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GEOLOGICAL MODELLING OF THE HVERAGERDI GEOTHERMAL FIELD, ICELAND

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ABSTRACT

The Hveragerdi geothermal field is situated in south-west Iceland within the extinct Grensdalur volcano in the vicinity of the Hengill Central Volcano. The Hveragerdi geothermal field has been utilized for district heating and other industrial use since the mid-twentieth century. Well HV-05 was drilled in 1960 to 1206 m depth. In this project well cuttings from HV-05 were analysed by binocular, petrographic microscope, and X-ray diffractometry. The results from the studies of drill cutting is that the lithology in the well consists of crystalline basaltic lavas and basaltic hyaloclastite. The grade of alteration is high, and the well is within the chlorite and chlorite-epidote alteration zone. Calcite is seen regularly overprinting alteration minerals such as epidote indicating that the geothermal reservoir has cooled over time and that is further confirmed by temperature logs in the wells in the area which show a maximum reservoir temperature of around 190°C. The results from the cuttings analysis are combined with geophysical, geochemistry and well data to better understand the geothermal system in the Hveragerdi geothermal field to build a geological and a conceptual model. Targets for a production well and a re-injection well were defined using the geological model aiming at high temperature and permeability. This work shows that the field has potential for further utilization and might be suitable for carbon mineralization.

1. INTRODUCTION

The Hveragerdi geothermal field is located on the eastern margin of the Western Rift Zone (WRZ) and on the western end of the South Iceland Seismic Zone (SISZ) (Geirsson and Arnórsson, 1995). The Hveragerdi geothermal field is situated on the extinct Grensdalur volcano in the active Hengill volcanic system. The extinct Hveragerdi volcano was formed by tensional stress parallel to the spreading direction. A fracture system oriented in N30-35°W direction intersects the Hengill central volcano, creating geothermal manifestations such as fumaroles and hot springs from the Hveragerdi center area to the Hengill center area, transecting the main fissure swarms. The main heat source of the Hveragerdi geothermal system is located in the volcanic rift zone which is connected to the Hengill central volcano by faults and fissure swarms (Fridleifsson, 1979). Volcanic rocks in Hveragerdi geothermal field are mainly basaltic with various lithofacies of sub-glacial origin.

Well HV-05 was drilled in 1960 at the Hveragerdi geothermal field. This well is vertical with a total depth of 1206 meters. The production casing is located at 193 meters depth with main feed zone at 236 - 240 meters and 294.5 – 298.5 meters as predicted by well temperature profile, spinner, and borehole televiewer. The water level is at 80 meters (Jónsson et. al, 2021). For well HV-05, several datasets are available such as drill cuttings, wireline logs, temperature logs, spinner and other well data. Integrated analysis of these datasets has been conducted to build a geological model of the Hveragerdi geothermal field. The geological model has been combined with geophysical data, geochemistry, and temperature measurement from wells to build a conceptual model. Based on the conceptual model and well data, this field can possibly be utilized for district heating and carbon capture storage.

2. BACKGROUND

2.1 Regional geology

Iceland is formed by the rising Icelandic mantle plume and crustal accretion at the diverging American and Eurasian lithospheric plates. The complicated tectonic and volcano-stratigraphic structure of Iceland is due to the relative movement of the lithospheric plate boundary in relation to the stationary mantle plume and the eastward shifting of the volcanic belts in Iceland (Ward and Björnsson, 1971; Saemundsson, 1974; Jóhannesson, 1980; Óskarsson et al., 1985; Einarsson, 1989; Hardarson et al., 1997). The majority of volcanic eruptions in Iceland are basaltic while rhyolitic eruptions occur mainly in mature volcanic systems. Continuous volcanic activity in Iceland leads to an abnormally high geothermal gradient at the vicinity of volcanic zones. Many high temperature geothermal fields are located close to volcanic zones.

2.2 The Hveragerdi geothermal field

2.2.1 Geological settings

The Hveragerdi geothermal field is located 40 km South-East of Reykjavik, Iceland. The field is situated on the eastern margin of the Western Rift Zone and on the western end of the South Iceland Seismic Zone (Geirsson and Arnórsson, 1995).

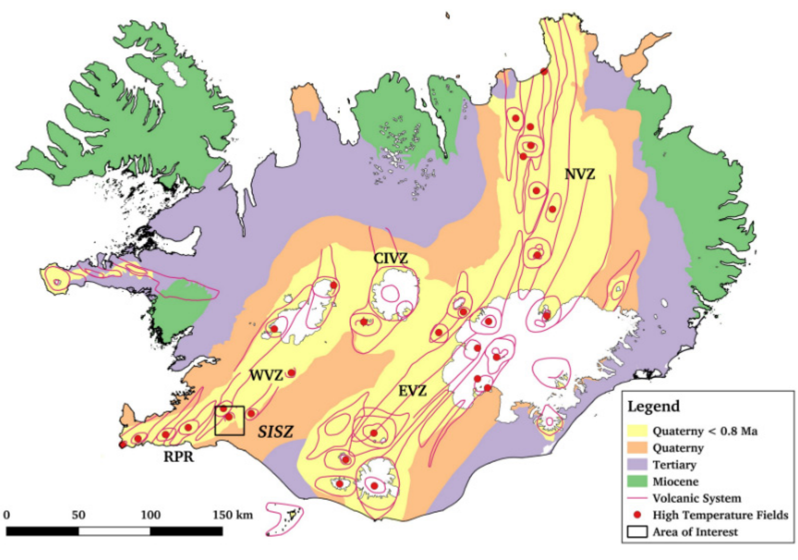


FIGURE 1: Location of the Hveragerði geothermal field (Landmælingar Íslands, 2019)

The square in the geological map of Iceland shows the location of the Hveragerdi geothermal field (Figure 1). The field is located between the Reykjanes Peninsula Rift (RPR), Western Volcanic Zone (WVZ) and South Iceland Seismic Zone (SISZ).

The Hveragerdi geothermal field is located within the extinct Grensdalur volcano in the vicinity of the active Hengill volcanic system, which has shifted about 5 kilometers west from the rift axis over the last 500,000 to 1 million years (Fridleifsson, 1979). The extinct Grensdalur volcano was formed by tensional stress parallel to the spreading direction. A fracture system oriented in N30-35°W direction intersects the Hengill central volcano, creating geothermal manifestations such as fumaroles and hot springs from the Hveragerdi center area to the Hengill center area, transecting the main fissure swarms (Fridleifsson, 1979). The main heat source of the Hveragerdi geothermal system is located in the volcanic rift zone which is connected to the Hengill central volcano by faults and fissure swarms (Fridleifsson, 1979). The volcanic rocks in the Hveragerdi geothermal field are mainly basaltic with various lithofacies of sub glacial origin.

2.2.2 Tectonic settings

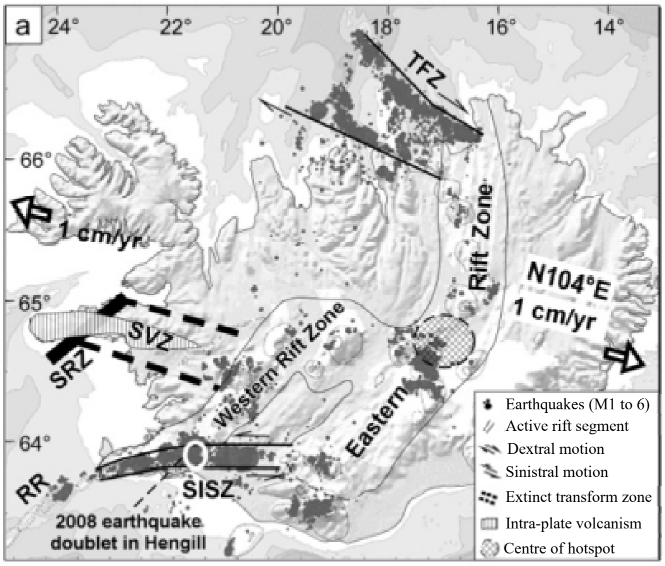


FIGURE 2: Active rift and transform zone around the Hengill Volcanic Complex (Khodayar and Björnsson, 2010)

The Hveragerdi geothermal field is located on the eastern margin of the Western Rift Zone (WRZ) and on the western end of the South Iceland Seismic Zone (SISZ) (Geirsson and Arnórsson, 1995). The SISZ active transform zone connects the Western Rift Zone (WRZ) with the Eastern Rift Zone (ERZ) (Khodayar and Björnsson, 2010) (Figure 2). The SISZ is roughly 80 km in length and 25 km in width and runs from east to west. It forms a narrow zone from the intersection with the WRZ, devolves into the oblique swarms of the Reykjanes Peninsula before connecting to the Reykjanes Ridge.

The SISZ is a typical Riedel shear zone with a total of six shear fractures. Active fractures are oriented in N-S, ENE and WNW directions (Rögnvaldsson et al., 1998; Árnason and Magnússon, 2001; Khodayar and Franzson, 2007). The Riedel shears have normal-slip with displacement up to ten meters along the N-S faults in Reykjafjall area, while north of the Hengill area, the ENE fractures have acted as eruptive fissure in rare cases. The Hveragerdi geothermal field has geothermal manifestations that are aligned on the N-S and NNW faults (Wangombe, 1987; Bazaale-Dolo, 1990; Saemundsson and Kristinsson, 2005).

2.3 Geophysical exploration

Resistivity is one of geophysical methods that have been used to explore geothermal resources. Low resistivity indicates the location of a cap rock in a geothermal system while the reservoir is characterized by a resistive core which is located below cap rock.

The cap rock in a geothermal system is commonly composed of smectite – zeolite minerals. A smectite-zeolite zone which correlates with low temperatures (<180ºC) is characterized by low resistivity (10 ohm-m), while higher temperature zones are characterized by the minerals chlorite and epidote. If the temperature indicated by the mineral fits the well temperature measurement, this means that no cooling has been taking place. Therefore, the resistivity data can be used as a marker to delineate the boundaries of the geothermal reservoir.

Transient Electromagnetic (TEM) resistivity measurements have been conducted at Ölfusdalur – Hveragerdi by The National Energy Authority in Iceland in the year 2000 (Figure 3). The data indicated a resistive core below a low resistivity zone. This resistivity structure indicates that at one timethere was a high temperature geothermal system in Hveragerdi. The map below shows the low resistivity measured based on 1D inversion of TEM data in Hveragerdi geothermal field while the sections show TEM resistivity measurement in Grændalur (left) and Gufudalur (right). TEM resistivity data in Gufudalur shows that the resistive core in the northern part is shallower than in the southern part of the Hveragerdi geothermal field (Eysteinsson, 2000).

