Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

The Hengill-Hellisheiði Geothermal Field. Development of a Conceptual Geothermal Model

Hjalti Franzson[1)], Bjarni Reyr Kristjánsson[1)], Gunnar Gunnarsson[1)], Grímur Björnsson[1)], Arnar Hjartarson[1)], Benedikt Steingrímsson[1)], Einar Gunnlaugsson[2)], Gestur Gíslason[2)].

[1)] ISOR Iceland GeoSurvey, 9 Grensásvegur, 108 Reykjavik, Iceland

[2)] Reykjavik Energy, Bæjarhálsi 1, 110 Reykjavik, Iceland,

hf@isor.is, brk@isor.is, grb@isor.is, arh@isor.is, bs@isor.is, einar.gunnlaugsson@or.is, gestur.gislason@or.is

Keywords: Hellisheiði, drilling, geology, hydrothermal alteration, formation temperature, conceptual model.

ABSTRACT

The Reykjavik Energy has to date drilled 10 deep wells into the Hellisheiði high-temperature field, which is situated in the southern sector of the 110 km^2 Hengill low resistivity anomaly. The geothermal system is found within the NE-SW fault zone and the graben of the Hengill central volcano.

While adequate geological information is available from the wells down to below 2000 m b.s.l. in the western part of the field, reliable information is only available down to about 600 m b.s.l. in the central part of the field due to total circulation losses. The sub-surface basaltic strata comprises mostly hyaloclastite volcanic formations down to some 1000 m b.s.l. depth and underlain by a more dominant lava succession. An age of about 0.4 m.y. is proposed for the Hengill central volcano, which also puts an upper age limit on the geothermal system. Intrusions are scant down to about 800 m b.s.l. depth but become more common below that. They are mostly of basaltic composition but a few are more evolved.

Permeability in the reservoir is believed to relate largely to intrusive boundaries and major faults. Of particular interest are two NE-SW basaltic dykes of 2000 and 5000 year old fissure eruptions, which are believed to provide the main geothermal flow channels of the system from a proposed upflow zone in the central part of the Hengill volcano towards south. The same eruptive fissures play a similar role in the Nesjavellir system on the north side of Hengill central volcano.

A preliminary study of the hydrothermal alteration shows that minor cooling has occurred in the western part of the system while progressive heating appears to be occurring along the aforementioned recent volcanic fissures above about 600 m b.s.l. Again this is a similar behavior as found in the Nesjavellir system to the north. A pronounced temperature reversal is observed in the fault zone in the Hellisheiði field. A temperature maximum of about 280°C is found between 200-600 m b.s.l., but below that depth temperature declines to 200-220°C at 2 km depth. A comparison between measured temperatures and alteration suggests that a cooling has taken place in the deeper part of the central Hellisheiði field.

The exploration data from Hellisheiði have been interpreted and compared to the data from the other parts of the Hengill area, especially the Nesjavellir field. The conclusion is that the geothermal activity at the Hengill central volcano and its fissure swarm can be explained by a conceptual model assuming one or more upflow zones underneath the Hengill volcano, 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 upflow. The main recharge channel is deep within the NA-SW fault zone that crosses the Hengill volcano where the permeability is believed to be highest. Higher up under Hengill the upflow divides where some fluid flows to NE into the fissure swarm towards Nesjavellir and some to SW towards Hellisheiði. Simulation studies quantify the upflow as some 100 kg/s of boiling mixture of steam and water with an enthalpy of more than 2000 kJ/kg.

1. INTRODUCTION

The main emphasis of Reykjavik Energy is to supply geothermal water for space heating for Reykjavik and in later years cogeneration of electricity for the town. Iceland GeoSurvey, formerly a part of National Energy Authority of Iceland, has supplied a significant part of the exploration work for the Reykjavík Energy. Reykjavík Energy has explored and developed the Nesjavellir high-temperature field at the northern side of Hengill mountain where they presently generate 90 MWe and about 300 MWt of hot water.

