE-22 #03 (94 m)



HE-22 #09 (280 m)

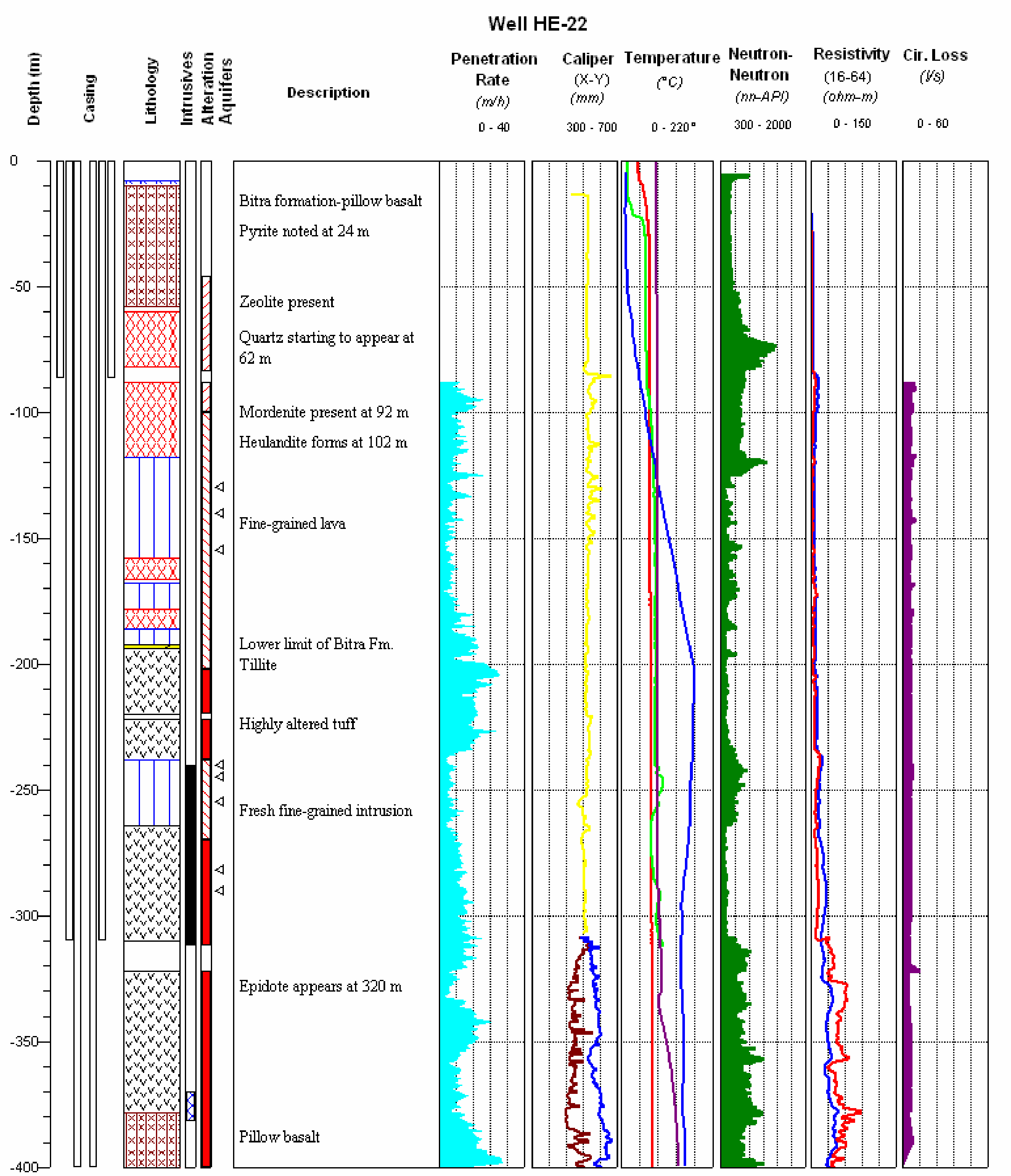


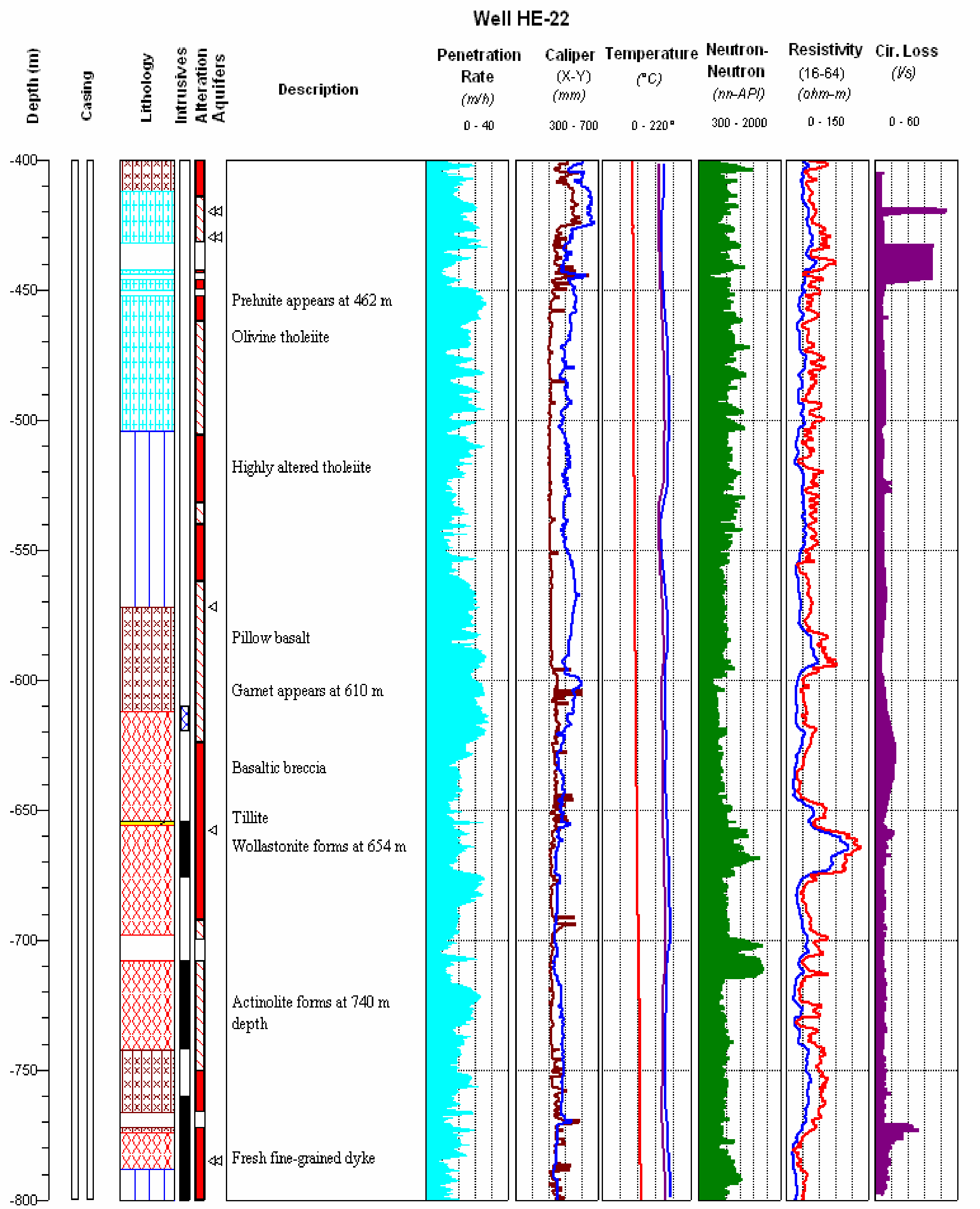
HE-22 #23 (788 m)



APPENDIX II: Detailed geological and geophysical loggings of well HE-22

(see Figure 9 for geological symbols)




Well HE-22
Depth (m)
Casing
Lithology
Intrusives
Alteration
Aquifers
Description
Penetration Rate (m/h) 0 - 40
Caliper (X-Y) (mm) 300 - 700
Temperature (°C) 0 - 220°
Neutron-Neutron (nn-API) 300 - 2000
Resistivity (16-64) (ohm-m) 0 - 150
Cir. Loss (l/s) 0 - 60
-400
-450
-500
-550
-600
-650
-700
-750
-800
Prehnite appears at 462 m
Olivine tholeiite
Highly altered tholeiite
Pillow basalt
Garnet appears at 610 m
Basaltic breccia
Tillite
Wollastonite forms at 654 m
Actinolite forms at 740 m depth
Fresh fine-grained dyke