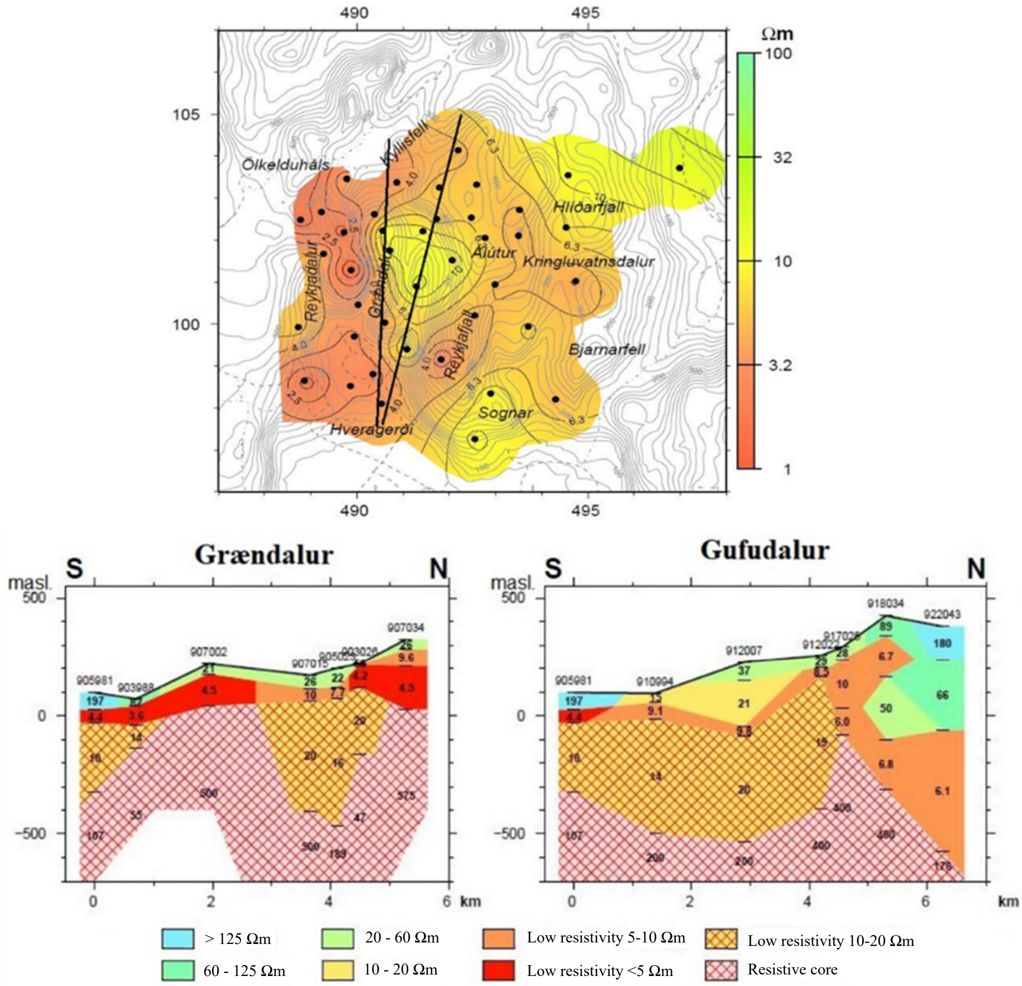


FIGURE 3: Resistivity data from TEM measurements in Hveragerdi geothermal field (Eysteinsson, 2000)

2.4. Geothermal manifestations and geochemistry

There are several types of geothermal manifestations in Hveragerdi geothermal field such as fumaroles, mud pools and hot springs (Figure 4). The manifestations indicate geothermal activity in the subsurface. Almost all the manifestation are located on N-S and NNE-SSW lineaments which are in agreement with the orientation of faults and fissures in The Hveragerdi geothermal field. The pattern of faults and fissures is very important to know because those are the fluid pathways for geothermal fluid from deeper parts of the crust to the shallower zone.

Surface mapping of geothermal manifestations and a study of CO_2 and H_2S content from fumaroles have been conducted by Reykjavik Energy from 2007 to 2013 (Bragadóttir, 2019). That study indicated that reservoir temperature increases towards the northern part of the Hveragerdi geothermal field.

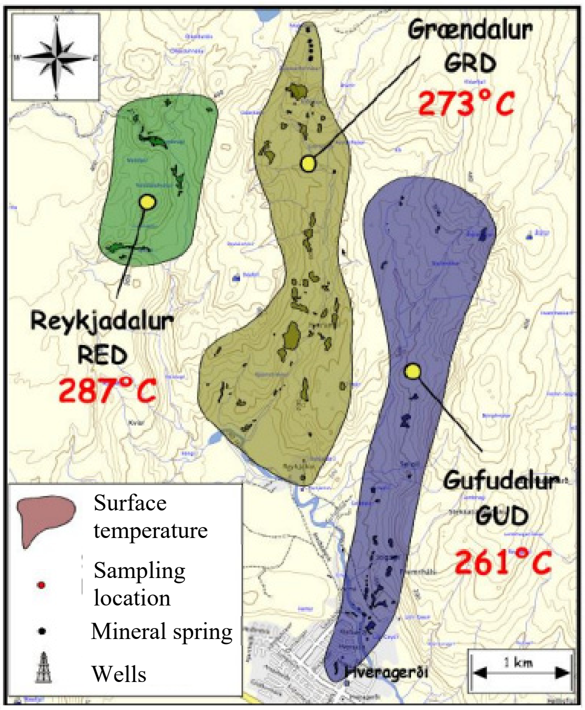


FIGURE 4: Location of surface geothermal manifestations in Hveragerði (Ívarsson et al., 2011). The temperature in Olkelduhals was predicted to be maximum 305°C by measuring chemical temperatures from CO_2 gas (Bragadóttir, 2019). The predicted temperature at Gufudalur is around 261°C, 273°C in

The chemical composition of surface geothermal manifestation can be used to identify characteristics of the geothermal fluid in the subsurface. Hot springs in Hveragerdi area are characterized by chlorine water. The fluid was predicted to originate from the northern part of the Hveragerdi area.

Table 1 shows chemical compositions of geothermal fluid in part per million (ppm) from wells HV-02, ASI-1, OL-1 and SO-01 in Hveragerdi geothermal field. The chemical composition from well SO-01 indicates that the fluid originates from a different water system which is dominated by precipitation, whereas other wells have fluid of marine origin. Well HV-02 has the highest measured temperature in the area. Low values of CO_2 in well ASI-01 indicate boiling (Sæmundsson and Arnórsson, 1971).

The chemical composition of geothermal fluid in Hveragerdi geothermal field indicates the possibility of calcite scaling in the upper most part of the wells and amorphous silica scaling in surface facilities.

TABLE 1: Chemical composition of geothermal fluid at several wells in Hveragerdi geothermal field (Saemundsson and Arnórsson, 1971)

Chemicals	HV-02	ASI-1	OL-1	SO-01
pH	7.1	8.1	7.1	9.5
SiO_2	269.5	161.0	202.5	87.0
Na^+	157.0	158.0	143.0	59.0
K^+	4.8	5.2	9.5	3.6
Ca^{++}	2.0	8.5	14.5	1.1
Mg^{++}	0.1	0.1	0.5	0.1
CO_2	102.6	52.0	113.0	84.0
SO_{4-}	44.0	49.2	48.4	4.1
H_2	60.5	<0.1	<0.1	<0.1
Cl^-	121.8	184.8	132.8	11.3
Silica temperature	199°C	160°C	178°C	84°C
Measured temperature	190°C	149°C	160°C	84°C

2.5 Sub-surface data / Well information

Figure 5 shows both production and re-injection wells in Hveragerdi geothermal field. All production wells in this area have been utilized for district heating (Bragadóttir, 2019).

Geological data and other well data such as lithology and temperature measurements are available for several wells in Hveragerdi. These data have been used to build a geological, temperature model and a conceptual model of the Hveragerdi geothermal field.

Well HV-05 was drilled in 1960 at Hveragerdi geothermal field (red arrow on Figure 5). The National Energy Authority is the owner of this well. It is a vertical well with a total depth of 1206 meters. A production casing with an inner diameter of 220.5 mm is located at 193 meters. Feed zones in around 236 - 240 meters (38%) and 294.5 – 298.5 meters (62%) were predicted by well temperature, spinner, and borehole televiewer data. The water level is located at 80 meters depth (Jónsson et. al, 2021).

Various data set from Well HV-05 are available such as drill cuttings, calliper log, gamma, televiewer log, resistivity log, cement bound log, neutron – neutron log and production capacity. The cuttings were retrieved every 2 meters while the log data exists for the depth interval between 332 – 374 meters.

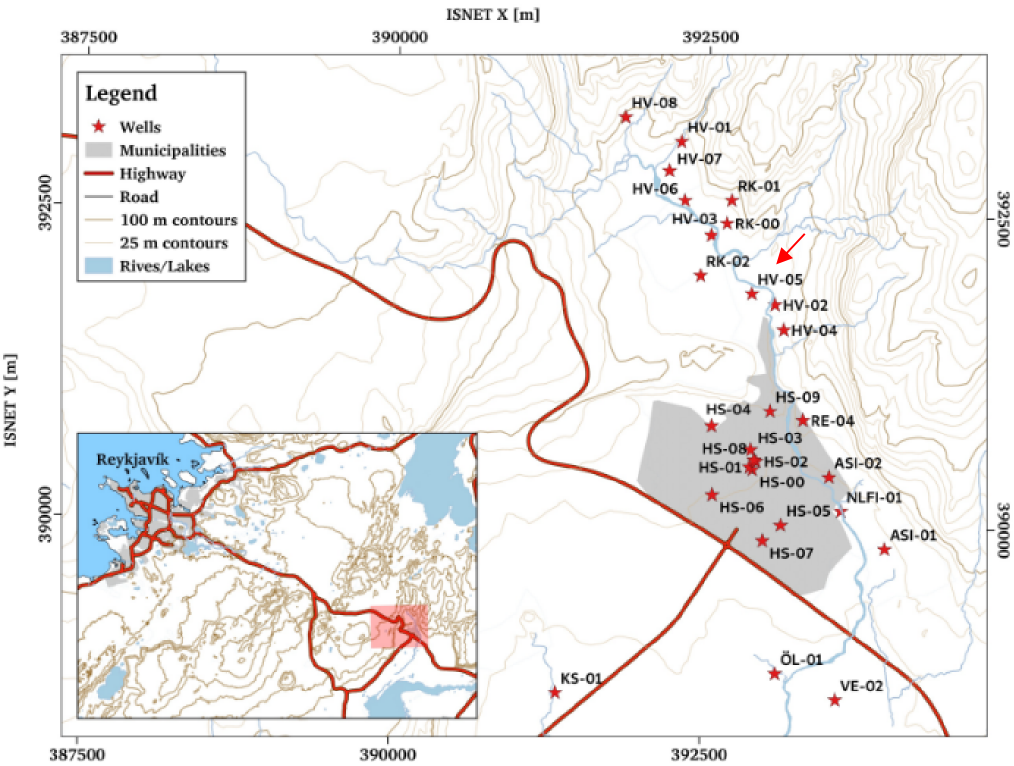


FIGURE 5: Location of well HV-05 (Reykjavík Energy, 2019)

3. METHODS

In this study, data from well HV-05 in Hveragerdi was analysed. The cutting samples are available every 3 – 6 feets in this well but for this study samples were selected to represent approximately every 2-meter. Drill cuttings from the well were studied using standard rock cutting analysis methods, namely the study of thin sections from drill cuttings using binoculars, a petrographic microscope and X-ray diffractometry (XRD) for the analysis of clay minerals.

3.1 Cutting analysis (binocular and thin sections)

Binocular analysis is a method to determine rock type and mineralogy on a megascopic scale. The selected cuttings from well HV-05 have been analysed using a binocular microscope to determine rock type, mineralogy, alteration, alteration sequence, and physical characteristic of the rock such as colour, grained size, and hardness.

Petrographic analysis with a polarizing microscope was carried out using cutting thin section samples of selected depths to determine the micro-optic properties of individual minerals. Eight thin section samples were selected based on variations of lithology and mineralogy for in binocular analysis.

3.2 X-ray diffractometry (XRD)

X-ray diffractometry (XRD) has advantages when the particles to be identified are too small to be clearly resolved with a microscope, such as clay particles or when minerals exist as solid solutions or mixtures (Chen, 1977). There are three types of XRD analysis for clay treated analysis: air dried, ethylene glycol, and heated. This method is used in the geothermal industry to identify variations of the clay alteration in the cuttings. Ten samples from selected depth have been analysed using XRD. The samples were taken from around 50 m intervals in the shallow zone and from more than 100 m intervals in the deep zone.

3.3 Geological Modelling

In this research, the Leapfrog software was used to build a geological model based on borehole geological data from well HV-05 and others geothermal wells in Hveragerdi geothermal field. Additional data have been used such as topography, a geological surface map, locations of surface geothermal manifestations and several physical data sets from wells in Hveragerdi geothermal field (Helgadóttir, 2019). The result of this modelling has been combined with geophysical, geochemistry and temperature data to create a preliminary plan of development for the Hveragerdi geothermal field.

4. RESULT

4.1 Well HV-05

4.1.1 Geology

As mentioned before, drill cuttings from every 2 m in well HV-05 were analysed using a binocular microscope. Petrographic analysis has been carried out of 8 thin sections from 78 m, 86 m, 265 m, 274 m, 296 m, 317 m, 602 m, and 1197 m depth. In addition, X-ray diffractometry (XRD) analysis was conducted for 10 samples from 53 m, 112 m, 153 m, 190 m, 237 m, 298 m, 351 m, 441 m, 796 m, and 1019 m depth.