The Hellisheiði high-temperature field is a part of the 110 km^2 Hengill low resistivity anomaly. The field is situated in the southern sector of the Hengill central volcano in SW-Iceland and some 20 km south of the Nesjavellir high-temperature field (Fig.1). The extent of the present well field covers some 12 km^2. The first exploration well was drilled in 1985 at Kolviðarhóll at the west boundary of the Hellisheiði field and followed by a well at Ölkelduháls east of Hengill in 1995. This was succeeded by a vigorous exploration at Hellisheiði with the drilling of seven wells in the last four years. Four out of the nine wells drilled are deviated, and all are designed as production wells. The depths range from near 1000 m to a maximum of 2800 m which is the deepest high-temperature well drilled to date in Iceland. Plans are to complete ten more exploitation wells within the next two years to sustain a new 80 MWe power plant that is to be commissioned in late 2006. All of the wells have been drilled by Jardboranir Ltd, the main drilling company in Iceland.

The index Fig. 1 shows the location of the Hengill central volcano in the SW rift zone of Iceland. The volcano is in 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 glacials, forming highlands. Interglacial lavas on the other hand flow down and accumulate in the surrounding lowlands. The age of the volcano has been assessed from Nesjavellir data to be about 300,000 years (Franzson 1998), but this data is reassessed using the Hellisheiði data. Fig. 2 shows the main faults/fissures and fossil and active thermal manifestations.

Extensive geological mapping, fluid geochemistry and geophysical surveys preceded the main drilling phase in Hellisheiði and showed the existence of a large geothermal high temperature anomaly (e.g. Árnason, 1986, Björnsson et al. 1986, Saemundsson 1995, Árnason and Magnússon 2001, Ívarsson 1998). Reservoir characteristics are simultaneously being monitored as more data is gathered from the increasing number of wells drilled and fed into iTOUHG2 reservoir model (Björnsson et.al. 2003).

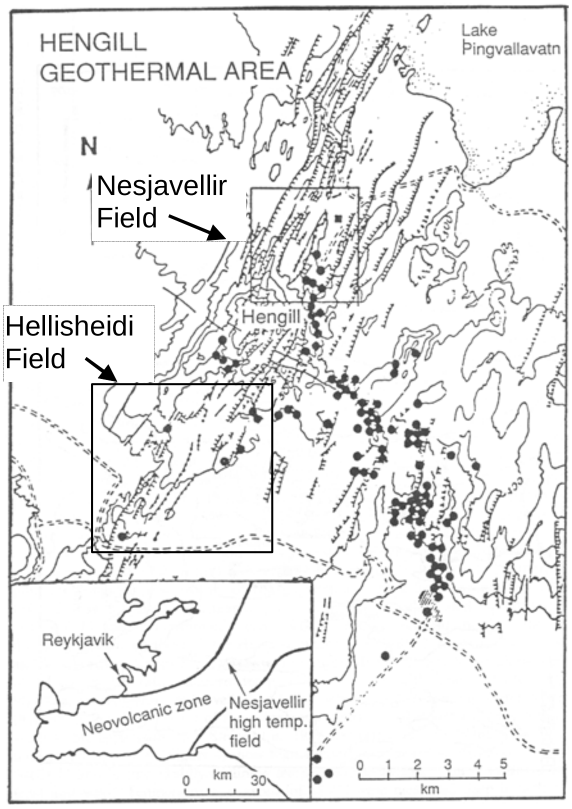

Figure 1. Location of Hengill central volcano in SW-Iceland, fissure/fault swarm, main geothermal manifestations (black dots) and the location of Nesjavellir and Hellisheiði fields (modified from Björnsson 1986).

The paper is largely built on data from the first seven wells drilled in the area, but available data from the more recently drilled wells are included where available. The geological data is mostly based on cutting analysis of samples taken at 2 m interval during drilling, and accompanying geophysical borehole logs (resistivity, caliper, neutron-neutron, natural gamma). Intense production drilling is presently taking place at Hellisheiði, and wells 12 and 13 are being completed at the time of writing of this paper, and further 7 wells will be completed in less than two years.

