Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Geology and Hydrothermal Alteration of the Hverahlid HT-System, SW-Iceland

Steinþór Níelsson and Hjalti Franzson

ISOR Iceland GeoSurvey. 9 Grensásvegur. 108 Reykjavik, Iceland

steinthor.nielsson@isor.is , hf@isor.is

Keywords: Hengill, Hverahlid, geothermal system, geology, hydrothermal alteration, geothermal model.

ABSTRACT

The Hverahlid high-temperature system is located in the southern sector of the Hengill central volcano in SW-Iceland. Reykjavik Energy has today drilled three exploration wells into the geothermal reservoir in order to study its potential for electrical production. The 2000-2800 m deep wells that show a high-temperature system of 200°C -320°C below 600 m-1000 m depth. Lava successions dominate the strata with less hyaloclastite formations. Hydrothermal alteration ranges from totally fresh rocks in the overlying cold groundwater system through zeolite assemblage and into high-temperature mineral assemblage including chlorite, epidote, wollastonite and actinolite.

1. INTRODUCTION

The main emphasis of Reykjavik Energy is to supply geothermal waters for space heating for Reykjavik and in later years cogeneration of electricity for the town and companies. Iceland GeoSurvey has supplied a significant part of the exploration work for Reykjavik Energy.

The Hverahlid high-temperature field is a part of the 110 km^2 Hengill low resistivity anomaly (Franzson et. al, 2010). The field is situated in the southern sector of the Hengill central volcano in SW-Iceland. Today three exploration wells have been drilled in the Hverahlid high-temperature system where two out of three are deviated and all designed as production wells. The depth range of the wells is from 2000 m down to 2800 m. Plans are to complete 15 more exploitation wells in Hverahlid high-temperature system to sustain a new 90 MW$_e$ power plant. All of the wells have been drilled by Iceland Drilling Ltd.

Fig. 1 shows the location of the Hengill volcanic system in the SW rift zone of Iceland. The central volcano occupies the central part of 60-100 km long volcanic fissure/fault swarm. It is mainly built up of hyaloclastite formations erupted underneath the ice sheet of the last glacial period and formed highlands. Interglacial lavas erupting in the high-lands, on the other hand flow down and accumulate in the surrounding lowlands. The age of the volcano has been assessed from Nesjavellir high-temeprature area at the northern sector of Hengill to be about 300,000 years (Franzson 1998), while data in the southern part may indicate somewhat higher age or about 400,000 years (Franzson et al 2005).

The highlands pin-point the locus of high volcanic accumulation rate and the center of the Hengill main volcano. The edges of the Hengill volcanic system a large graben faults, which strike NE-SW. Postglacial volcanism includes three fissure eruptions of 9, 5, and 2 thousand years and they play an important role in the permeability in the Hengill geothermal field. The geothermal activity at the Hengill central volcano and its fissure swarms is explained by one or more up-flow zones underneath the Hengill volcano. The upflow is caused by buoyancy as hot intrusions in the roots of the volcano heat up groundwater. This also creates a pressure-low deep under the volcano so fluids from the outer boundaries of the system recharge the up-flow (Franzson et al., 2005).

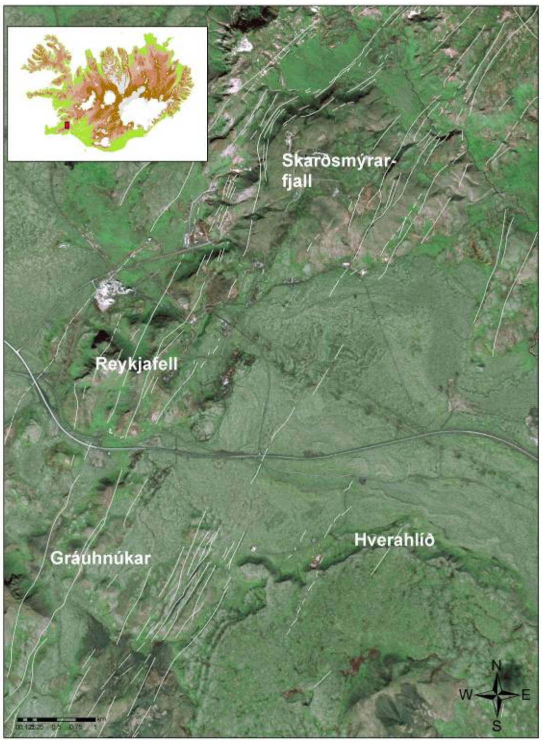

Figure 1: Location of Hverhlid high-temperature field with apparent faults.