The results from binocular, petrography and XRD analysis were integrated to make a simplified stratigraphy of well HV-05. The stratigraphy consists of the formations listed below (Figure 6 and Table 2):

9 – 27 m, Sedimentary (surface) rock. This is the shallowest zone for which cutting data was retrieved. It is dominated by sedimentary rocks mixed with crystalline basalt. The sedimentary rocks consist of sandstone and mudstone while the crystalline rocks consist of fine – medium grained basalt and medium – coarse grained basalt. The rock is dominated by brownish and greyish colours and soft – medium hardness. It is medium - highly altered and has a high content of clay.

27 – 33 m, Hyaloclastite 1. This formation consists of dark grey, fine grained basaltic breccia, medium - hard hardness, low - medium altered, with veins filled by calcite. Some alteration minerals were found in this zone such as medium – coarse grained clay (most likely chlorite), calcite and quartz.

33 – 242 m, Basalt 1. The lithology in this formation consists of crystalline, medium – highly altered basalt. Alteration minerals are dominantly chlorite and calcite. Other alteration minerals found are epidote, chalcedony, pyrite, and quartz. The mineral sequence is dominated by calcite in the lower section. There are veins and vesicles at depth intervals 47 – 68 m, 84 – 95 m, 112 – 95 m, and 112 – 172 m and they are filled by alteration clay, calcite, quartz, oxidation, epidote, and chalcedony. Cubical pyrites were found at 175 – 192 m and mesolite was found at 82 – 84 m in this formation.

242 – 302 m, Hyaloclastite 2. This formation is dominated by hyaloclastite with high intensity of alteration. Secondary minerals consist of epidote, chlorite, wairakite, and quartz. Mineral sequences show the dominance of calcite in the last section. The cuttings have high contents of chlorite at 240 – 290 m and 298 – 302 m and are rich pyrite and calcite at 242 – 278 m. Veins at 287 – 298 m and vesicles at 242 – 290 m are filled by calcite, epidote, and some oxidation is noted. Epidote is common at 242 – 290 m.

302 – 521 m, Basalt 2. The lithology in this zone is dominated by basalt and basaltic breccia in between lava (basalt) layers. The rocks have medium – high intensity of alteration. Secondary minerals consist of epidote, chlorite, calcite, and quartz. The mineral sequence shows calcite in the last section. This zone has a high content of chlorite at 351 – 378 m, 408 – 433 m, and 489 – 492 m, high content of oxidation at 315 – 338 m and abundant epidote at 430 – 433 m, 441 – 442 m, 450 – 452 m, and 489 – 492 m. Veins and vesicles are very rare in this formation. There are indications of possible basaltic intrusions at around 300 m. This is supported by wireline logs data. The resistivity log increases dramatically and the neutron – neutron and gamma log also increase in value compared to previous depths.

521 – 731 m, Hyaloclastite 3. The hyaloclastite in this formation consists of basaltic breccia and basaltic tuff that is medium – highly altered. Secondary minerals consist of epidote, chlorite, calcite, pyrite, wairakite, and quartz. The mineral sequence is dominated by calcite in the last section. The cuttings have a high content of chlorite at 522 – 535 m, 539 – 541 m, 544 – 553 m, 562 – 593 m, 629 – 637 m, 642 – 648 m, 655 – 658 m, and 666 – 694 m depth. High content of calcite was found at 539 – 541 m, 562 – 593 m, 612 – 623 m, 666 – 696 m, and 722 – 731 m. Epidote was abundant at 522 – 532 m and 539 – 541 m, Euhedral calcite at 562 – 592 m and cubical pyrite at 539 – 541 m and 562 – 593 m. Veins are filled by calcite and epidote at 544 – 553 m and 694 – 696 m and by calcite at 553 – 562 m, 608 – 612 m, 642 – 648 m, and 692 – 722 m. The possible basaltic intrusions were found at 604 – 608 m, and 623 – 629 m.

731 – 936 m, Basalt 3. The crystalline basalt in this formation is mostly made of fine – medium grained basalt and an interlayer of basaltic tuff was found in some samples. The crystalline rock is low – medium altered and the basaltic tuff medium – high altered. Secondary minerals at this depth are chlorite, euhedral calcite, and pyrite. Abundant epidote was found at 796 – 800 m, 811 – 820 m, 874 – 882 m, 898 – 907 m, and 911 – 934 m depth. Vein and vesicles are filled by calcite, oxidation, and epidote. At 739 – 770 m, 800 – 811 m, 888 – 891 m and 934 – 936 m, there are possibly intrusive rocks.

936 – 1129 m, Hyaloclastite 4. The hyaloclastite in this formation consists of basaltic breccia and basaltic tuff with high intensity of alteration. The cuttings have a high content of chlorite at 939 – 949 m and 1019 – 1023 m, are high in calcite at 939 – 949 m and 952 – 960 m, and abundant in epidote at 936 – 939 m. Vein and vesicles are filled by calcite and epidote.

1129 – 1206 m, Basalt 4. The lithology at this depth is mostly basalt, either crystalline or glassy. The crystalline rock is characterized by low alteration intensity whereas the basaltic tuff is medium – highly altered. Secondary minerals include chlorite, calcite, quartz, epidote, and pyrite. High contents of calcite at 1198 – 1206 m and chlorite at 1197 were found in the petrography sample. Veins are filled not only by calcite at 1167 – 1182 m, and 1198 – 1206 m but also bz quartz,and calcite at 1197 m in the petrography data.

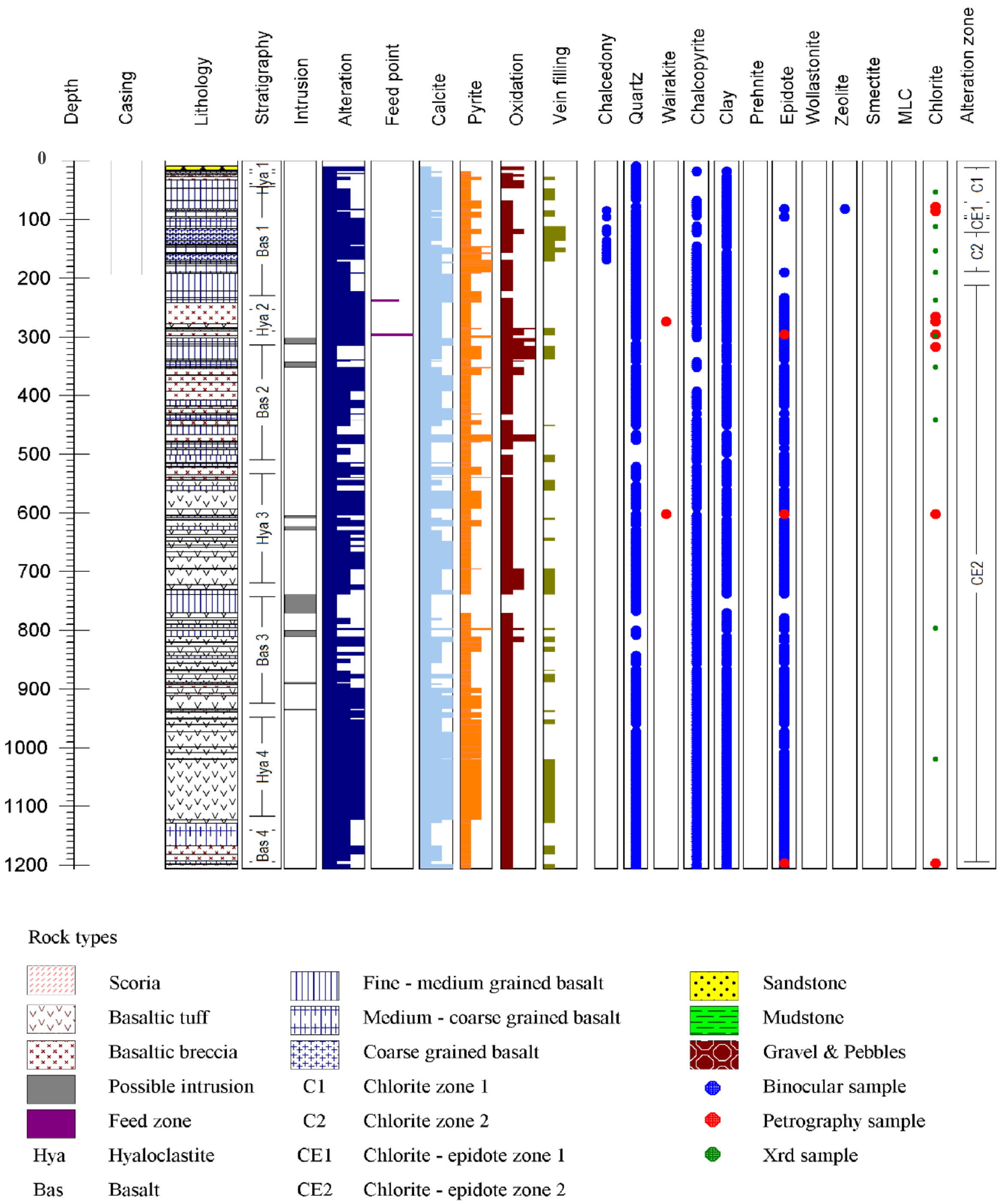
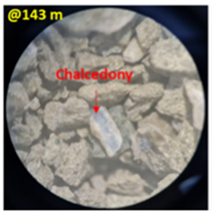
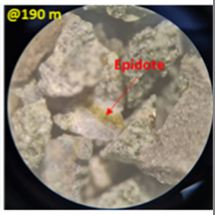
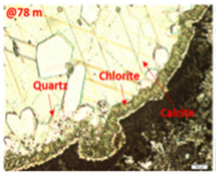
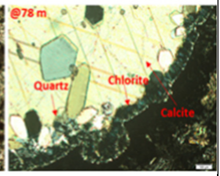
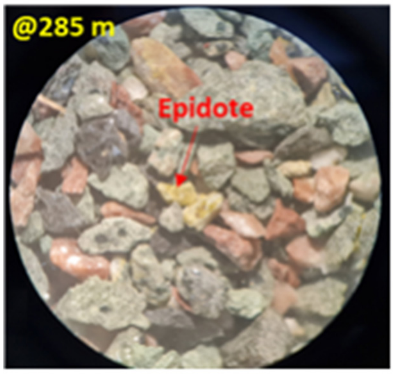
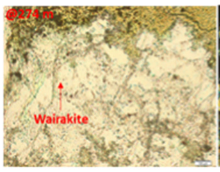
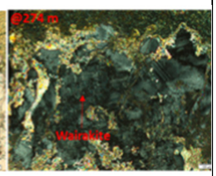
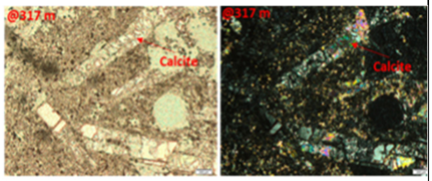
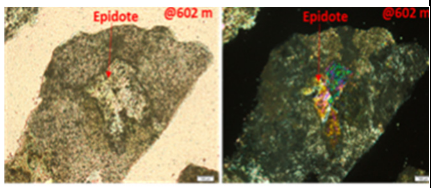
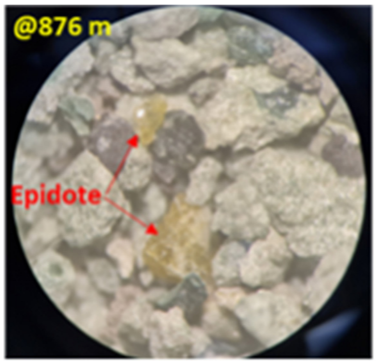
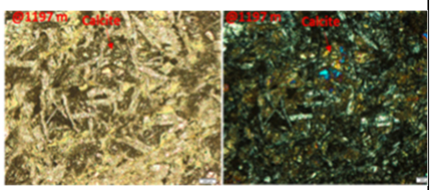


FIGURE 6: Lithological log of HV-05 with intrusions, feed points and alteration minerals and alteration zones