2. GEOLOGICAL STRUCTURES

Fig. 2 shows the topography of the southern part of Hengill mountain complex rising up to some 600 m elevation at Skarðsmýrarfjall. Fault and major fractures strike mostly NE-SW and are conspicuous in the east and west marking the boundaries of the fault and fissure zone of the volcano. Postglacial volcanism includes three fissure eruptions of 9, 5 and 2 thousand years. The volcanic fissures of the latter two are shown on Fig. 2. They can be traced further to the north, through the Nesjavellir field and into Lake Thingvallavatn (Sæmundson 1995). At Nesjavellir these volcanic fissures act as the main outflow channel of the geothermal system towards north. These fissures are also believed to act as major outflow zones in the Hellisheiði field as will be discussed later.

The geological data in boreholes are, as previously mentioned, derived mainly from cutting analysis of samples taken at 2 m interval during drilling, analyzed in binocular and petrographic microscopes, and alteration minerals further analyzed by XRD where applicable. Geological information is available down to over 2000 m depth in the west part of the field, while such information is lacking below about 600 m depth b.s.l. in the eastern part due to total circulation losses in the wells there. A large part of the data has been published in reports by Iceland GeoSurvey (ISOR) specialists for Reykjavik Energy.

2.1 Volcanic succession

The cross sections presented in the paper are located along the lines A-A´ and B-B´ (Fig. 2). The simplified volcanic succession are shown in Figs. 3 and 4. It is mainly composed of two rock types; hyaloclastites and lava series. The former is dominant and is formed in sub-glacial eruptions, while lava series form during interglacials. Basaltic hyaloclastite form when magma quenches during eruption into the base of the glacier, and piles up into a heap above the orifice, mostly as pillow basalts, breccias and tuffs. Although of relatively high porosity, these formations tend to have low permeability, especially when they have been hydrothermally altered. Hellisheiði field is within the Hengill central volcano where volcanism is most intense, and where hyaloclastites have formed highlands. Interglacial lavas, however, when erupting in the highlands will flow downhill and accumulate in the lowlands surrounding the volcano. This is shown in Figs. 3 and 4 where hyaloclastites dominate in the central part of the field while lava series intercalate the hyaloclastites in the western part and rapidly thin out towards east.

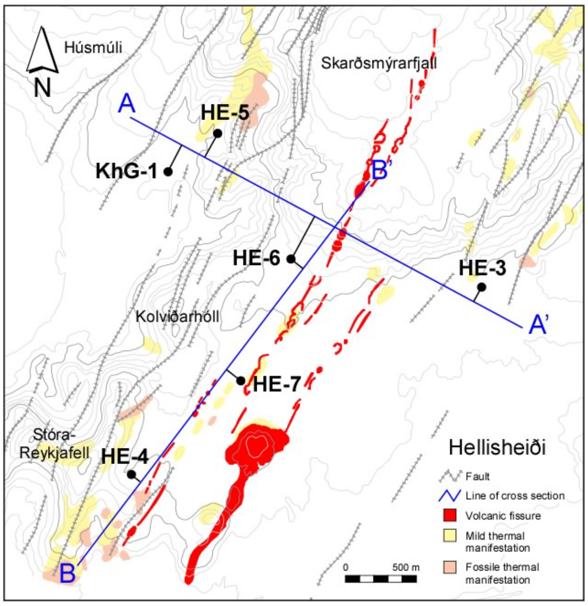

Figure 2. A topographic map of the Hellisheiði high-temperature field showing thermal manifestations (yellow=active, pink= fossil), location of wells and cross section lines, and two postglacial volcanic fissures (marked in red) discussed in text. Location of wells 8 to 11 are shown in Figures 7 to 10.

The top of the thick lava series found at about 900 m b.s.l. in well KhG-1 is interpreted as representing the base of the Hengill central volcano. This boundary is inferred to lie at about 1000 m b.s.l in the central part of the field, deduced from unpublished drillhole data of recently drilled well HE-10. This boundary is somewhat deeper than found in the Nesjavellir field in the north, where an age assessment of the boundary was about 300,000 years. This would suggest that the age of the Hengill central volcano may be somewhat older or around 400,000 years. That 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.

