Geology and Hydrothermal Alteration in the Reservoir of the Hellisheiði High Temperature System, SW-Iceland

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ABSTRACT

The Hengill central volcano is situated in the Western Volcanic Zone in Iceland on a triple junction where two active rift zones meet a seismically active transform zone. The area is a high temperature geothermal field which Reykjavík Energy has been exploring and exploiting. Presently the drilling of well number 55 is taking place in the Hverahlíð field at the southeastern sector of the Hengill area. Aside from those the drilling of 12 reinjection wells has already taken place.

The dominant rock formation in the Hellisheiði field is hyaloclastite (tuffs, breccias and pillow lavas) formed sub-glacially. This is to be expected as the area is a part of the Hengill central volcano where sub-glacial rock formations pile up. Lava successions from interglacial periods flow to the lowlands and are therefore less common. Hverahlíð field is, however, different from the Hellisheiði field in respect of the build up of lavas since the dominant rock formation in Hverahlíð wells is lava series. This would suggest that Hverahlíð has been outside the domains of the Hengill central volcano.

Aquifers in 57 wells at Hellisheiði have been located using down-hole temperature logs. Aquifers in the wells were assessed and placed at 100 m depth intervals and normalised with respect to the number of wells reaching each depth interval showing that large aquifers are not found below 2000 m depth.

Hydrothermal alteration ranges from totally fresh rocks in the overlying cold groundwater system through zeolite assemblage and into high-temperature mineral assemblage including epidote, wollastonite and actinolite. The comparison of alteration and formation temperatures seems to indicate minor cooling at the western side of Skarðsmýrarfjall as well as a cooling front from the east between Skarðsmýrarfjall and Hverahlíð. The Gráuhnúkar area, at the south western sector of the Hellisheiði field seems to be heating up and the same can be said about a certain part of the Hverahlíð field. Formation temperature and hydrothermal alteration indicate three upflow zones beneath Gráuhnúkar, Reykjafell and Hverahlíð.

1. INTRODUCTION

Iceland, being formed within the rifting environment of the Mid-Atlantic ridge, consists mostly of igneous rocks of which about 90% are basalts. Sedimentary rocks are less than 5% of the bedrock and are dominantly erosional from the volcanic succession. The Hengill central volcano sits in the middle of the Western Volcanic Zone in Iceland (figure 1). The volcano consists mainly of hyaloclastite formations, the products of sub-glacial eruptions. Occasionally they are interrupted by lava successions which have flowed to the lowlands during interglacials.

The area is a triple junction where two active rift zones (the Reykjanes Peninsula Volcanic Zone and the Western Volcanic Zone) meet a seismically active transform zone (the South Iceland Seismic Zone). The Hellisheiði and Hverahlíð high-temperature fields are a part of a 110 km^2 low resistivity anomaly of the Hengill central volcano and situated in its southern sector.

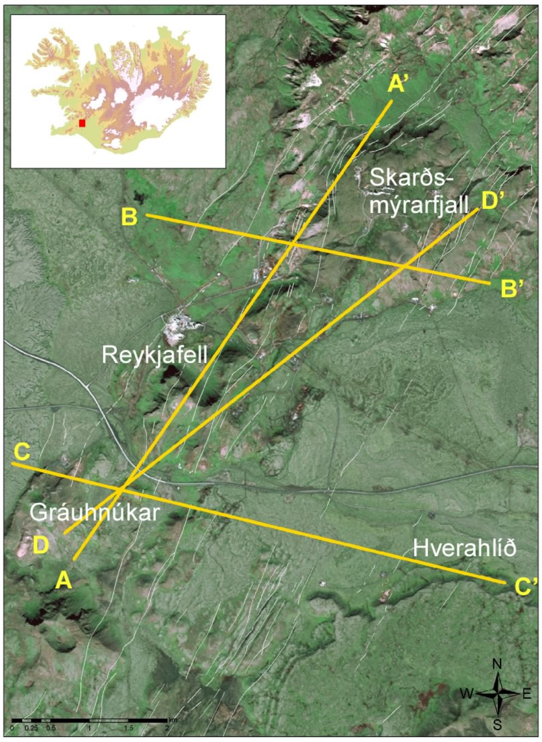

Figure 1: Location of Hellisheiði high-temperature field, with apparent faults and cross section lines.

The first exploration well of the Hellisheiði area was drilled in 1985 at Kolviðarhóll at the western boundary of the field. Since then a vigorous exploration and drilling of the field has taken place, especially in the last three years. More than fifty production and exploration wells (HE-wells) have been drilled to date as well as twelve reinjection wells (HN-wells). All of the wells have been drilled by Jardboranir Ltd, the main drilling company in Iceland. The Hellisheiði power plant's current production capacity is 213 MWe but further power plants in the area are being constructed. The eventual production is estimated to be 300 MWe and 400 MWt (Harðarson et al. 2009). Presently the drilling of well

HE-55 is taking place in the Hverahlíð field southeast of the Hellisheiði field but of the 55 production wells 46 have been drilled in Hellisheiði and 5 in Hverahlíð. The depths of the wells range from around 800 m to more than 3000 m. Directional wells dominate in both Hellisheiði and Hverahlíð fields.