TABLE 2. The simplified stratigraphy of well HV-05

No	Stratigraphy	Description		XRD	Photo
		Binocular	Petrography		
1	Surface rock (0 – 27 m)	Dominant of sandstone and mudstone.			
2	Hyaloclastite 1 (27 – 33 m)	Basaltic breccia, low – medium altered.			
3	Basalt 1 (33 – 242 m)	Fine – medium grained basalt, medium – coarse grained basalt, coarse grained basalt. Medium – highly altered, high content clay alteration, pyrite and calcite. Secondary minerals consist of epidote, chalcedony, pyrite, and dominant of calcite.	@78 m: basalt, Little glassy, high content of calcite, and a lot of vesicles were filled by chlorite. Plagioclase were replaced dominant by calcite. Secondary minerals: chlorite, calcite, quartz. Mineral Sequences: chlorite – calcite, chlorite – quartz – calcite, oxidation – calcite and chlorite. @86 m: basalt, crystalline, high content of plagioclase altered. There are veins and vesicles with little – medium fractures. Some of plagioclase and pyroxene were replaced by calcite. Secondary minerals: chlorite, calcite, quartz. Mineral sequences: chlorite – calcite and quartz	@ 53 m: chlorite @ 112 m: chlorite @ 153 m: chlorite @ 190 m: chlorite @ 237 m: chlorite	   
4	Hyaloclastite 2 (242 – 302 m)	Basaltic breccia and basaltic tuff, highly altered, and common epidote	@265 m: basaltic breccia, Glassy, high content of calcite. A lot of vesicles were filled by chlorite – calcite. Secondary minerals: chlorite, calcite, quartz. Mineral sequence: chlorite – calcite. @274 m: basalt, crystalline, high content of plagioclase altered and calcite. There are several veins. Secondary minerals: chlorite, calcite, quartz, wairakite. Mineral sequences: chlorite – calcite and quartz. @296 m: basaltic breccia, high content of calcite. Little veins and vesicles. Secondary minerals: chlorite, calcite, quartz, epidote. Mineral sequence: chlorite – calcite.	@ 298 m: chlorite	  

5	Basalt 2 (302 – 521 m)	Dominant of fine – medium grained basalt, medium – coarse grained basalt and minor basaltic breccia. Medium – highly altered, high content clay alteration, some of depth abundant epidote, rare vein and vesicles	@ 317 m: basalt, crystalline, high content plagioclase altered. Little veins and vesicles. Veins were filled by calcite. Secondary minerals: chlorite, calcite, quartz. Mineral sequence: chlorite – calcite	@ 351 m: chlorite @ 441 m: chlorite	
6	Hyaloclastite 3 (521 – 731 m)	Basaltic breccia and basaltic tuff, medium – highly altered, high content clay alteration and calcite, some of depth abundant epidote, veins and vesicles were filled by calcite and epidote.	@ 602 m: basaltic tuff, High content of calcite. Little vesicles. No vein. Secondary minerals: chlorite, calcite, quartz, epidote, opaq, wairakite. Mineral sequences: chlorite – calcite, chlorite – quartz.		
7	Basalt 3 (731 – 936 m)	Fine – medium grained basalt although at some of depth were found basaltic tuff.Low – medium altered at crystalline rock and medium – high altered at basaltic tuff. Some of depth consist of abundant epidote.		@ 796 m: chlorite	
8	Hyaloclastite 4 (936 – 1129 m)	Basaltic breccia and basaltic tuff, highly altered. High content of clay alteration, calcite, epidote, and chalcopyrite.		@ 1019 m: chlorite	
9	Basalt 4 (1129 – 1206 m)	Dominant medium – coarse grained basalt although at some of depth were found basaltic breccia. Low altered at crystalline rock and medium – high altered at basaltic tuff. Some of depth consist of abundant calcite.	@ 1197 m: basaltic, glassy and crystalline. High content of chlorite and calcite. Some veins were filled by calcite and quartz. Secondary minerals: chlorite, calcite, quartz, epidote, opaq.		

4.1.2 Hydrothermal alteration of well HV-05

It is important to know the hydrothermal alteration of the rocks in a geothermal system. It can be used to identify the characteristics of the reservoir and the evolution of the geothermal system (Thompson and Thompson, 1996).

Hydrothermal alteration in well HV-05 indicates water rock interaction between the geothermal fluid and the rock in the vicinity of the well. The secondary minerals were identified using binocular and petrographic microscopes as well as X-ray diffractometry (XRD) analysis. Different hydrothermal alteration processes can be observed in this well such as deposition and replacing of primary minerals. Some secondary minerals fill vesicles and veins.

By comparing the results of binocular and petrographic analysis as well as X-ray diffractometry (XRD), six alteration zones were defined in HV-05. The alteration zones are Chlorite zone 1, Chlorite – Epidote zone 1, Chlorite zone 2, and Chlorite – Epidote zone 2.

Chlorite zone 1 is from surface to 82 m. This zone was defined based on findings of chlorite in the binocular, petrography and XRD analysis. This zone has a high content of calcite and most vesicles are filled with chlorite.

Chlorite – Epidote zone 1 is from 82 to 110 m. This zone was defined based on findings of chlorite and epidote in the binocular, petrography and XRD analysis. First trace epidote was found at 82 m. This zone is composed of basalt and hyaloclastite rock. It is characterized by a high content of altered plagioclase and calcite found in the petrographic analysis.

Chlorite zone 2 is from 110 to 200 m. This zone was defined based on findings of chlorite in the binocular, petrography and XRD analysis (Figure 7). This zone is composed mainly of hyaloclastite rock. It is highly altered and has a high content of chlorite.

Chlorite – Epidote zone 2 is from 200 to 1206 m. This zone was defined based on findings of chlorite and epidote in the binocular, petrography and XRD analysis. This zone is composed of hyaloclastites and basalts. It is medium – highly altered and has a high content of chlorite and epidote.

Generally, all cutting samples from well HV-05 show a high content of calcite and chlorite from top to the bottom of the well. Epidote was found in several depths. This mineral indicates temperatures of about 240°C at the time of forming (Reyes, 2000). Calcite has overprinted almost all primary minerals in this well (Figure 8).

This condition indicates cooling in the Hveragerdi geothermal system since the time when it was highly active in the rifting belt. This is supported by temperature measurements in well HV-05 where the maximum temperature is only 190°C.

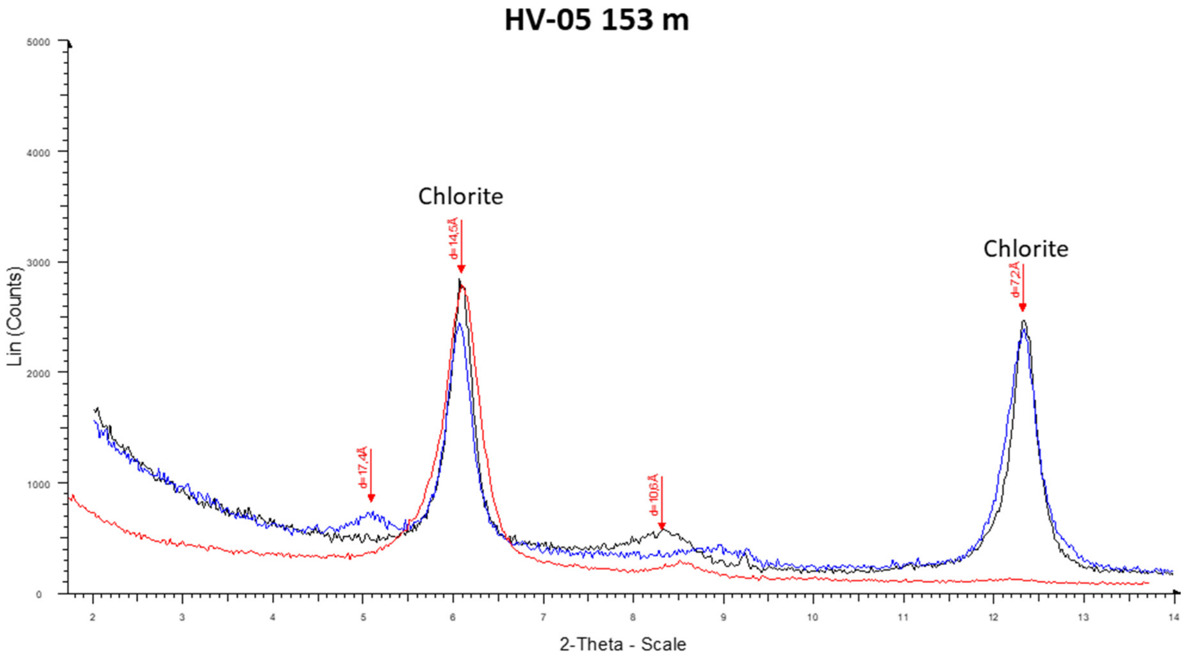


FIGURE 7: A sample from 153 m depth in HV-05 shows a typical signature of chlorite in the XRD analysis with peaks around 14 and 7 Å (angström)

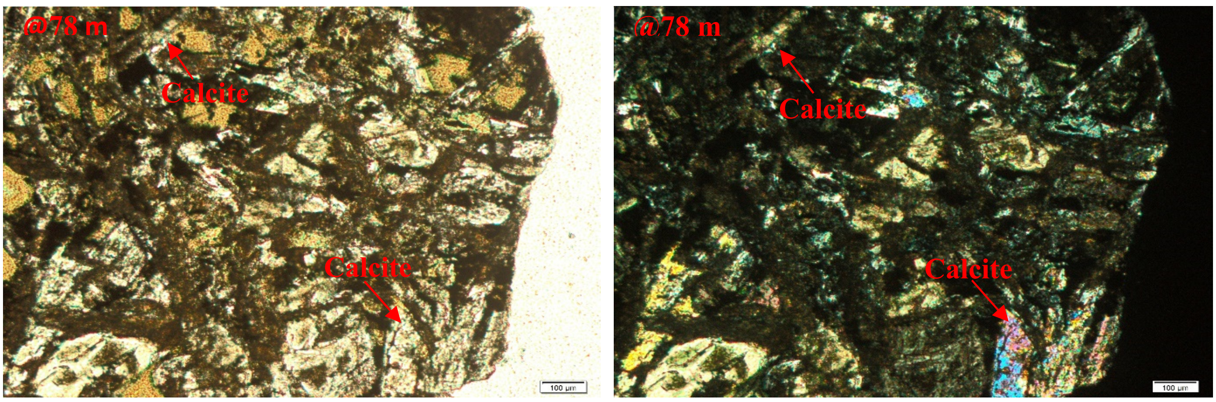


FIGURE 8: Thin section from 78 m depth in HV-05. Primary minerals such as plagioclase and pyroxene are replaced by calcite. The pictures are shown in plane polarized light (left) and in crossed polarized lights (right)

4.1.3 Wireline logs

Various log data from Well HV-05 are available such as caliper, gamma, televiewer, resistivity, neutron – neutron, cement bound log and temperature log. Due to restrictions in the well at 374 m, almost no logging tools were able to pass beyond this depth. The well logs can therefore not be used to support the geological analysis in the deeper parts of the well.

The resistivity log increases dramatically at around 300 m, possibly caused by an intrusive rock at this depth. This is supported by neutron – neutron and gamma logs which also show an increase in value compared to previous depths (Figure 9). A small peak in the resistivity log at around 230 m might be caused by basaltic rock at this depth.

4.1.4 Intrusive Rocks

Intrusive rocks in well HV-05 are identified by using binocular and petrographic microscopes together with multiple wireline logs in the upper part of the well. There are several depths where intrusive rocks might be present in this well. The existence of intrusive rocks at depth 302 – 312 m was supported by wireline logs data (Figure 9). Based on the binocular analysis, the possible intrusive basalt is dark grey and reddish, medium - hard, fine - medium grained, with low - medium alteration where oxidation, calcite, and epidote are noted.

The log in Figure 9 and Table 3 summarizes the possible occurrences of intrusion rocks in the well. Based on the result of the petrography analysis, there is no indication of intrusion rock at 317 m depth because at this depth a lot of vesicles were found.