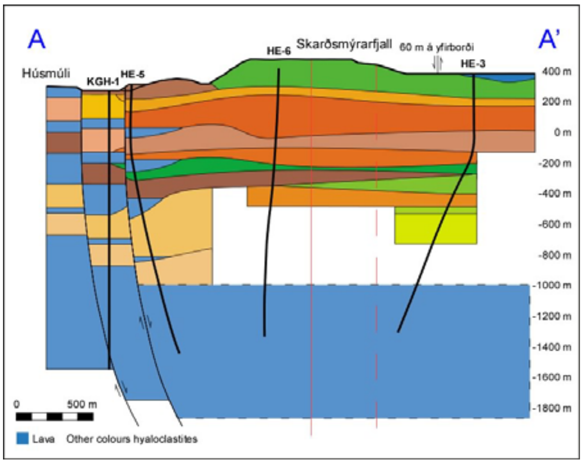

Figure 3. Geological cross section along line A-A`. Blue formations are lava series, and formations of all other colours are individual hyaloclastite formations. Note the large fault displacements to the left in the figure. The trace of the wells are shown as black lines. Thin orange coloured lines between wells 6 and 3 are traces of volcanic fissures of 2 and 5 thousand years.

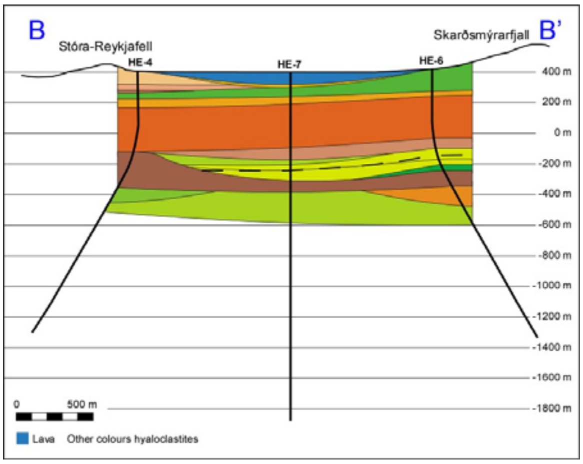

Figure 4. Geological cross section B-B´. Same legend as in previous Figure.

2.2 Faults

The geological cross section A-A´ shows the presence of two major NE-SW faults in the west part of the field with a total throw of about 260 m. These large faults can be traced to Jórukleif about 15-20 km to the northeast, where throw of the faults approach some 200 m towards SE. They are believed to represent the western margin of the Hengill fissure/fault zone (Árnason 1986, Sæmundsson 1995). Other major faults in the area are not found, and minor faults are more difficult to identify due to the lack of reliable horizontal marker horizons, such as lava series.

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 n-n and resistivity values. Figs. 5 and 6 show the occurrence of intrusions in the wells presented in the cross sections (Gunnarsson and Kristjánsson 2002). They are of two types: Fine grained basalt and fine grained andesitic to rhyolitic intrusions indicating that they are dykes and/or sills. The intrusions are scant down to about 800 m b.s.l. but become more numerous below. Similar intrusive rock types are found at Nesjavellir in the north, but preliminary study suggests that the intensity may be considerably less at Hellisheiði.

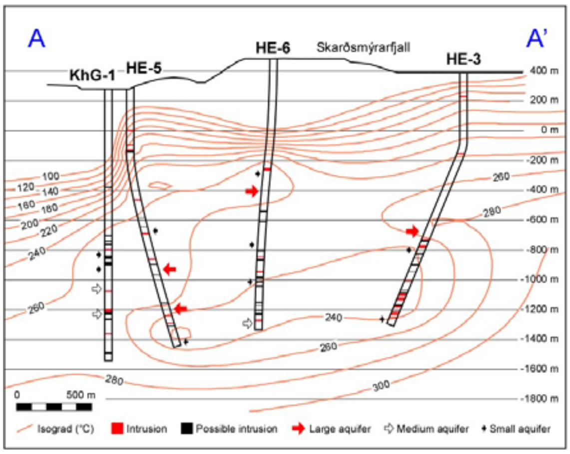

Figure 5. Cross section along line A-A´ showing temperature distribution, main aquifers and intrusions.