This paper is largely built on preliminary well data from specifically chosen wells from various areas within the southern part of the Hengill central volcano (Hellisheiði field and Hverahlíð field). The intense drilling of the last few years has given researchers limited time to explore in detail the data that has already piled up. Reykjavík Energy has, however, started off a number of studies in the area (e.g. Gunnlaugsson and Gíslason 2005, Franzson et al. 2005, Franzson et al. 2010, Harðarson et al. 2010 and Níelsson and Franzson 2010) and intends to continue this work in the near future. The geological data is primarily based on cutting analysis of samples taken at 2 m interval during drilling, temperature logs, XRD studies on clay in some of the wells, and geophysical borehole logs (resistivity, caliper, neutron-neutron, natural gamma). The data is used to determine rock formations, thermal alteration and permeability structures in the wells. The data has been integrated into a conceptual model of the reservoir using Petrel, a 3D reservoir engineering software.

Reservoir studies have shown that permeability in the upper part of boreholes in Iceland is mostly controlled by stratification boundaries. On the other hand, faults and fractures along intrusive boundaries seem to dominate the permeability in the lower part of the wells (Franzson et. al., 2001). This will not be evaluated here as this has not been studied in any detail at this point.

2. GEOLOGICAL STRUCTURES

The southern part of the Hengill area rises up to approximately 600 m elevation at Skarðsmýrarfjall (figure 1). A large geothermal high temperature anomaly has been proved to exist in the area by means of extensive geological mapping and geophysical exploration (e.g. Árnason and Magnússon 2001). The Hengill system is dominated by a NE-SW strike of major fractures and faults. In some places, however, the fractures are intersected by easterly striking features which may affect the permeability of the Hellisheiði field (Harðarson et al. 2007). Volcanic fissures of 5 and 2 thousand years seem to play an important role as major outflow zones in the field (e.g. Sæmundsson 1995, Björnsson 2004 and Franzson et. al. 2005). These fissures have been one of the two main drilling targets in the Hellisheiði field. Large NE-SW fault structures at the western boundary of the Hengill graben, with more than 250 m total throw (Franzson et al. 2005, Harðarson et al. 2009) have also been targeted as these serve as major feed zones of the hydrothermal system. In addition they have also been used as targets for the reinjection wells of the area.

2.1 Volcanic Succession

The cross sections presented here are located along the lines A-A’, B-B’, C-C’ and D-D’ (figure 1). The simplified volcanic successions are shown in figures 2-5. In short the area is mainly built up of hyaloclastite formations and the occasional lava series. Hyaloclastites are dominant and (as stated before) are formed in sub-glacial eruptions resulting in highlands. The fact that the area is dominantly made of hyaloclastites would suggest that the Hellisheiði field is within the Hengill central volcano where eruptions were most frequent, forming highlands during glacial (figures 2, 3 and 5). Lava series are, however, formed during inter-glacials, flowing downhill and accumulating in the surrounding lowlands (Franzson et al. 2005). Hverahlíð field is somewhat different to the rest of the area as the stratigraphy is dominantly built up of lava successions (figure 4). This would suggest that the Hverahlíð field was outside the main volcanism of the central volcano during glacials (Níelsson and Franzson 2010). The relation of the lava series in Hverahlíð to Gráuhnúkar area is not clear. The drilling of well HE-55, at the western sector of Hverahlíð, will hopefully answer some questions about the matter.

Postglacial volcanism includes the two volcanic fissures mentioned before (5 and 2 thousand years old) along with a fissure eruption of 9 thousand years. Postglacial lavas are shown in figures 2-5 as red manifestations at the surface. It is interesting to note that the postglacial lavas in Hverahlíð (figure 4) are considerably thicker than in other areas concerned.

The base of the Hengill central volcano is believed to be at about 900-1300 m b.s.l. (figures 2-5). A study from the Nesjavellir field (Franzson 1998) suggested that the age of the complex was around 300.000 years which seems to be an absolute minimum. The age has since then been suggested to be around 400,000 years (Franzson et al. 2005). The four lava series in cross-section B-B’ (figure 4) can be viewed as representations of four inter-glacials which would also suggest the same age (given that inter-glacials occur every 100.000 years approximately).