2. GEOLOGICAL STRUCTURES

Fig. 2 shows the topography of the Hverahlid high-temperature system the apparent relation of Hverahlið which is somewhat offset from the highland but apparently within the fault and fissure swarm of the Hengill volcanic system. Is it of interest to indicate that Hverahlid is situated in a lavafield outside of the main highlands, that may indicate that the Hverahlid high-temperature system is situated at the margin of or outside the main Hengill central volcano.

The only active surface manifestations in Hverahlid is the active geothermal field situated about 200 m south from well HE-21. The manifestation is around 400 m long and a few tens of meters wide and trends NE-SW. It apparently relates to a fault of the same direction. Another structural feature in the eastern part of the field is about 1 km wide very active fissure/fault zone that disappears under recent lavaflows to north (see Figure 2). The first well drilled in

Hverahlid was HE-21. It was sited in the neighborhood of the geothermal manifestation as shown in figure 2 and aimed at the geothermal structure that is feeding the surface manifestations. The second well HE-26 was sited to the northeast from well HE-21 in order to explore the northern perimeter of the geothermal system, as well as being in a continuation of the NE-SW geothermal structure. Seismic activity was monitored during the injection tests of well HE-21 towards northeast from the well which further established the well siting. Well HE-36 was located about 1 km west from HE-21 and its purpose was to explore the western part of the field, in particular the existence of a geothermal system associated with an active fissure swarm. For that purpose the well was deviated towards west crossing the fault-swarm.

The geological data in boreholes are derived mainly from cutting analysis of samples taken at 2 m interval during drilling, analyzed in a binocular and petrographic microscopes, and alteration minerals further analysed by XRD where applicable. Data is also collected from geophysical lithological logs in the well along with temperature and pressure logs. Drilling data such as circulation losses, penetration rate were used for further confirmation on the geological structures. A large part of the data has been published in preliminary reports by Iceland GeoSurvey (ISOR) specialists for Reykjavik Energy (Gudmundsson et al. 2006, Helgdottir et al. 2009, Helgadottir et al. 2006, Kristjansson et al. 2006, Mortensen et al. 2006, Nielsson 2008, Nielsson and Haraldsdottir 2008).

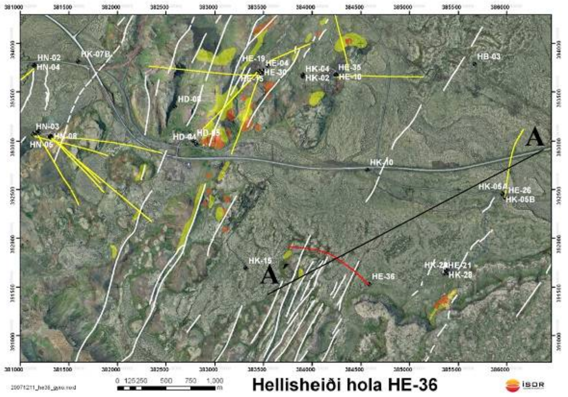

Figure 2: A topographic map of the Hverahlid high-temperature field showing thermal manifestations (yellow=active, orange=fossil), locations of wells and cross section trace.

2.1 Volcanic Succesion

Lithology in the Hverahlid high-temperature system is mainly composed of two rock types; hyaloclastites and lava series. The latter is dominant and is form during inter-glacial periods, while the hyaloclastites are formed in sub-glacial eruptions. Basaltic hyaloclastite form when magma cools during eruption into the base of the glacier, and piles up, mostly as pillow basalts, breccias and tuffs, forming highlands. Although of relatively high porosity, these formations tend to have low permeability, especially when they have been hydrothermally altered. Interglacial lavas, however, when erupting in the highlands will flow downhill and accumulate in the lowlands.