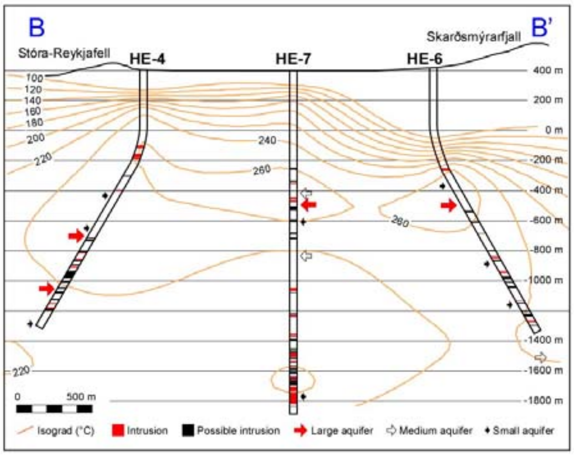

Figure 6. Cross section along line B-B´ showing temperature distribution, main aquifers and intrusions.

2.4 Aquifers

Aquifers (feed points) in the wells are located using circulation losses, temperature logs, hydrothermal alteration, and other relevant drilling data. A detailed analysis of these data and their exact relation to the geological factors is still ongoing. Aquifers are shown in Figs. 5 and 6, and it is interesting to see that they seem to be largest at locations of highest temperatures. The available evidence indicates that the large boundary faults found in the western part of the area may be major feed zones. Permeability along the two postglacial eruptive fissures is believed to be high causing a strong outflow towards south out of the Skarðsmýrarfjall hyaloclastite mountain. At least some of the aquifers encountered in the wells can be directly related to margins of intrusions indicating the dominance of fracture permeability in the geothermal reservoir.

2.5 Flow test and chemistry

Flow test has been completed for the wells drilled before 2004. The total flow is in the range of 30-70 kg/s. One well is producing almost dry steam (HE-9) but all other wells have enthalpy between 1200 and 1500 kJ/kg. The chemical composition shows that the fluid is dilute with total dissolved solids less than 1500 ppm, as is common in high-temperature geothermal fields in Iceland. Non condensable gases in the steam is also quite low (<0.5%).

3. HYDROTHERMAL ALTERATION

Hydrothermal alteration has been studied in some detail in the first six wells drilled in the area, and preliminary data are available in wells HE-8 to HE-11.

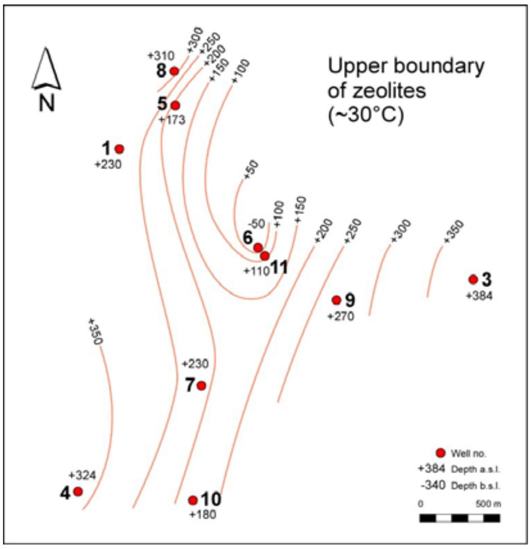

Figure 7. Depth contours to the upper boundary of low temperature zeolites occurrence.

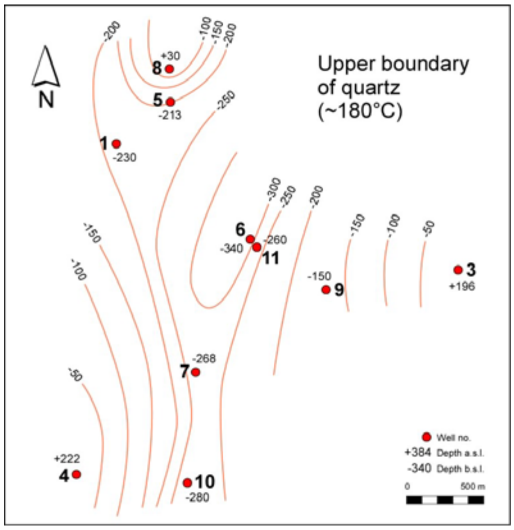

Figure 8. Depth contours to the upper boundary of quartz occurrence.