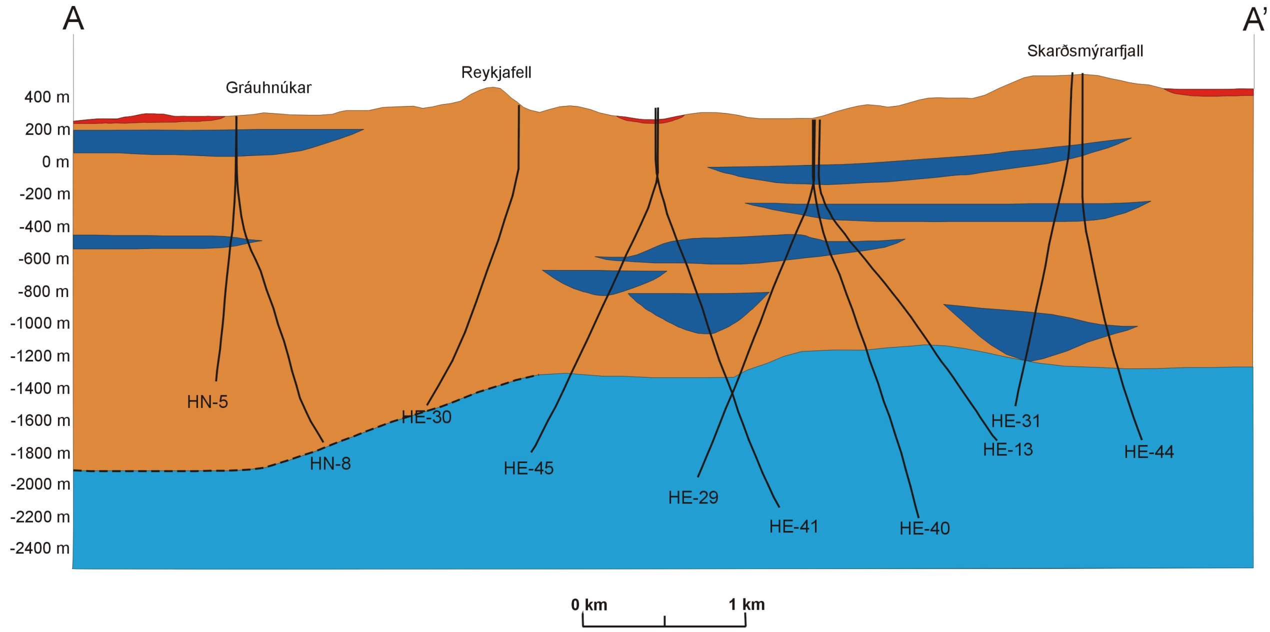

Figure 2: Geological cross section along line A-A'. Blue formations are interglacial lava series and the light blue formation is interpreted as the bottom of the Hengill central volcano. Red formations are postglacial lavas. Brown formations are hyaloclastite formations. Dotted, black line represents areas where no data is available.

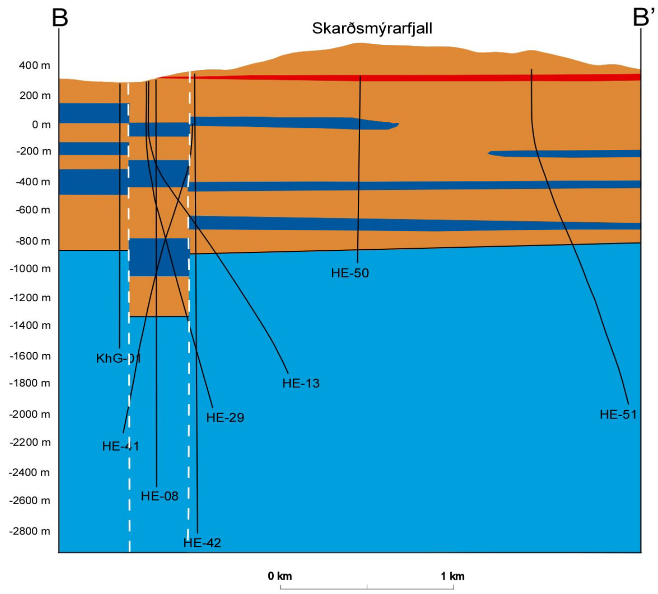

Figure 3: Geological cross section along line B-B'. Same legend as in figure 2.

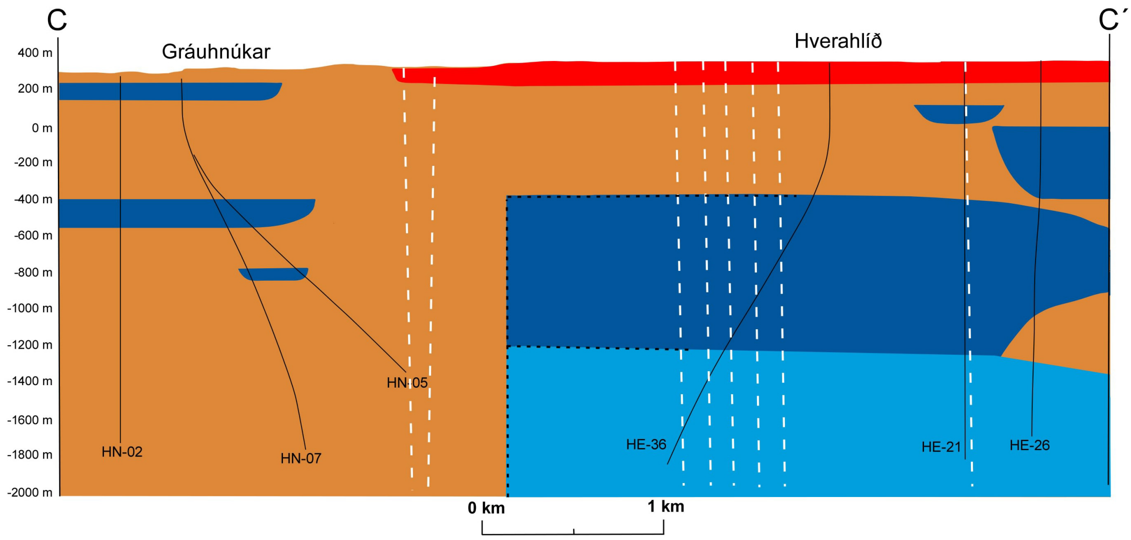

Figure 4: Geological cross section along line C-C'. Same legend as in figure 2.