In Fig. 3. the simplified lithology of well HE-36 is shown together with intrusions, aquifers, alteration state and the main alteration minerals. The upper most 100 m are made of post-glacial lavas. Below is a pillow-basalt formation down to about 100 m a.s.l. Those two formations can be traced in the other two wells (c.f. figure 4). Below the pillow-basalt formation there are tuffacious formations down to 450 m b.s.l. Below 450 m b.s.l. the lithology is mostly built up of lava formations.

The cross sections presented in the paper are located on the line A-A´ (Fig 2.). The simplified volcanic succession is shown in Fig. 4. The top of the thick lava series found at about 1000 m b.s.l. in the Hverahlid high-temperature system is interpreted as representing the base of the Hengill central volcano. This boundary is deeper than found in the Nesjavellir field in the northern boundary of the Hengill central volcano where the boundary was about 300,000 years ago. This would suggest that the age of the Hengill central volcano may be somewhat older or around 400,000 years (Franzson et al., 2005). This also puts an age limit on the high-temperature system, as it assumed that the system is related to the anomalous heat flow of the volcano.

2.3 Intrusive Rocks

Intrusive rocks are identified by their compact nature, relatively low alteration, and sometimes by oxidation found at their margins. Geophysical logs often show them to have relatively high neutron-neutron and resistivity values. Fig. 3 shows the occurrence of intrusions in well HE-36. There are two types of intrusive rocks in the Hverahlid high-temperature system: Fine grained basalt intrusion are dominant but evidence is also often grained andesitic to rhyolitic intrusions. The fine-grained nature of the intrusions indicate that they are dykes and/or sills. The intrusions are infrequent down to about 800 m b.s.l. but become more numerous below. Below 1600 m b.s.l. the intrusive rocks become more dominantpart of the lithology. This is deeper than in the other sectors of the Hellisheidi field (Gunnarsson and Kristjánsson, 2003).

2.4 Aquifers

Acquifers (feed points) in the wells are located using circulation losses, temperature logs, hydrothermal alteration, and other relevant drilling data. Fig. 3 shows the position of the main aquifers in well HE-36. A detailed analysis of this data and their exact relation to the geological factors are still ongoing.