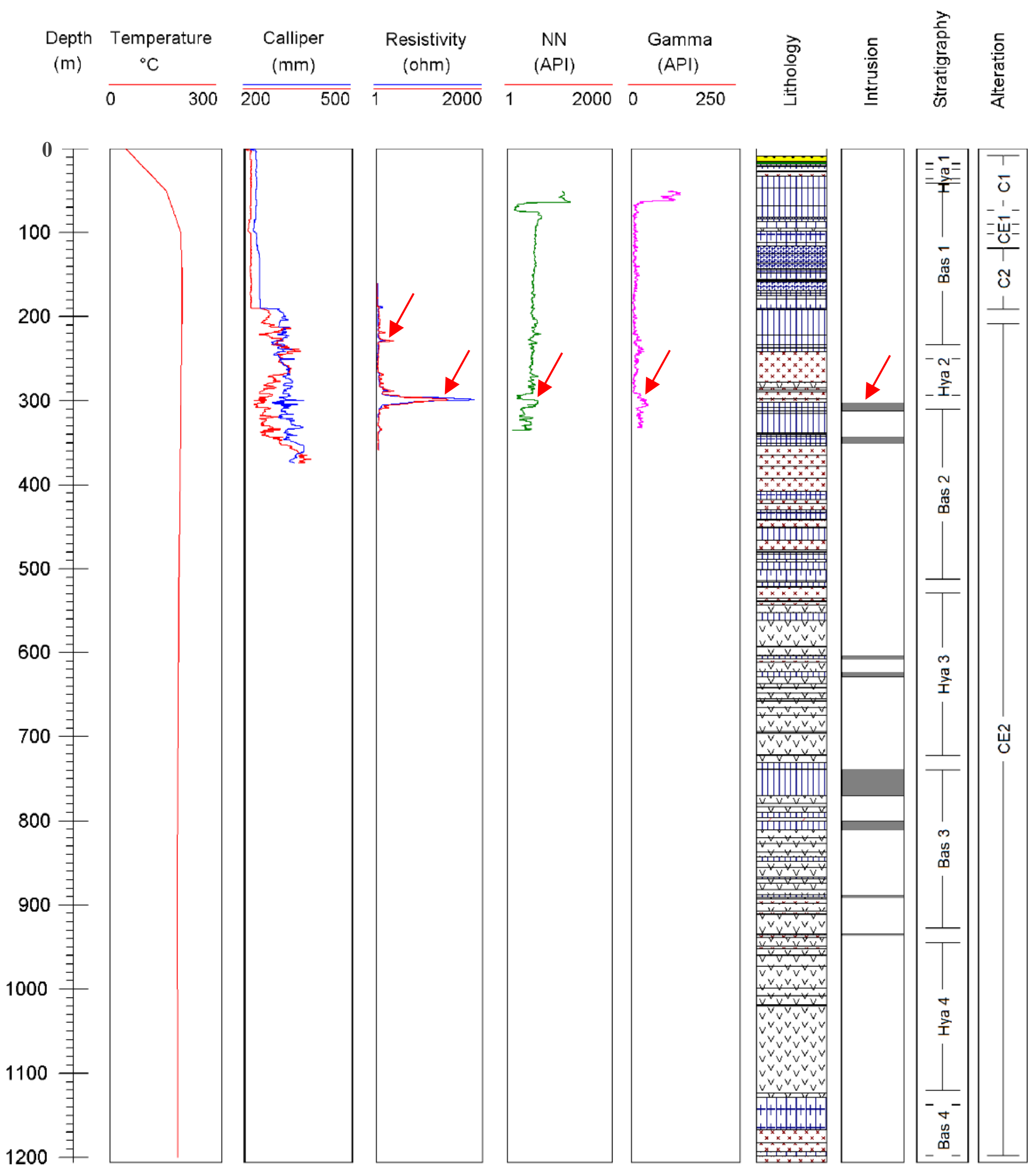


FIGURE 9: Lithology and wireline logs in well HV-05. Wireline logs and borehole geology data indicate intrusive rocks at around 302 - 312 m depth

TABLE 3: Summary of intrusion rocks in well HV-05

Top (m)	Bottom (m)	Evidence	Remarks
302	312	Resistivity log increase dramatically, gamma and neutron - neutron increase	Dark grey and reddish, medium - hard hardness, fine - medium grained, low - medium altered become oxidation, calcite, and epidote
343	351		Slightly black, hard hardness, medium - coarse grained, relatively fresh, some primary minerals as plagioclase and pyroxene
604	608		Dark grey - slightly black, medium - hard hardness, fine - medium grained, low altered - relatively fresh become calcite, chalcopyrite, clay
623	629		Dark grey - slightly black, medium - hard hardness, fine - medium grained, low altered become clay, calcite, chalcopyrite, epidote
739	770		Dark grey - slightly black, hard hardness, fine - medium grained, low altered - relatively fresh
800	811		Dark grey - slightly black, hard hardness, fine - medium grained, low altered - relatively fresh
888	891		Dark grey - slightly black, medium - hard hardness, fine - medium grained, low altered - relatively fresh become clay, calcite, chalcopyrite, pyrite, epidote
934	936		Dark grey - slightly black, medium - hard hardness, fine - medium grained, low altered - relatively fresh become clay, calcite, chalcopyrite, epidote, oxidation

4.2 Aquifers

Aquifers or feed zones are important for geothermal utilization because they function as fluid pathways. Geothermal fluid can be found in aquifers in the subsurface and is connected to faults and fractures in the sub-surface or positioned between formations. Location of aquifers can be determined by the interpretation of cuttings and wireline logs data.

The two main aquifers in well HV-05 are located at 236 - 240 meters depth, which is estimated to produce 38% of the permeability in the well, and at 294.5 – 298.5 meters depth which contributes 62% of the permeability. The feed zones in the well were identified using temperature, spinner, and borehole televiewer data. Interpretation of the televiewer log shows visible fractures with high and low confidence at 293 – 300 meters depth (Jónsson et. al, 2021). The main aquifer is located within a highly altered basaltic breccia and high permeability is confirmed by high contents of pyrite and calcite. Epidote is found in relation with the aquifer. Location of aquifers in well HV-05 are shown in Figures 10 and 11.

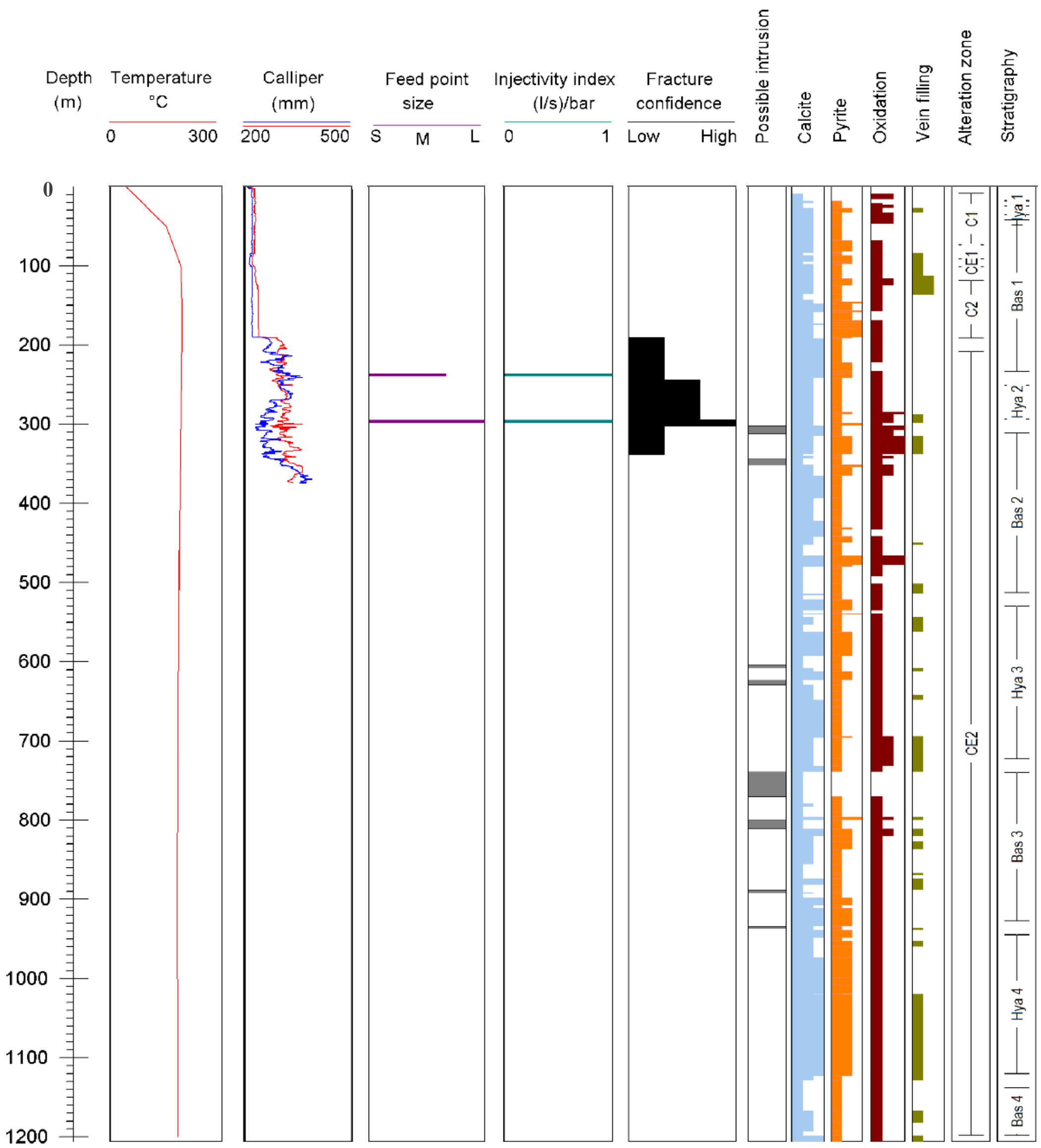


FIGURE 10: Log integration of well HV-05 interval 0 – 1206 m

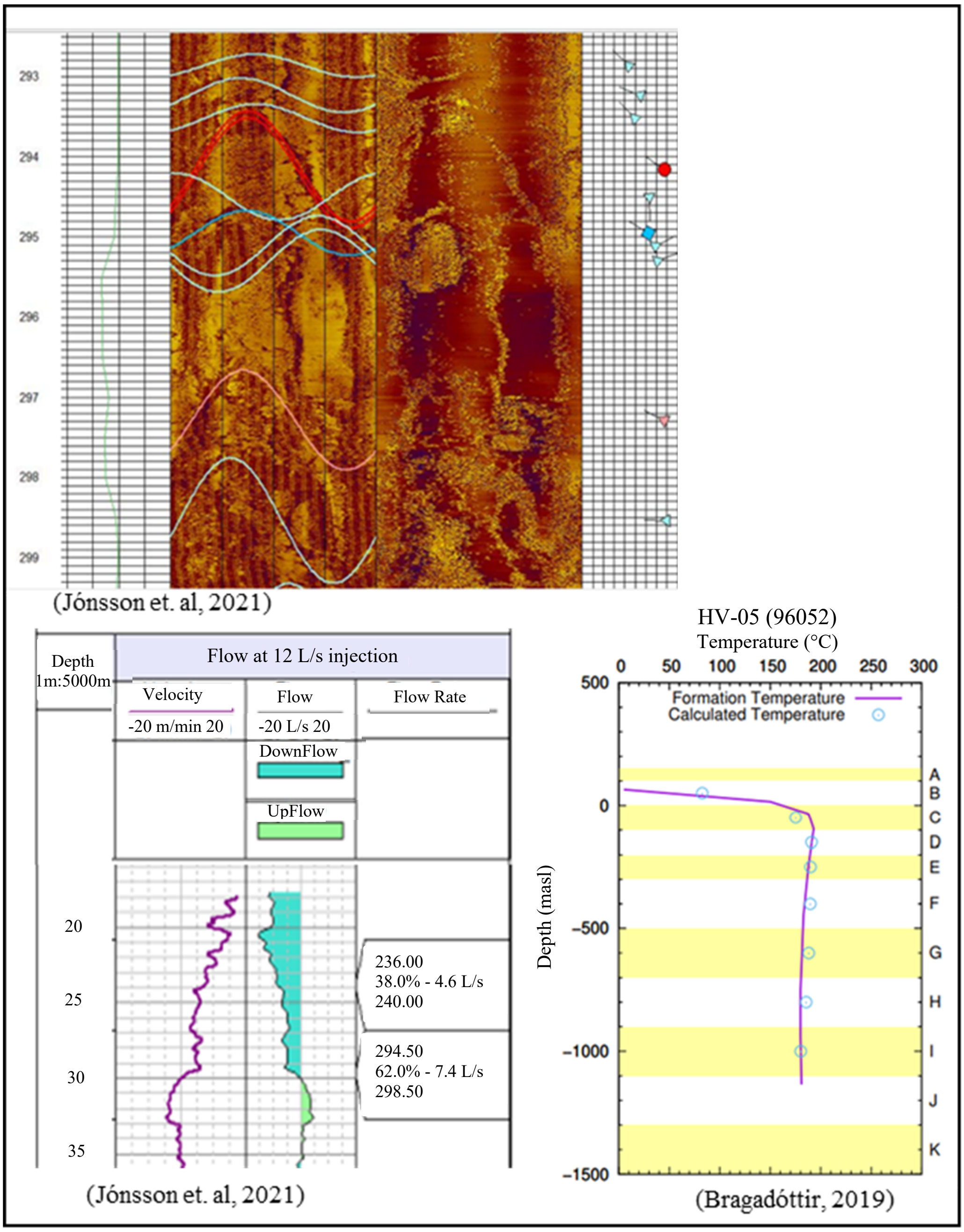


FIGURE 11: Borehole televiewer, temperature and spinner data indicate main feed zone in well HV-05

4.3 Geological Model of Hveragerdi

4.3.1 Datasets used for geological modelling

Various data sets have been used to build a geological model of the Hveragerdi geothermal field. When the well was drilled in 1960, the quality and availability of data was not great but additional work has been done since. The data have been compiled from published papers as well as from the internal database from the Iceland Geosurvey (ISOR) and from the GECO project.