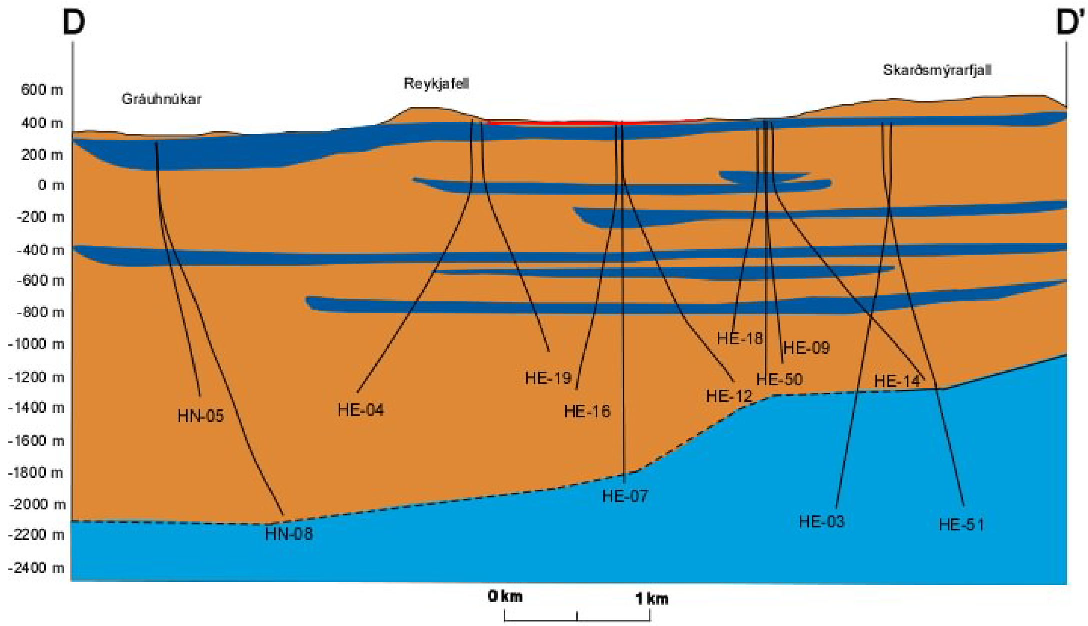

Figure 5: Geological cross section along line D-D'. Same legend as in figure 2.

2.2 Faults

Faults in the area will not be discussed in this paper as their study has not finished. The geological cross section B-B' shows, however, the presence of a distinct graben through Reykjafell mountain with a total throw of up to 500 m (figure 3). In the figure this is simplified by showing two apparent faults on either side of the graben. The other cross sections do not show faults except in C-C' where possible faults are shown as white, dotted lines. According to Franzson et al. (2005, 2010) the fissure swarm of the Hengill area is a depression structure with major NE-SW faults in the western part with a total throw of more than 300 m. The faults in the eastern part are not as accurately located although it is assumed that a similar overall throw will be found, perhaps on a wider horizontal scale. This awaits future research as the total throw at the western boundary of the Hengill central volcano seems to be more than stated above (Franzson et al. 2005).

2.3 Aquifers

Feed points, or aquifers, in the wells can be located using temperature logs, circulation losses, hydrothermal alteration and other relevant drilling data.

However, data used in our analyses has been determined using only down-hole temperature logs. Aquifers in 57 wells were assessed and placed at 100 m depth intervals. It is problematic to predict the size of aquifers from temperature logs alone and consequently the aquifers have been given an arbitrary size: small, medium and large. Depth of the wells ranges from 800 – 2700 m b.s.l. and the number of wells found at 100 m depth intervals can be found in table 1.

Figure 6 shows a histogram with the number of aquifers in each 100 m interval as well as a normalized version of the same histogram (normalized with respect to the number of wells reaching each 100 metre interval). The plot reaches a maximum at around 400-600 m b.s.l. The production casing is normally down to 400 m depth and drilling mud is used down to that depth. The fewer feed points recorded in that depth interval may to some extend be related to that the mud clogs the permeability structures. The histograms show that the probability of finding any aquifers in the production part of the wells drops below 1500 m depth and no big aquifers are found below 2000 m. The rapidly decreasing number of wells below 2000 m depth increases the error margin of such a statement.

While temperature logs are the best way to find aquifers (feed points) not all aquifers appear on them. In each well a pivot point is found at a certain depth. Above that point water flows out of an aquifer into the well and below water flows from the well and into an aquifer. Around the pivot point water is neither flowing in nor out and therefore aquifers do not show on a temperature log. Using the methods described here makes it almost impossible to place the pivot point accurately in each well. Consequently it is difficult to evaluate what effects these “invisible” aquifers will have on the results shown in figure 6. From figure 6 it is apparent that the number of aquifers drops significantly at 1500 m. However, this drop is not caused by the pivot point in the wells, as these points have been estimated to be located higher up in the 57 wells. At this stage in our research the reason for this drop is obscure.

The relationship between geological factors and the number and size of aquifers is not very well understood and further analysis is needed in order to define this connection. For example, the stratigraphy, the number of intrusives, alteration and tectonics can all play an important role and these factors will be investigated in the research ahead. There are, however, indications of the largest aquifers being located in highly altered areas (Harðarson et al. 2009, Franzson et al. 2005). There are also strong indications of aquifers occurring in association with intrusions (e.g. Franzson, 1998). This awaits further investigation.

Table 1: Number of wells at 100 m depth intervals. This data was used to normalize the number of aquifers (feed points) in the wells.