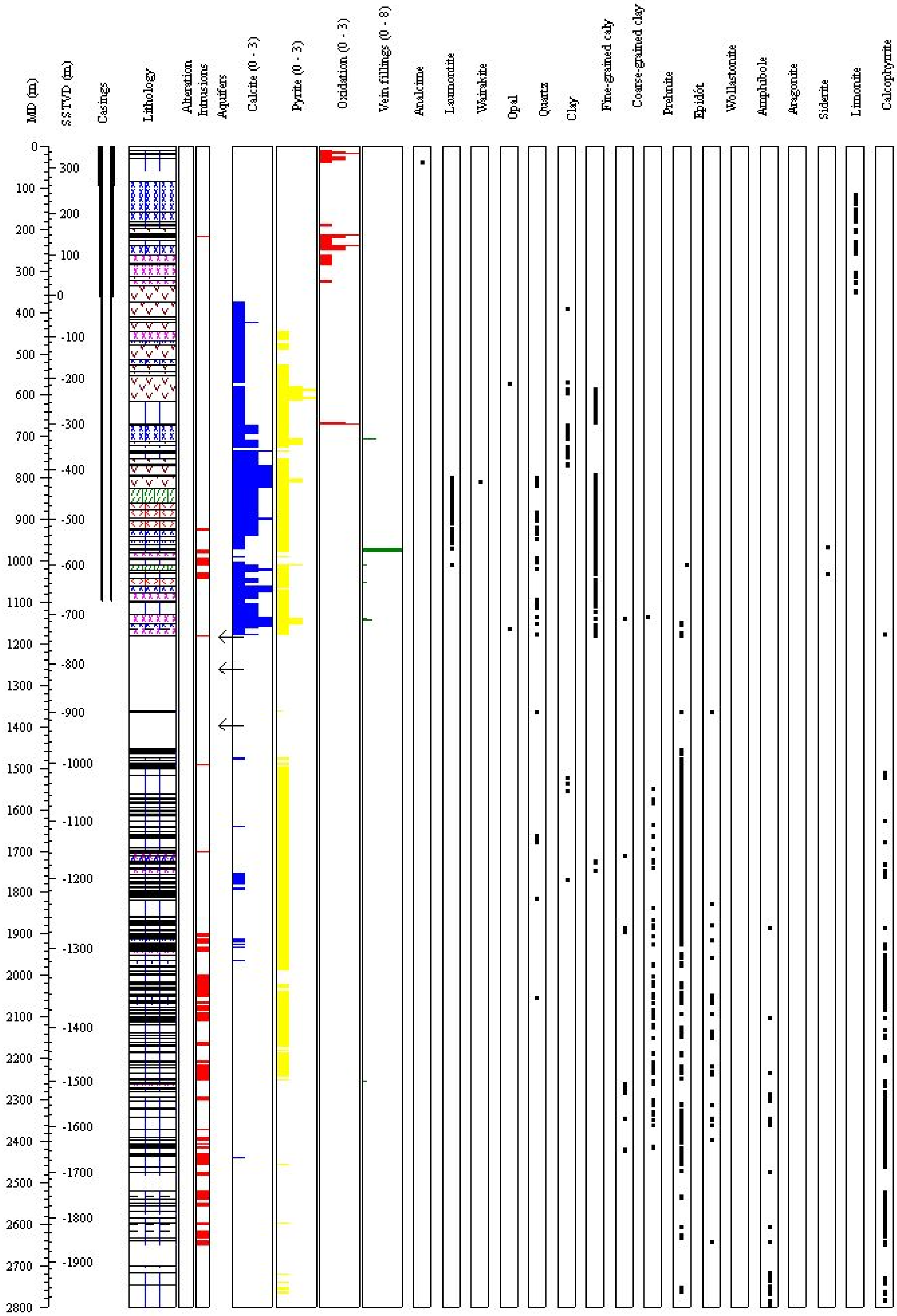

Figure 3: Lithology, alteration, alteration minerals and aquifers of well HE-36.

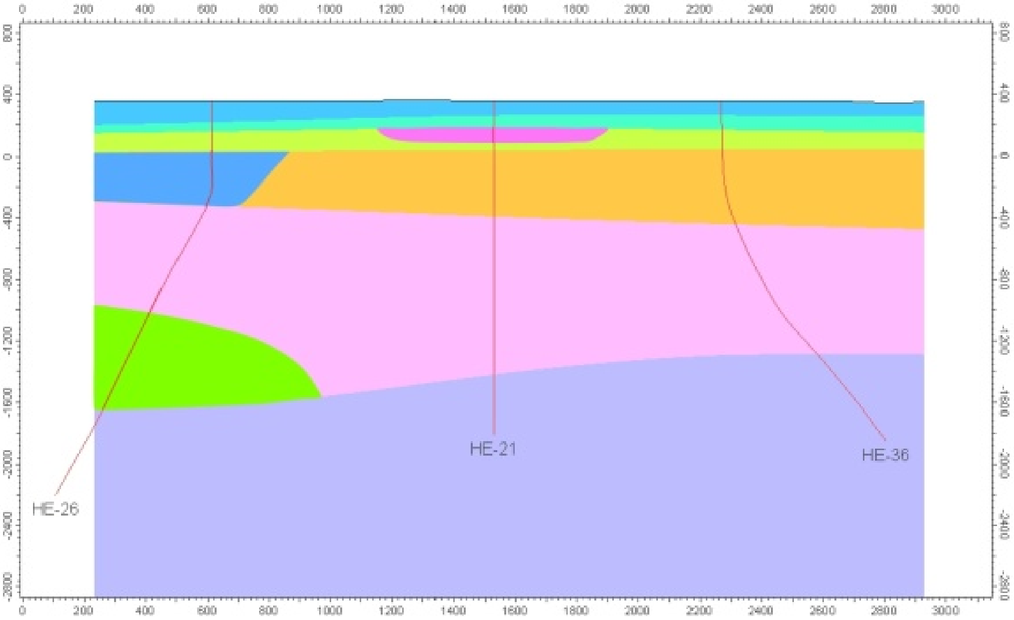

Figure 4: Geological cross section along line A-A'. Blue and pink formations are lava series, and green and yellow colors are individual hyaloclastite formations.