4.3.2 Construction of a geological model of Hveragerdi geothermal field

A geological model of the Hveragerdi geothermal field was built from borehole geological data, wireline logs and some additional data from the Hveragerdi geothermal field. The software Leapfrog from the company Seequent was used to build the geological model. All data for geological modelling such as topography, location of wells, structural data on surface, lithology of wells (Figure 12), and depth of first epidote from several wells in Hveragerdi that have been included in the model are listed in Table 4. An alteration model could not be built due to lack off alteration data from others geothermal wells within the Hveragerdi geothermal field.

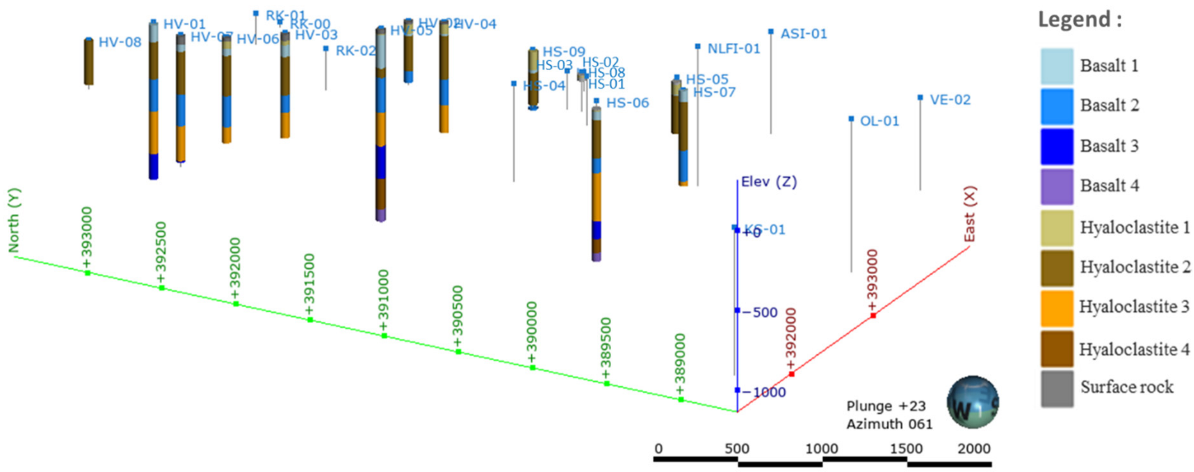


FIGURE 12: Lithology group in well HV-05

A structural geological model is needed to build a geological model. The geological structure is a very important part of a geological model because it can be used to identify permeable zones. The geological structures in Hveragerdi geothermal field are controlled by a fault system with N-S and NE-SW directions (Khodayar and Björnsson, 2010) (Figure 13). The location of the faults is related to the location of geothermal surface manifestations. These faults possibly have good permeability.

A geological model has been built of the Hveragerdi geothermal field based on borehole geological data and surface data (Figure 14). The lithology in the field is mainly composed of basalt and hyaloclastite. The layers of basalt and hyaloclastite are relatively horizontal in the Hveragerdi geothermal field. The geological structure showed two fault zones with N-S and NE-SW orientations.

Temperature data is important to identify geothermal resources in a geothermal field. The best available temperature data are direct temperature measurement from wells. These measurements have been used to build a temperature model of the Hveragerdi geothermal field. The temperature model shows that the reservoir temperature increases to the northern part and decreases to the southern part of the Hveragerdi geothermal field (Figure 15). The maximum temperature of well HV-05 is about 190°C. Well HV-05 is located at the centre of the Hveragerdi geothermal field.

The conceptual model indicates an upflow zone located at the northern part and an outflow zone in the southern part of the Hveragerdi geothermal field (Figure 16). The location of the upflow zone is related to the location of a deep heat source around Hveragerdi extinct volcano. Temperature measurement from 6 wells in the northern part showed higher temperature than those from wells in the middle and southern part of this field. Well HV-05 data indicates a temperature maximum of approximately 190°C. A reservoir temperature of approximately 150°C was found at shallow depth in the middle and southern part of this field. The reservoir in this field is composed of basaltic and hyaloclastite rocks with medium - high intensity of alteration. Fractures/faults zone with high permeability are oriented in NE-SW and N-S directions. The recharge area is possibly located at high elevation in the northern part and at low elevation in the southern part of the field.

TABLE 4: Data for geological modelling

Data type	Data	Descriptions	Sources
Surface data	Topography	in image map	Database ISOR
	Geological map	in image map	Database ISOR
	Location of surface manifestations	in image map	Ívarsson, G. Á., Sigurðardóttir, Kristinsdóttir, B. E., Þrastarson, Ö. S., Gretarsson, and Þorsteinsson, Þ., 2011: *Yfirborðsjarðhiti á Hengilssvæðinu IV [Surface geothermal heat in the Hengill area]*. Orkuveita Reykjavíkur, 34 pp.
	Geological structure map	in image map	Khodayar, M., and Björnsson, S., 2010: *Surface deformation of May 29, 2008 earthquake near Hveragerdi, South Iceland Seismic Zone and Hengill geothermal area.* Icelandic Geosurvey, prepared for Bergsprungur Project, Tech. Rep. 540102.
	Well locations	in excel file	Data base ISOR
	Collar	in excel file	Data base ISOR
	Chemistry data	in image table	Saemundsson K., and Arnórsson, S., 1971: *Greinargerð um borholu ASÍ 1 hjá Ölfusborgum í Ölfusi [A report on well ASÍ 1 at Ölfusborgin in Ölfus]*. Orkustofnun, Tech. Rep., 1971.
Subsurface data	Drill cutting of well HV-05	drill cuttings	Database ISOR
	Petrography of well HV-05	thin sections	Database ISOR
	XRD of well HV-05	in word file	Database ISOR
	Depth of feed zone well HV-05	in excel file	Database ISOR
	TEM resistivity map	Image map	Eysteinsson, H., 2000: *TEM-viðnámsmælingar í Grændal [TEM resistivity measurements in Grændalur]*. Orkustofnun, Tech. Rep. OS-2000/066.
	Lithology of wells	In excel file	Database ISOR
	Alterations of wells	In excel file	Database ISOR
	Well trajectory	Total Depth 1206 meters in excel file	Database ISOR
	Calliper log	Maximum depth 374 meters in excel file	Database ISOR
	Gamma log	Maximum depth 332 meters in excel file	Database ISOR
	Subsurface temperature log	Maximum depth 1200 meters in excel file	Database ISOR
	Spinner log	Maximum depth 380 meters in image	Database ISOR
	Neutron - neutron log	Maximum depth 335 meters in excel file	Database ISOR
	Resistivity log	Maximum depth 359 meters in excel file	Database ISOR
	Borehole televiewer	Depth 188-340 meters in image	Database ISOR
	Depth of production casing (220.5 mm)	casing shoe at 193 meters depth in excel file	Database ISOR

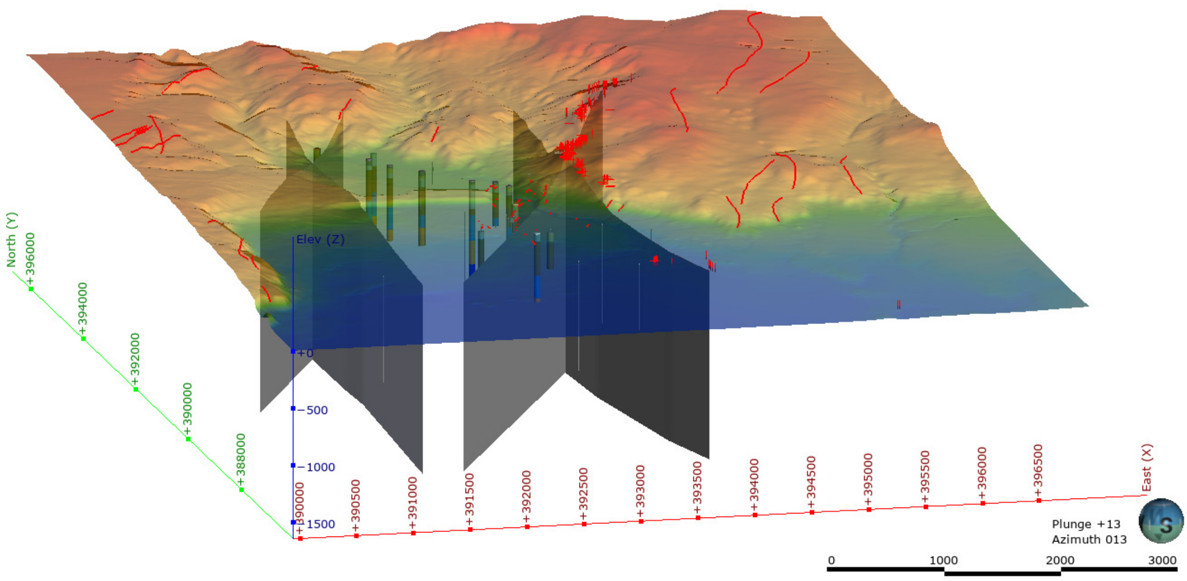


FIGURE 13: Geological structure in Hveragerði geothermal field including structural model and N-S and NE-SW faults. Red lines shows geological structure data on the surface from Khodayar and Björnsson (2010) and Helgadóttir (2019)

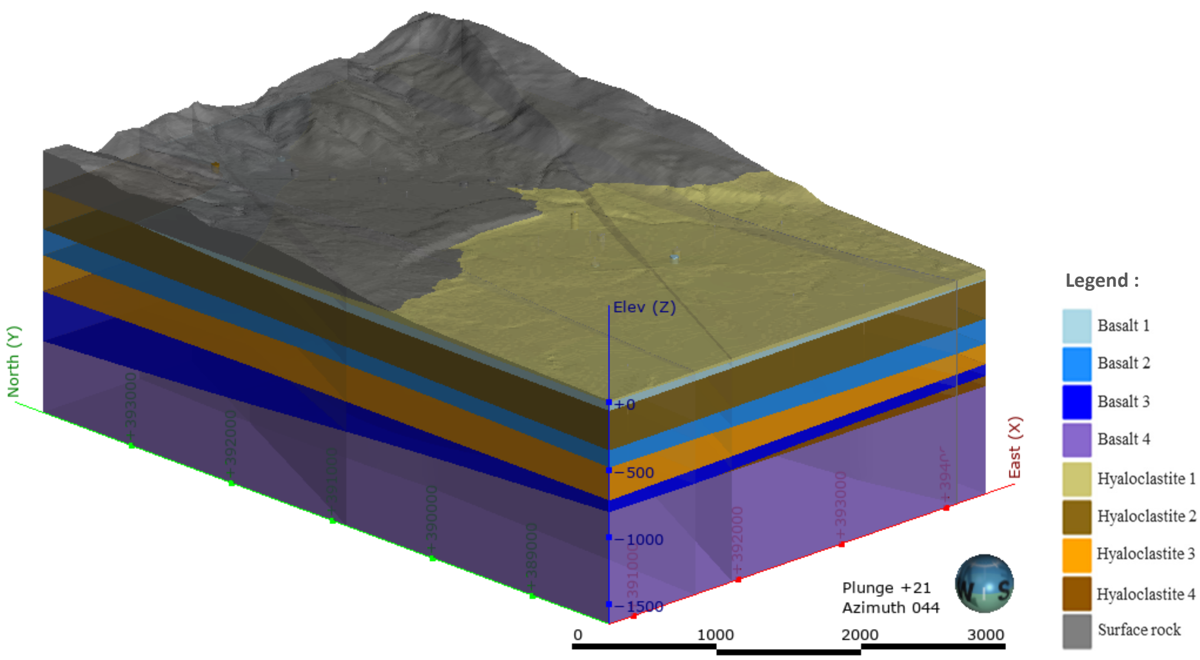


FIGURE 14: Geological model of Hveragerði geothermal field. Red lines on the surface shows geological structure data from Khodayar and Björnsson (2010) and Helgadóttir (2019)