Depth intervals	Number of wells
400 to 300 m	57
300 to 200 m	57
200 to 100 m	57
100 to 0 m	57
0 to - 100 m	57
-100 to -200 m	57
-200 to -300 m	57
-300 to -400 m	57
-400 to -500 m	57
-500 to -600 m	57
-600 to -700 m	57
-700 to -800 m	57
-800 to -900 m	56
-900 to -1000 m	54
-1000 to -1100 m	51
-1100 to -1200 m	50
-1200 to -1300 m	48
-1300 to -1400 m	41
-1400 to -1500 m	35
-1500 to -1600 m	34
-1600 to -1700 m	29
-1700 to -1800 m	27
-1800 to -1900 m	19
-1900 to -2000 m	16
-2000 to -2100 m	13
-2100 to -2200 m	8
-2200 to -2300 m	5
-2300 to -2400 m	3
-2600 to -2700 m	1

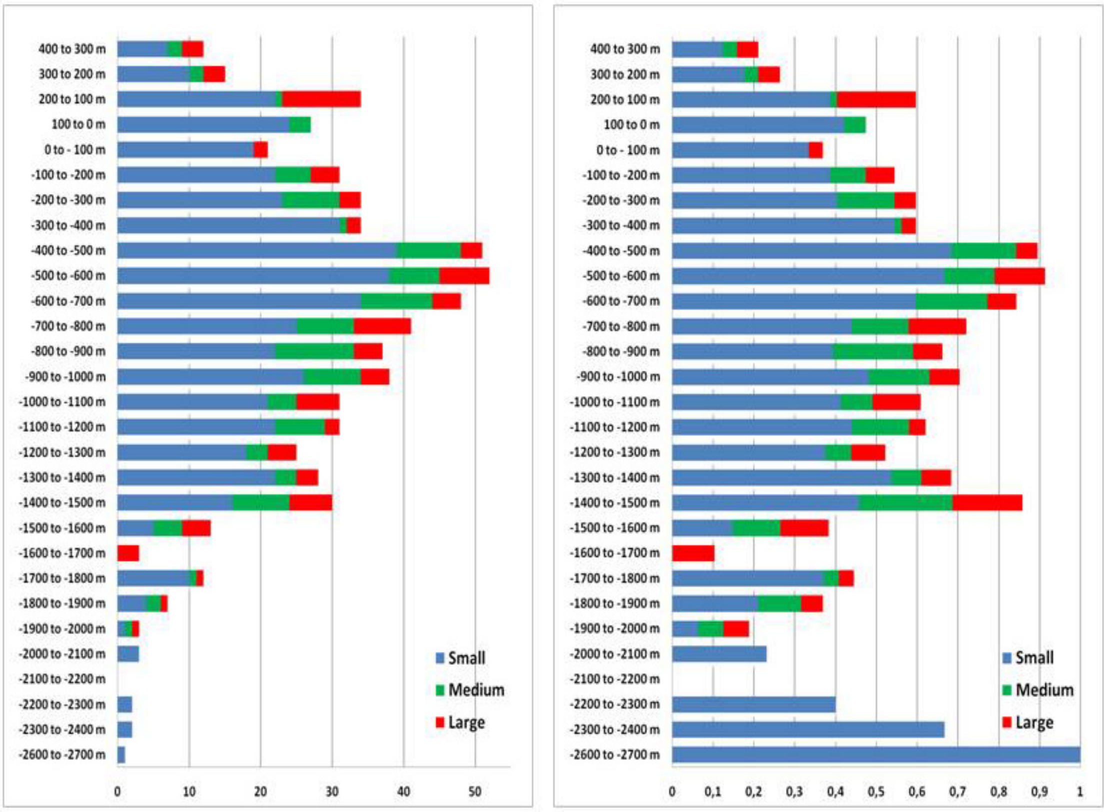

Figure 6: Aquifers at 100 m intervals in wells in Hellisheiði. The histogram to the right is normalized.

3. HYDROTHERMAL ALTERATION AND TEMPERATURE DISTRIBUTION

Hydrothermal alteration has been studied in some detail in about half of the wells in the area and preliminary data is available in all of the other wells.

In general all the typical hydrothermal alteration zones are observed; from totally fresh rocks to the epidote-amphibole zone. Our main emphasis is to show the variation in depth of some of the temperature dependant minerals and to compare this alteration with the present formation temperatures in the system. The minerals used are quartz (>180°C), epidote (>230°C -250°C), wollastonite (>260°C) and amphibole (>280°C).

The topography of the hydrothermal system is shown in figures 7-10 where the formation temperature is pictured along with the contour lines of the first occurrence of quartz, epidote, wollastonite and amphibole in each of the cross sections. By comparing the formation temperature with the temperature dependant minerals we get a notion of whether the specific area is in equilibrium, cooling down or heating up.

The formation temperatures in the geothermal system of the Hellisheiði and Hverahlíð fields have been interpreted on grounds of well logging. The data has been imported into Petrel, a 3D software program, which produced the figures in question.