3. HYDROTHERMAL ALTERATION

Hydrothermal alteration has been studied in some detail by observing drill-cutting samples collected at a 2 m interval and analyzed in a binocular and a petrographical microscope, and also by use of XRD-analysis. In Fig 3. the alteration minerals in well HE-36 are shown. In general the hydrothermal alteration spans all the typical hydrothermal alteration zones from totally fresh rocks to epidote-amphibole zone. In this paper the main emphasis will be to show the depth variation of some of the temperature dependant minerals, and to compare the alteration with the present formation temperature in the geothermal system. The topography of the hydrothermal system is exemplified here by the first occurrence of quartz (180°C), epidote (250°C) and amphibole (>280°C).

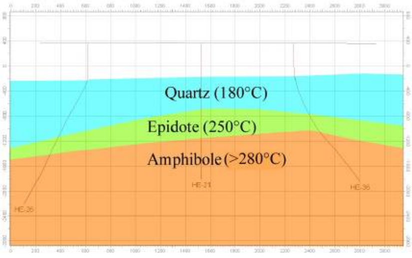

Figure 5: Cross section along line A-A' showing the topography of hydrothermal alteration in Hverahlid high-temperature system.

Figure 5 shows that the depth of hydrothermal alteration is greatest in well HE-26 but reaches shallowest in well HE-21. The alteration in well HE-36 is somewhat lower than in HE-21. The hydrothermal alteration is considerably deeper in Hverahlid high-temperature system compared with other sectors of the Hellisheidi high-temperature system.

4. TEMPERATURE DISTRIBUTION

Formation temperature is based on temperature logging during heating up and discharge of individual wells. The hydrothermal alteration temperature relies on the first appearance of temperature dependent alteration minerals. The latter may be considered as reflecting the long term condition and the highest stage of the geothermal system. A comparison of these two types of temperature curves may therefore show the most recent temperature changes that has occurred in the geothermal system, whether it indicates recent cooling or heating. Figure. 6 shows this comparison in the three wells. The curves correlate fairly well in HE-21, where formation temperature seems to lie a little higher than the alteration. Similarly, in HE-36, the formation temperature lies a little higher than alteration down to 1200 m, but becomes markedly lower below that depth reaching a minimum of about 215°C at 2000 m depth, which is about 60° lower than expected from the alteration assemblage. The difference is quite marked in well HE-26 where the alteration is 50°C -70°C higher from 700 m down to about 2000 m, but equilibrates below that depth.

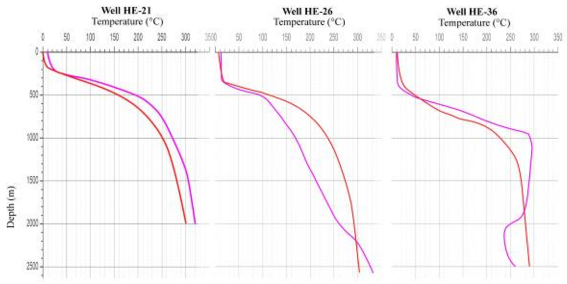

Figure 6: Comparison of alteration temperature (red line) and formation temperature (purple line) from wells HE-21, HE-26 and HE-36.

The formation temperature in the geothermal system is shown in a cross section in Fig. 7. These temperatures are attained by the estimated formation temperatures of the individual wells and then extrapolated throughout the drilled area (Björnsson and Hjartarson, 2003). The figure shows an increasing temperatures with depth reaching a maximum of just over 320°C in the bottom of wells HE-21 and HE-26, at around 2000 m b.s.l. The reverse temperature gradient is clearly seen in well HE-36 below 800 m b.s.l. where temperatures lowers from 300°C at 700 m b.s.l. down to about 215°C at about 2 km depth. Other wells in the Hellisheidi geothermal field that have been drilled at the western margin of the area show similar reversed thermal gradient as well HE-36.