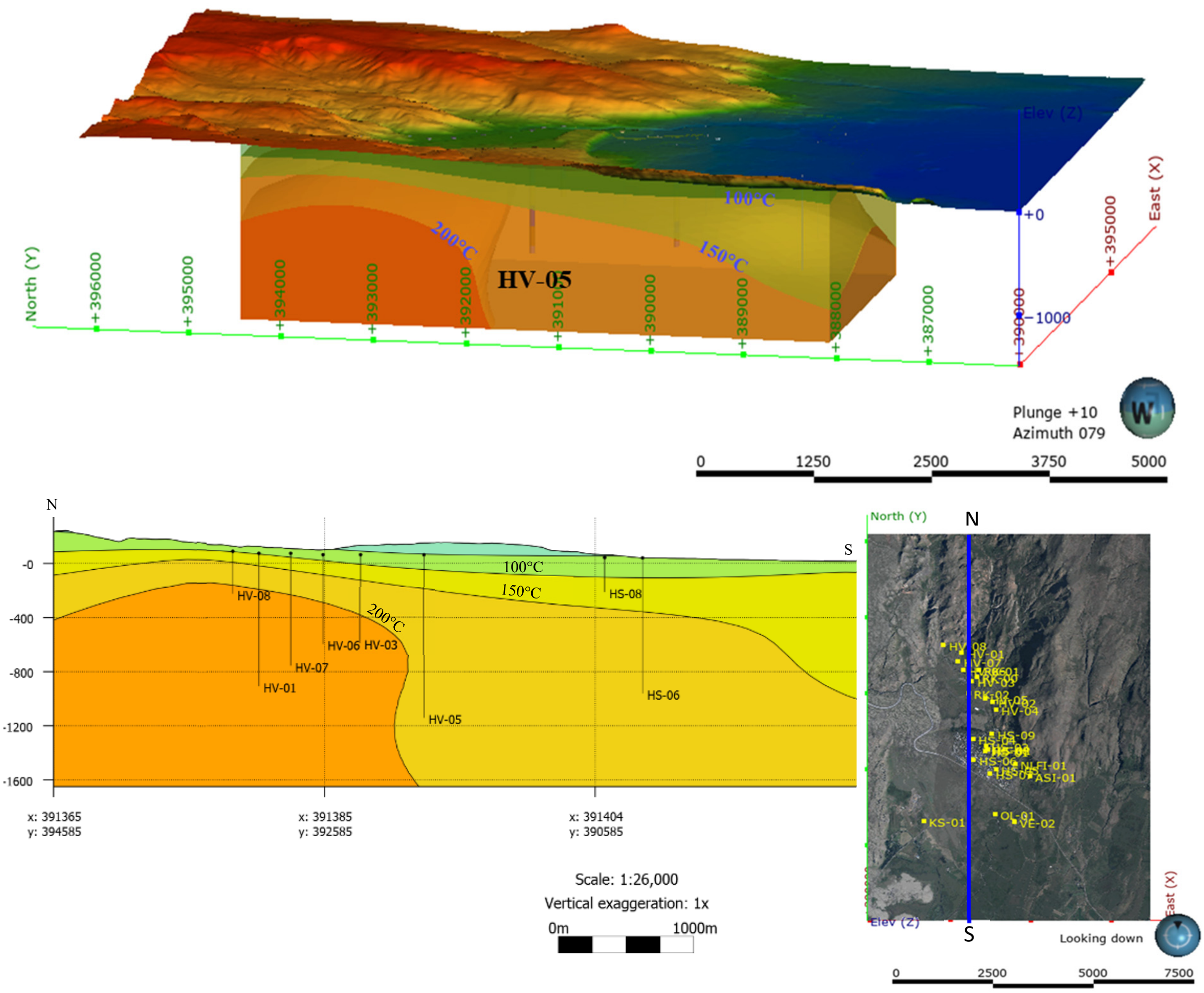


FIGURE 15: Temperature model of Hveragerði geothermal field

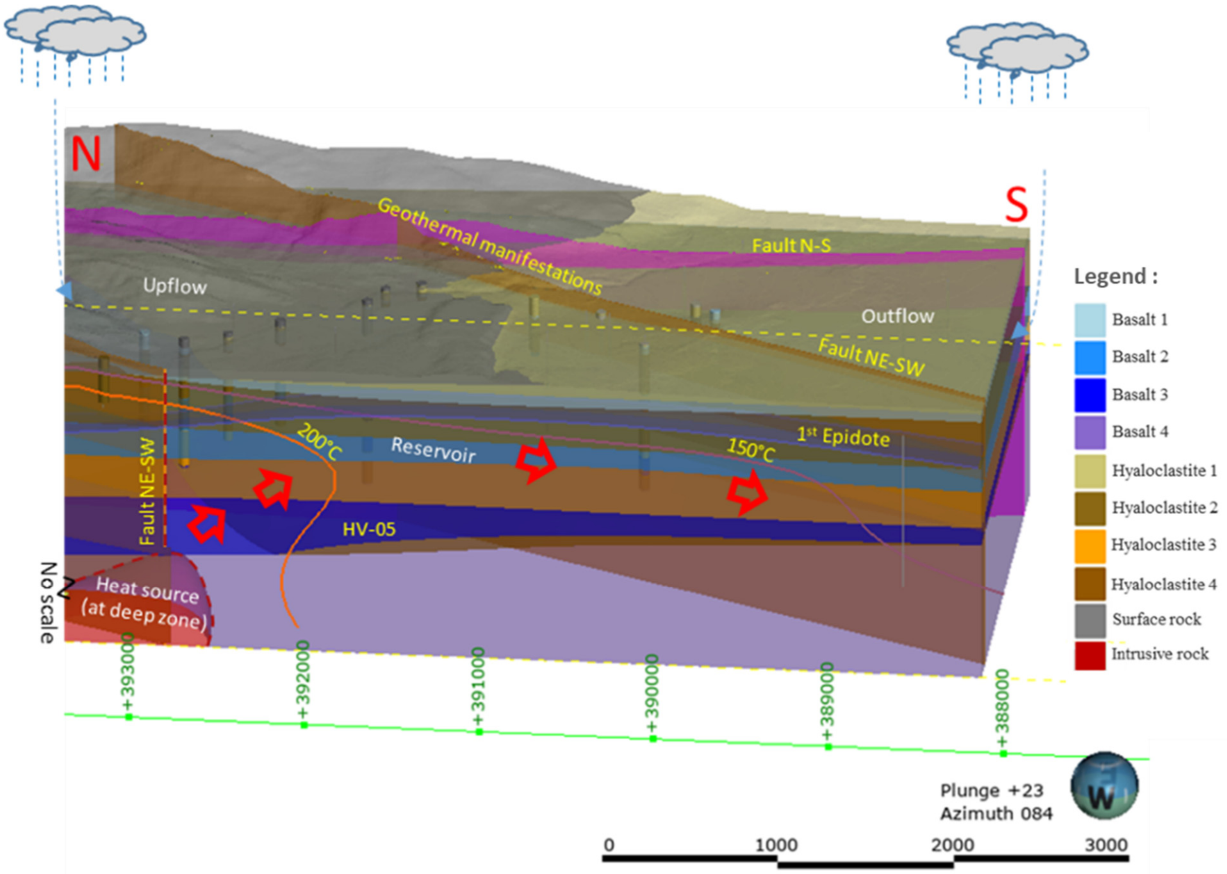


FIGURE 16: Conceptual model of Hveragerði geothermal field

5. DISCUSSION

5.1 Exploration and exploitation strategy of the Hveragerdi geothermal field

Hveragerdi town is located close to Hveragerdi geothermal field. The town has been utilizing geothermal fluid from the Hveragerdi geothermal field for district heating since the late 1920s. The population in Hveragerdi town will increase in the future. Therefore, additional heat energy will be needed to meet energy demand. The future demand could be supplied by geothermal energy from Hveragerdi geothermal field. The field will need further exploration to better understand the size of the geothermal reservoir. Further structural mapping and tracer testing is essential to better understand fluid flow in the reservoir. The size of the reservoir will best be determined by drilling carefully sited exploration wells. These exploration wells can be drilled as production and re-injection well.

A study of the carbon mineralization potential of the reservoir would also benefit from additional mapping and tracer testing. Injection of CO_2 into HV-05 and additional studies will reveal if further CO_2 injection can be applied, but the well should be adequate for CO_2 injection for mineralization.

5.1.1 Siting of production and re-injection wells

Geothermal wells are needed to gain a better understanding for the geothermal resources in the Hveragerdi geothermal field. In this paper there are two wells proposed. One well for production should be drilled in the upflow zone and one well for re-injection should be drilled south of the new production well. The production and re-injection well should be drilled as directional wells with total measured depth of 1500 m (m MD).

Based on borehole and geochemistry data, upflow zone is located in the northern part of the Hveragerdi geothermal field. The lithology in this area is composed of basalt variations and hyaloclastite. The permeability is controlled by faults with N-S and NE-SW directions. The heat source is predicted to be located around Grændalur area or the northern part of the Hveragerdi geothermal field.

Resistivity data from TEM measurements indicate that the top of the reservoir is shallower in the northern part than in the southern part. This pattern is supported by temperature measurements from wells in the Hveragerdi geothermal field. The temperature data from wells indicate increased temperature in the northern part of Hveragerdi. The temperature measurements in the northern part indicate more than 200°C.

Well data is available in this area such as production capacity and depth of feed zones (Bragadóttir, 2019). Wells located close to the upflow zone indicate good production capacity. Feed zones were found at around 90 m bsl – 659 m bsl (Figure 17).

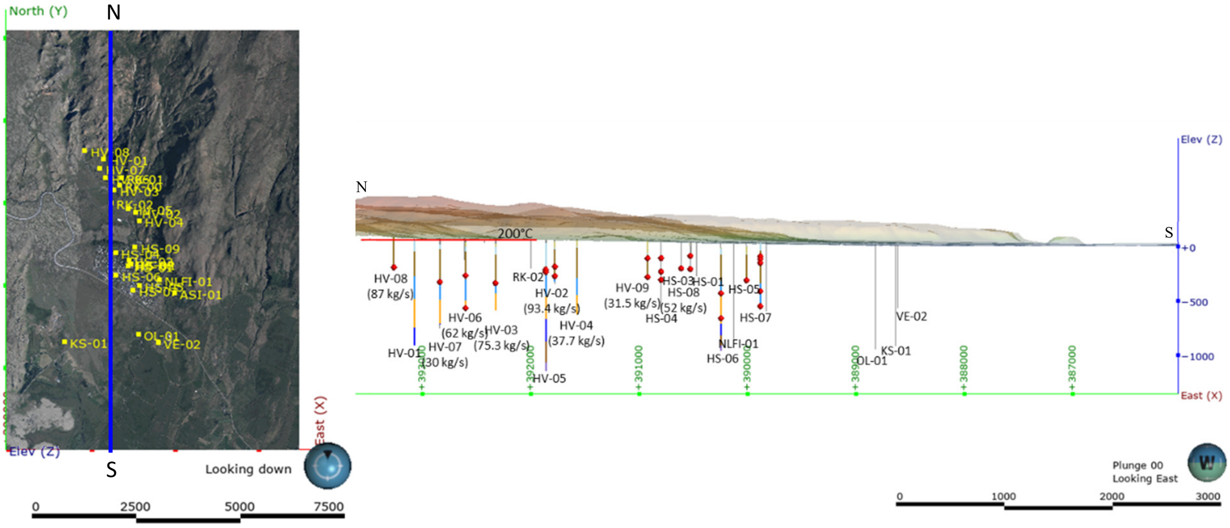


FIGURE 17: The map on the left side shows the location of geothermal wells in Hveragerði. The N-S section on the right side shows the production capacity of several geothermal wells in Hveragerdi

It is proposed to drill an exploration well HV-P1 for future production in the northern part of the Hveragerdi geothermal field. The well directionally drilled to N 295°E/15° with a total depth of 1500 m MD. According to the geological model, the well could intersect a high permeability zone when intersecting faults with directions NE-SW at 720 m MD and N-S at 775 m MD and the bottom temperature would be around 220°C. Based on data from well HV-08, the estimated production capacity from this well could be around 87 kg/s. Location of the feed zone is expected at 720 – 775 m MD (Figure 18). According to the geological model, lithology in this well will be composed mainly of basalt and in some depth ranges, of hyaloclastite. There is no indication that swelling clay or high H_2S gas is to be expected in this well (based on data from well HV-05) and therefore no indication that this will create significant problems during the drilling of this well. The distance between new and existing production well should be kept minimal (around 225 m) to avoid interference among them. Surface conditions around the well pad are relatively flat terrain, far from community, with a good access road and close to river for water supply during the drilling of this well. If production well HV-P1 is successful, further development around this well is possible.