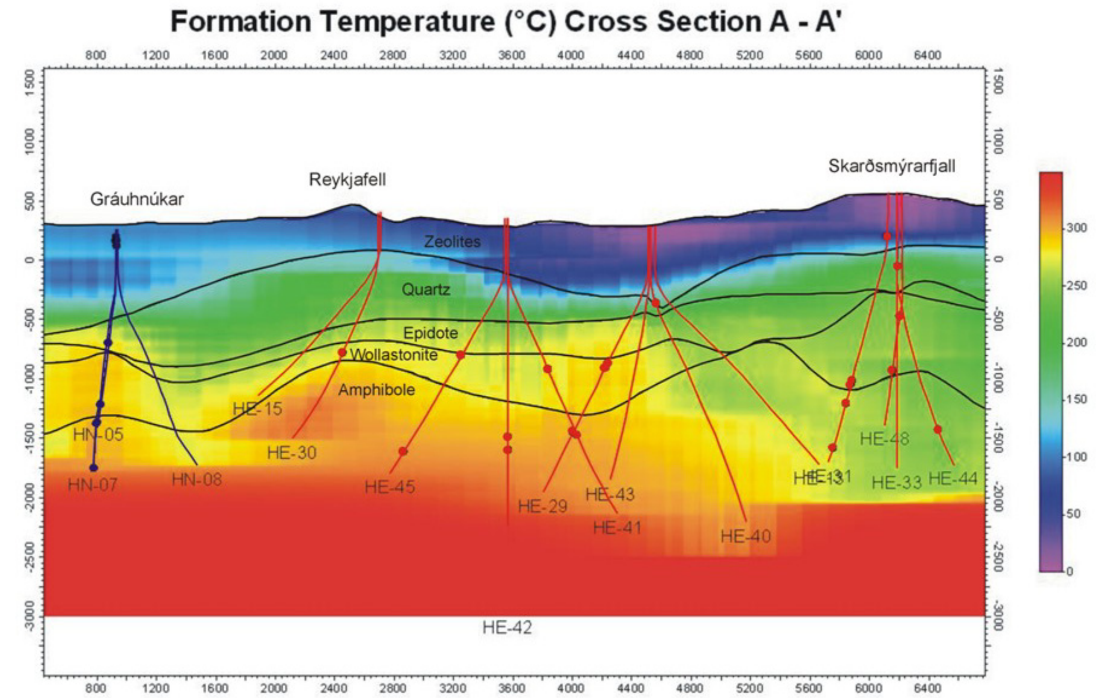

Figure 7: Cross section along line A-A' showing formation temperatures along with the upper limit of common temperature dependent alteration minerals. Main aquifers are also shown.

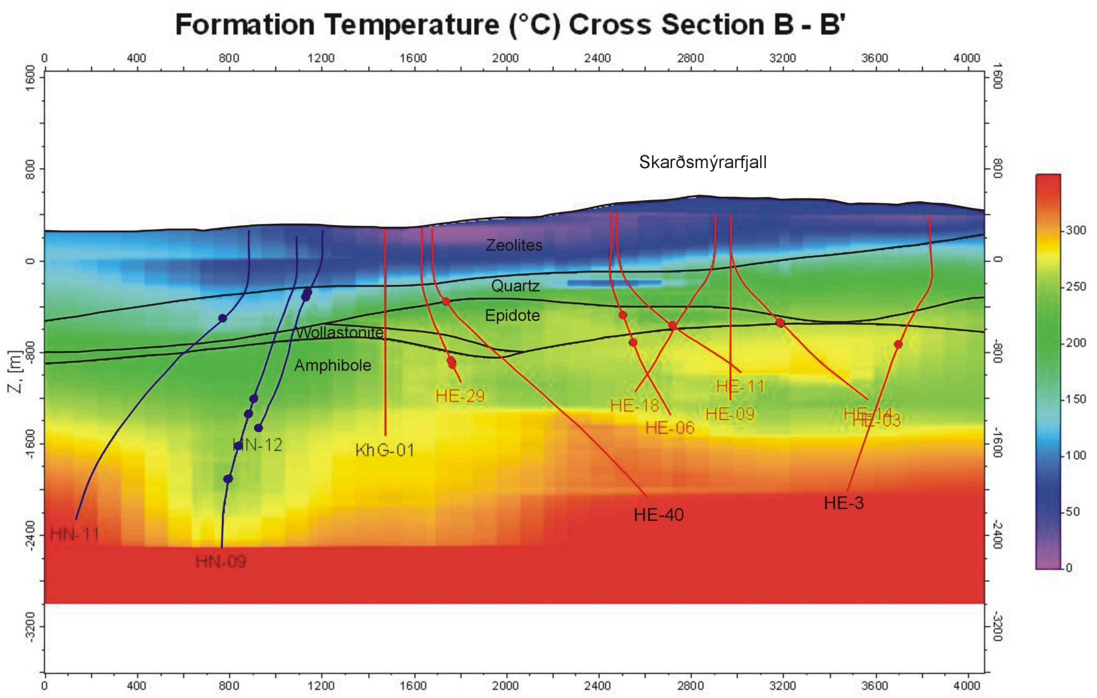

Figure 8: Cross section along line B-B' showing formation temperatures along with the upper limit of common temperature dependent alteration minerals. Main aquifers are also shown.