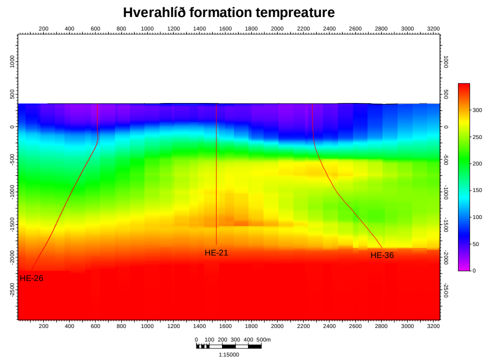

Figure 7: Cross section along line A-A' showing the heat distribution in the Hverahlid high-temperature system.

5. DISCUSSION

The first three exploration wells in Hverahlid give a good first indication on the probable condition of the high-temperature reservoir and is a first step towards making a geothermal model.

5.1 Geological Relations

The geological succession of the Hellisheidi is dominantly built up of hyaloclastites, which are formations of relatively limited horizontal extent and tend to build up and form highlands. While the lava series tend to flow down from the highlands and down to the lowlands. Because the stratigraphy in the Hverahlid cross-section is mainly built up of lava series one could suggest that the Hverahlid field has never been part of the Hengill highlands. This may indicate, that while it is a part of the main fissure system of the Hengill that it has a separate origin to the central volcano.

5.2 Comparison of Alteration and Formation Temperatures

When the present formation temperature and alteration temperature is compared a clear difference is observed where the measured temperature in the upper part of well HE-36 is considerably higher than the alteration temperature. On the other hand measured temperatures were considerably lower then the alteration temperature in the upper part of well HE-36 and well HE-26, while well HE-21 seems to be near equilibrium. Well HE-36 shows a conspicuous heating up in the upper part, while a noticeable cooling in the deeper part of the well (Fig. 8). As discussed above the alteration temperature is considered to reflect the long term high alteration state of the geothermal system, while the formation temeperature the present state, and the difference between the two would therefore not only indicate the latest change but also a change that has not had time to alter the overall geothermal alteration. This change must therefore be considered to be geologically very recent. If we look at the surface geological features with this in mind we may relate this with the following observations: Well HE-21 is drilled near to the only geothermal manifestation in Hverahlid. This manifestation cuts through a volcanic formation that erupted in late during last glacial and the geothermal manifestation may therefore date from Holocene and therefore be related to that geothermal event. Well HE-36 is deviated into the most active part of the fissure swarm. It is therefore tentatively interpreted that the heating and cooling reflects recent permeability changes and increased thermal mining associated with the opening up of the fissure warm. Well HE-26 shows an overall cooling down to 2000 m depth. A relation to recent acivity is not obvious, but it may be related to the pronounced cooling that is observed in wells drilled in Bitra field to the north. Figures 8 and 9 shows this scenario.

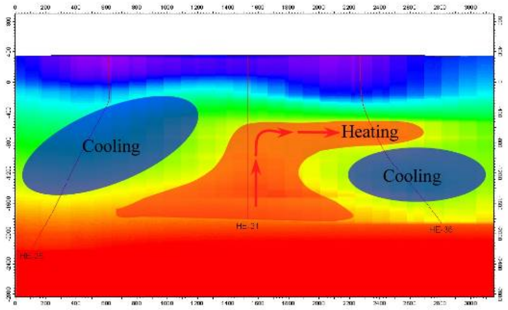

Figure 8: Cross section along line A-A' showing the heat distribution in the Hverahlid high-temperature system. Along with information about heating and cooling of the geothermal system.

6. CONCLUSIONS

The exploration and production drilling so far in the Hverahlid high-temperature area has revealed several features relevant to the hydrothermal system.

1. Intrusions become more abundant at around 1500 m b.s.l. which is a deeper then in other sectors of the Hellisheidi field.

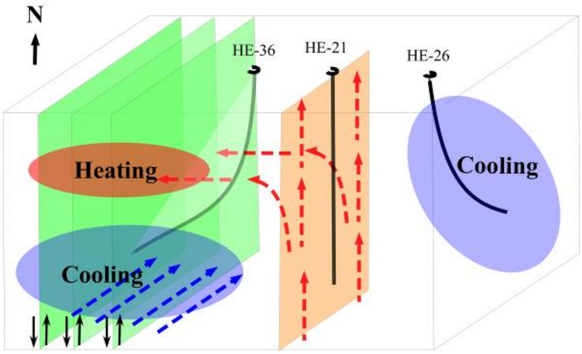

Figure 9: A conceptual model of the Hverahlid high-temperature field.