The re-injection well HV-R1 should be drilled south of the new production well. The well will be drilled as a directional well with direction N260°E/15° and a total depth of 1500 m MD. The well would encounter a high permeability zone in around 925 m MD when it intersects the N – S fault which is located close to the re-injection well pad. The distance between production well and re-injection well would be about 1500 m. That would minimize thermal breakthrough from re-injection fluid to reservoir fluid. The lithology was predicted to be mainly composed of basalt and hyaloclastite with varying degrees of alteration. There is no indication of significant problems during the drilling of this well. The reservoir temperature was predicted to be less than 180°C.

This re-injection well would be located at a lower elevation than the production well to minimize pump cost to deliver brine from the production well to the re-injection well. Brine from the production well would flow to the re-injection well driven by gravity. The location of the re-injection well pad is in relatively flat terrain, close to the river for water supply during drilling and with a good access road (Figure 18). The present understanding is the flow from the north towards to the south. That could change if the results of tracer tests indicate otherwise.

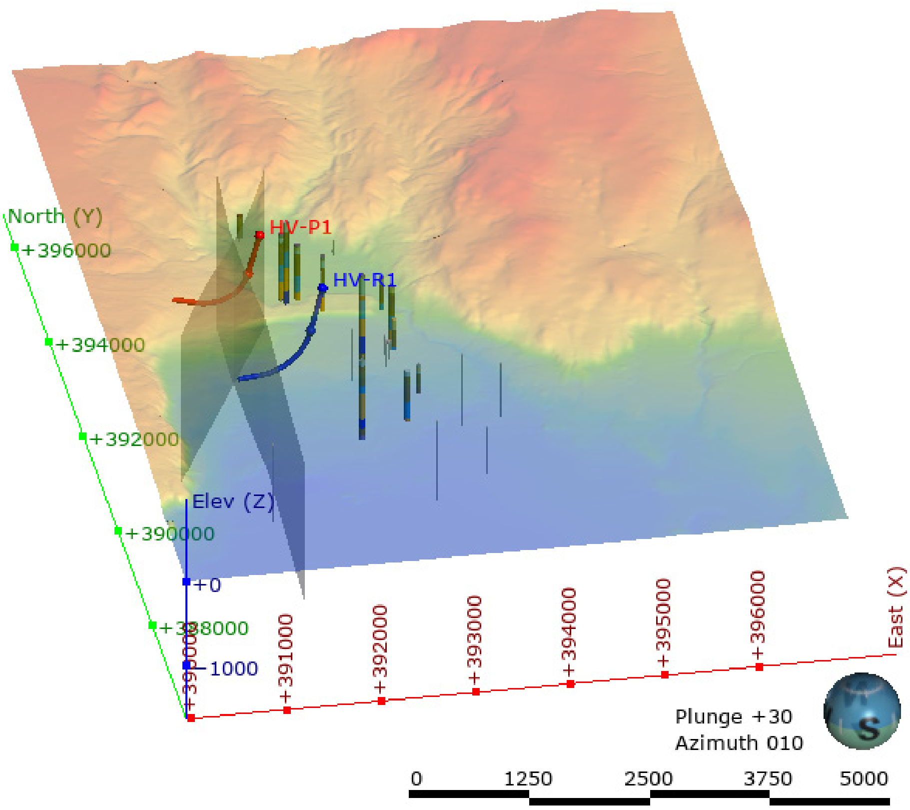


FIGURE 18: The HV-P1 production well would encounter a high permeability zone consisting of NE-SW and N-S faults, while the HV-R1 re-injection well would encounter a high permeability zone caused by a N-S fault

5.2 The potential of carbon mineralization within the Hveragerdi geothermal field

Carbon Capture Storage (CCS) is one of the most effective and successful methods to reduce atmospheric CO_2 and achieve the goals of the Paris Agreement to limit anthropogenic warming to 1.5-2°C (Peters et al. 2013; Knutti et al. 2016; Rogelj et al. 2016). Carbon mineralization as one of the CCS methods has successfully been applied at the Hellisheiði Geothermal Field using the CarbFix methodology (Sigfússon et al, 2018). Here, the CO_2 that is produced during the geothermal utilization is stored in the subsurface using the CarbFix method. Favorable rock formations, water and a source of

CO_2 are needed to apply the CarbFix method. By dissolving CO_2 in water, the water becomes acidic. When it is injected into the subsurface it will react with the rock formation, dissolving it and releasing cations. These cations (Fe, Ca, and Mg) will react with the CO_2 and subsequently form carbonates in empty voids and fractures of the rock. Basaltic rock is the most suitable rock for the application of this method because this rock contains high amounts of Fe, Ca, and Mg.

Within the H2020 programme, the GECO project works on advancing the techniques of carbon sequestration developed within the Carbfix project. In this method the CO_2 gas is captured, mixed with fresh water and subsequently injected into the basaltic subsurface where it mineralizes in the form of carbonate. Several geothermal sites in Iceland and continental Europe, such as Nesjavellir (Iceland) and Kisildere (Turkey) have been studied and used as demo sites for the GECO project. The objective of the project is to store the carbon dioxide permanently in the subsurface in a cost-effective way.

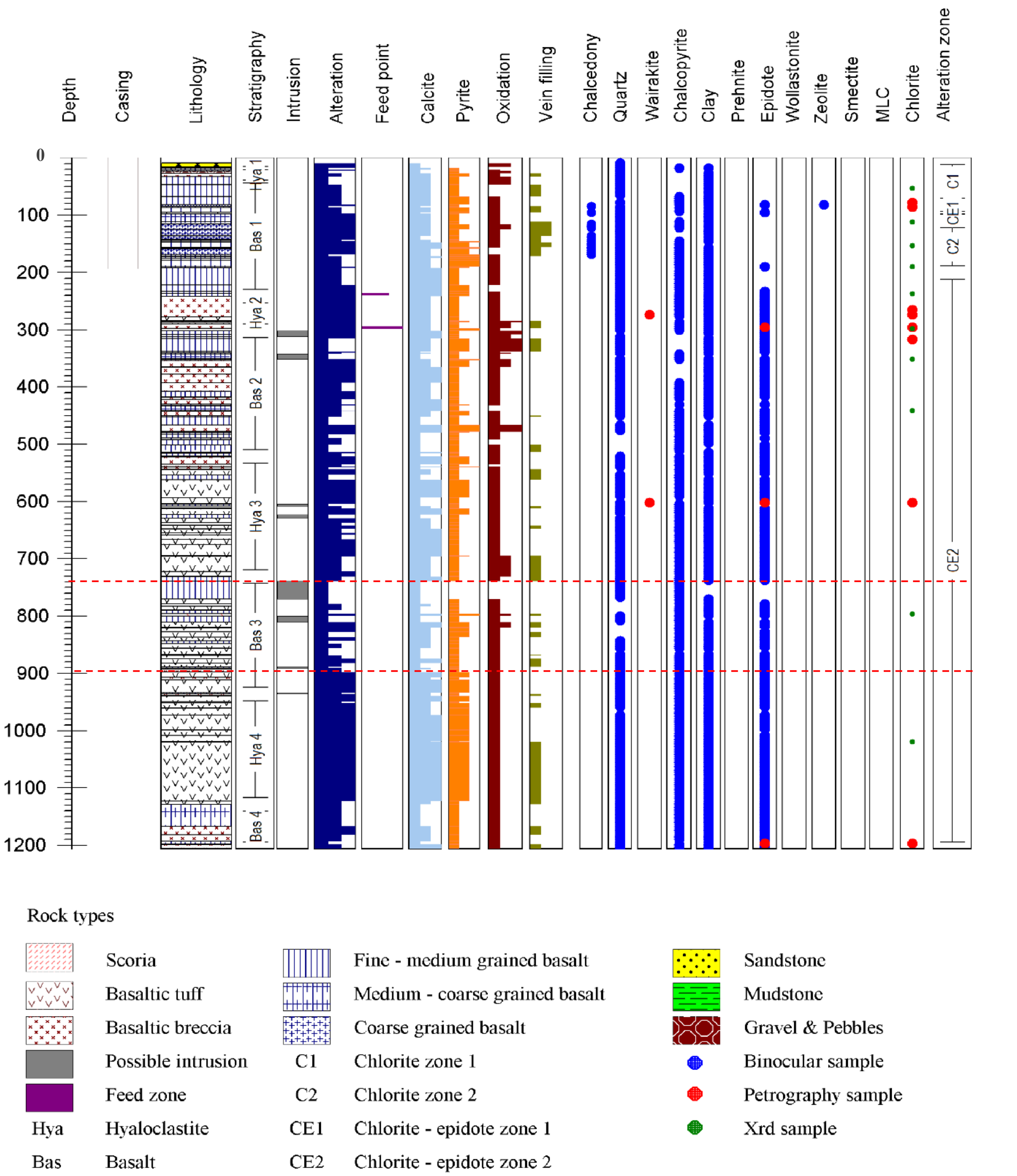


FIGURE 19: Low altered basalt at around 800 meters depth in well HV-05 can be used for CCS

Well HV-05 in Hveragerdi geothermal field has been studied using all available data. A favorable rock type, temperature, a water source and CO_2 from production wells promote the usage of the well for CCS using the CarbFix method. Low altered basalt at around 800 m depth with several veins is a possible for target injection zone (Figure 19). The temperature in this zone is around 180°C. This temperature is suitable for CCS. In addition, the shallow feed zones (~250-300 m) could also be targeted. There is plenty of water nearby, e.g., from river or brine from well HV-05. A source of CO_2 are the production wells in Hveragerdi geothermal field. As the CO_2 from nearby production wells is low, additional CO_2 could possibly be injected.

Before well HV-05 can be used for CCS, additional surveys should be carried out such as tracer injection tests, borehole televiewer measurements, and spinner data measurements down to the total depth of the well to identify deep permeability zones. A tracer injection test is needed not only for CCS but also for field management in the future.

6. CONCLUSIONS

There are several conclusions from this research:

1. Reservoir temperature has cooled from its maximum temperature as indicated by comparison of alteration minerals and temperature measurements in well HV-05.

2. A simple geological modelling of the Hveragerdi geothermal field has been established. The model shows relatively horizontal layers of basalt and hyaloclastite. The reservoir flow is likely governed by structures. Major structures have been identified and incorporated into the model. The flow could be better determined with tracer tests.

3. Hveragerdi geothermal field has the potential to produce more hot water. A target for a production well has been identified in the upflow zone in the northern part of the field. A re-injection well has been proposed south of the production area.

4. A preliminary study of HV-05 shows that it has the potential to be used for carbon sequestration using the CarbFix method. For a better understanding of the interaction of HV-05 with the reservoir a tracer injection test would be advised. Also, if cooling of the well is feasible, borehole televiewer and spinner data of the whole well would be very beneficial to identify deep permeability zones and for the modelling of the well. Finally, modelling of the fluid and rock interaction is crucial to be able to estimate the CO_2 carbonatization potential.

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