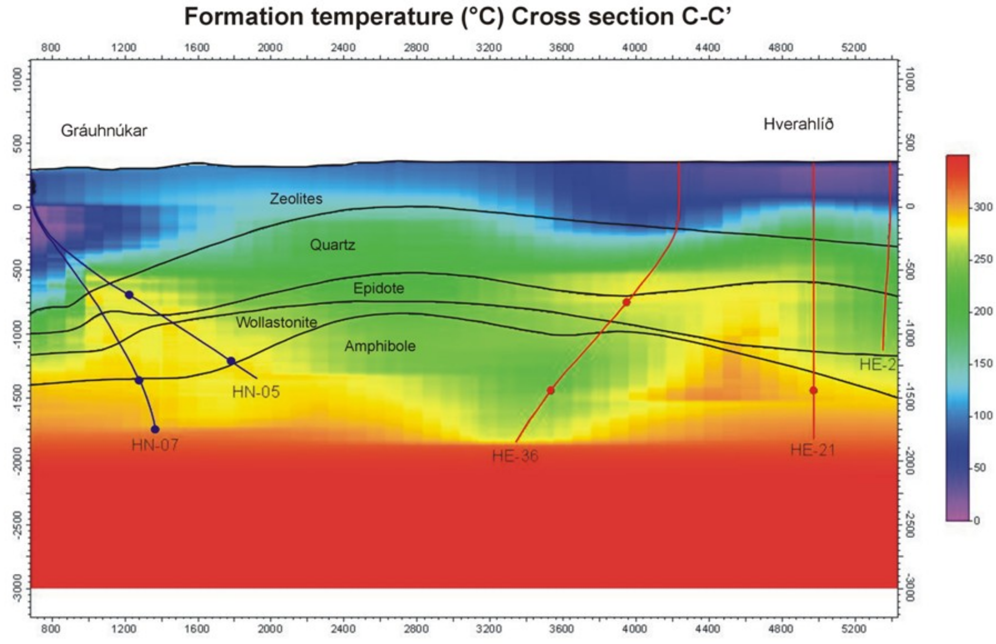

Figure 9: Cross section along line C-C' showing formation temperatures along with the upper limit of common temperature dependent alteration minerals. Main aquifers are shown.

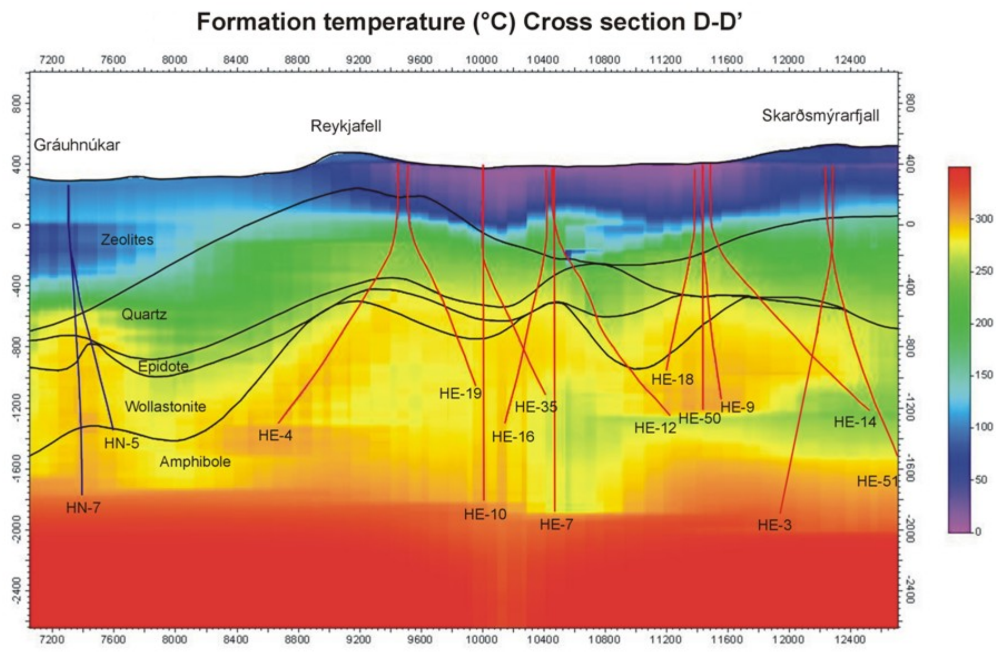

Figure 10: Cross section along line D-D' showing formation temperatures along with the upper limit of common temperature dependent alteration minerals.

4. DISCUSSION

Much of the data is preliminary and must therefore be assessed as such. In 2005 the first step towards the making of a geothermal model of the Hellisheiði area was made (Franzson et. al. 2005). Since then a large number of wells has been drilled and the data available is still expanding.

4.1 Geological Relations

The Hellisheiði field is dominantly built up of hyaloclastites, formations of limited horizontal extent. In this paper no distinction is made between different hyaloclastite formations. Lava series can be used as marker horizons but in this case the connection made between lava series is preliminary. At this time thin sections have not been inspected to verify the connection. This will be done in some of the wells in near future. In cross section B-B' (figure 3) four lava series are found. The deepest one is considered to be the base of the Hengill central volcano and all of the lava series are believed to indicate inter-glacials (which occur approximately every 100.000 years). The age of the volcano is therefore considered to be 400.000 years old (as stated in Franzson 2005). The base is not found in all of the wells and the depth to it ranges from approximately 900 m b.s.l. to 1300 m b.s.l. (figures 2-5) which supports the belief that the volcano is older than 300.000 years.

Since the stratigraphy of the Hverahlíð wells is dominantly built up of lava successions it is suggested that the Hverahlíð field has not been a part of the Hengill central volcano. This may indicate a separate origin although it seems to be a part of the main fissure system of the Hengill area (Níelsson and Franzson 2010) and is therefore connected to the hydrothermal system. Further drilling is now ongoing in Hverahlíð which will hopefully give a more comprehensive idea of the extent of the field.