2. Figure 9 shows the salient features of the geothermal system in Hverahlid. The fissure swarm is shown in green colour and these contribute to the permeability of the reservoir there. The red line shows the fault which well HE-21 is drilled into. The lower formation temperature in well HE-36 suggests that these fissure structures are causing inflow of colder waters while a geothermal upflow coincides with the fault underlying the surface manifestation and then flows laterally westwards towards and into the active fissure swarm, but does not reach into the area where HE-26 is drilled.

REFERENCES

Franzson, H., Kristjánsson, B.R., Gunnarsson, G., Björnsson, G., Hjartarson, A., Steingrímsson, B., Gunnlaugsson, E., and Gíslason, G.: The Hengill Geothermal Field. Development of a Conceptual Geothermal Model. *Proceedings*, World Geothermal Congress, Antalya, Turkey (2005).

Franzson, H.: Reservoir Geology of the Nesjavellir High-Temperature Field in SW-Iceland, *Proceedings*, 19th Annular PNOC-EDC Geothermal Conference Manila, Philippines (1998), 13-20.

Franzson, H., Árnason, K., Sæmundsson, K., Steingrimsson, B., Harðarson, B.S., and Gunnlaugsson, E.: The Hengill geothermal system, conceptual geological model. Proceedings World Geothermal Congress, Bali Indonesia (submitted).

Gudmundsson, A., Franzson, H., Sigurdsson, O., Danielsen, P.E,, Birgisson, K. and Þorgeirsson, A. Hverahlid – Well HE-21: Drilling for 9 5/8” production casing from 300 to 903 m. *Iceland GeoSurvey Report.* ISOR-2006/006 (in Icelandic), 65 p.

Gunnarsson, G., Kristjánsson, B.R.: An Assessment of Intrusive Intensity in Lower Part of Wells HE-3 to HE-7 at Hellisheidi. *NEA-Report* OS-2003/022 (in Icelandic) (2003), 41 p.

Helgadottir, H.M., Þórarinsson, S.B., Franzson, H. and Kjartansson, G.: Hverahlid – Well HE-26: Drilling for production part with 8 ½” bit from 972 to 2688 m. *Iceland GeoSurvey Report.* ISOR-2009/017 (in Icelandic), 115 p.

Helgadottir, H.M., Nielsson, S., Franzson, H., Sigurdsson, O. and Þorgeirsson, A.: Hverahlid – Well HE-26: Drilling for 18 5/8” surface casing to 92 m, 13 3/8 anchor casing to 319 m and 9 5/8” production casing to 972 m. *Iceland GeoSurvey Report.* ISOR-2006/052 (in Icelandic), 84 p.

Kristjánsson, B.R., Steingrimsson, B., Asmundsson, R.K., Egilsson, Þ., Richter, B., Sigurðsson, G. and Þorgeirsson, A.K.: Hverahlid – Well HE-21: Drilling for 18 5/8” surface casing to 95 m and 13 3/8” anchor casing to 300 m. *Iceland GeoSurvey Report* ISOR-2006/009 (in Icelandic), 54 p.

Mortensen, A.K., Egilson, Þ., Franzson, H., Richter, B., Asmundsson, R.K., Danielsen, P.E., Steingrimsson and Þorisson, S.: Hverahlid – Well HE-21: Hverahlid – Well HE-21: Production part: Drilling for 8 ½# production part from 903 m to 2165 m. *Iceland GeoSurvey Report* ISOR-2006/018 (in Icelandic) (2006), 79 p.

Nielsson, S. and Haraldsdottir, S.H.: Hverahlid – Well HE-36: Drilling for production part from 1104 m to 2808 m with 8 ½” bit. *Iceland GeoSurvey Report* ISOR-2008/046 (in Icelandic), 173 p.

Nielsson, S.: Hverahlid – Well HE-36: Drilling for surface casing to 105 m, anchor casing to 364 m and production casing to 1104 m. *Iceland GeoSurvey Report.* ISOR-2008/012 (in Icelandic), 100 p.