4.2 Formation Temperatures Compared to Alteration Temperatures

The distribution of formation temperatures and hydrothermal alteration indicates three upflow zones within the Hellisheiði and Hverahlíð reservoirs. These are situated beneath Gráuhnúkar, Reykjafell and Hverahlíð (figures 7-10). Speculations of a separate upflow zone in Reykjafell were made in 2005 (Franzson et. al. 2005).

Figures 7-10 indicate an overall correlation between formation temperature and alteration temperature. The most apparent exception is the area west of Skarðsmýrarfjall (figure 7) where minor cooling seems to have taken place. This is also obvious in cross section B-B' (figure 8) where the alteration temperatures lie at a considerably higher level than the formation temperature would suggest. Figure 10 shows a cross section through Skarðsmýrarfjall, further to the east than figure 7, where the formation temperatures and the alteration temperatures seem to be in more concordance. This suggests that the south eastern part of Skarðsmýrarfjall could be in equilibrium. Places of apparent heating up are beneath Gráuhnúkar on the southwestern sector (at least at shallower levels) (figures 7, 9 and 10) and in Hverahlíð, between wells HE-36 and HE-21 at -400 to -800 m b.s.l. (figure 9).

In figure 11 the contour lines of quartz can be seen. Compared to figure 12, where the contour lines of 180°C formation temperature is shown, it seems there is a cooling front on the western side of the field. The most apparent difference is evident in the western and northern part of the Skarðsmýrarfjall area, where quartz is considerably higher up than the equivalent formation temperature. This is interpreted as an area that has been cooling down; where formation temperatures used to be higher in the past. At the south eastern slopes of Skarðsmýrarfjall, the contour lines of quartz are, however, at a shallow depth and the formation temperature is in concordance with that. This fits nicely with the cross-sections in figures 7-10. The heating up of Gráuhnúkar and Hverahlíð is also noted when figures 11 and 12 are compared whereas a cooling front seems to invade from the east towards Reykjafell between Hverahlíð and Skarðsmýrarfjall.

The speculation of three separate upflow zones beneath Reykjafell, Gráuhnúkar and Hverahlíð therefore seem to be coherent with the results of the comparison between hydrothermal alteration and formation temperature.

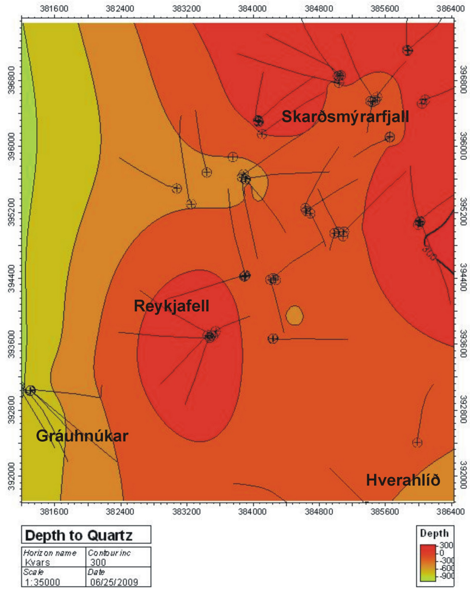

Figure 11: Depth to quartz.

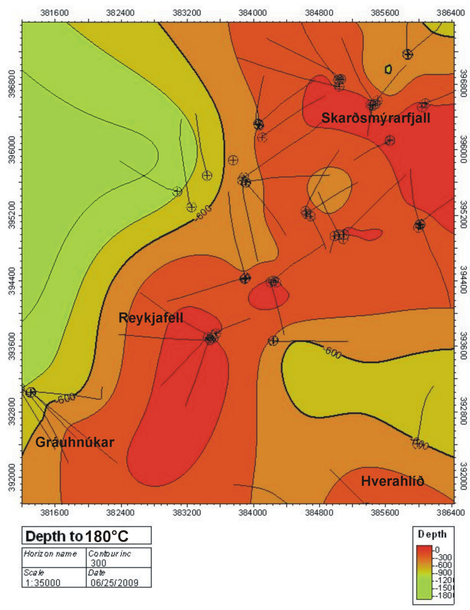

Figure 12: Depth to 180°C.

5. CONCLUSIONS

The drilling of numerous exploration, production and reinjection wells in the Hellisheiði and Hverahlíð fields has produced a pile of data that still needs research. What has been revealed in this paper is this:

1. Approximately 0,4 m.y. age of the base of the Hengill volcano is accepted as four different lava successions seem to be found in one of the cross sections. This is believed to represent four inter-glacial lava series.

2. The Hellisheiði field is mainly built up of hyaloclastite successions, indicating a placement within the Hengill central volcano. The Hverahlíð field, on the other hand, shows the dominance of lava successions in the stratigraphy, which suggests that the area was not part of the Hengill central volcano but rather a part of the lowlands beside the volcano.

3. Results of the assessment of aquifers show that the probability of finding aquifers drops below 1500 m depth and no large aquifers are found below 2000 m depth. Factors that can affect the results of the temperature logs are the location of the pivot point in wells and the use of mud while drilling. Since the relationship between geological factors and the number and size of aquifers is poorly defined, research in this area will be continued.

4. Hydrothermal alteration compared to formation temperatures suggests some cooling at the western boundary of the Hellisheiði field as well as a cooling front from the east towards Reykjafell. Heating is suggested in Gráuhnúkar and Hverahlíð. Otherwise the field appears to be in equilibrium.

5. There seem to be at least 3 upflow zones in the area concerned; beneath Gráuhnúkar, Reykjafell and Hverahlíð.

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