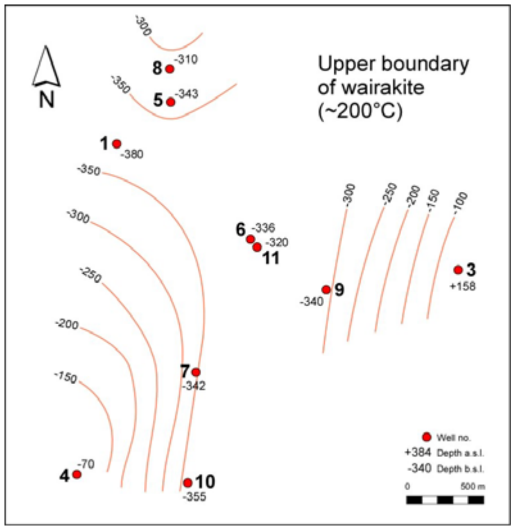

Figure 9. Depth contours to the upper boundary of wairakite occurrence.

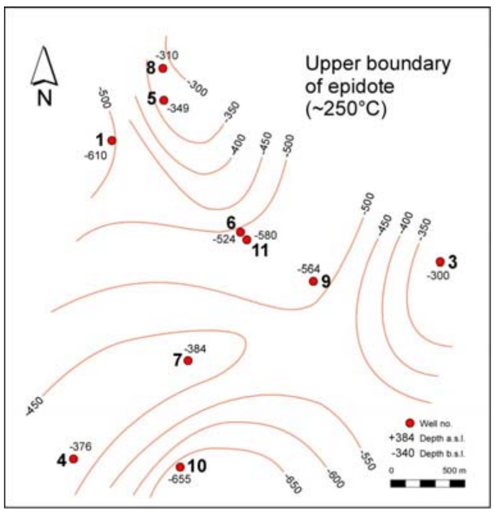

Figure 10. Depth contours to the upper boundary of epidote occurrence.

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 temperatures in the system.

The topography of the hydrothermal system is exemplified by the first occurrence of zeolites, quartz, wairakite and epidote as shown in Figures 7-10. All the figures show the elevation of hydrothermal alteration at shallower levels at three locations; firstly in the northwest, being most elevated in well HE-8, secondly in the east in well HE-3 where elevation of hydrothermal alteration reaches shallowest level and thirdly in the south around well HE-4. The hydrothermal alteration is lowest in wells HE-6, HE-9 and partly in HE-7, and these are situated in the central part of the drill field. The alteration stage becomes progressively higher with depth in the wells in the northwest part of the field, reaching well into the epidote-amphibole zone. Assessing the alteration in other parts was problematic due to lack of cutting samples until recently when HE-10 was drilled, where cutting samples were attained down to about 1900 m b.s.l.. The hydrothermal alteration in these wells show also progressive increase to epidote-amhibole zone around 1000 m b.s.l., with the latter mineral becoming abundant near the base.

4. TEMPERATURE DISTRIBUTION

The formation temperature in the geothermal system is shown in Figs. 5 and 6. These temperatures are attained by the estimated formation temperatures of individual wells and then extrapolated throughout the drilled area (Bjornsson and Hjartarson, 2003). Figure 5, which is an E-W cross section, shows an increasing temperature with depth reaching a maximum of just over 280°C in the depth range of 300-800 m b.s.l. in all wells, except those at Kolviðarhóll in the west (wells KhG-1). A reverse temperature gradient occurs below that depth where temperatures lower to about 240°C, and as far down as 220°C, as seen at about 2 km depths in wells HE-5 and HE-7. It is of interest to note that the largest aquifers (feed points) generally occur in areas of maximum temperatures, while aquifers are less common at depths of reversed gradients. Well KhG-1 in the western part of the field does not show a clear indication of reversed thermal gradient as in other parts of the field. It is interesting that permeability in that well is generally considerably lower. The temperature maxima observed in the wells, excluding the Kolvidarhóll one, is interpreted as an outflow zone from the inner part of the Hengill central volcano. Data from well HE-9, which is drilled between wells HE-3 and 6 to a depth of 1200 m b.s.l., and between the 5 and 2 thousand years old postglacial fissure eruptions, shows no indication of reversed thermal gradient below 800 m b.s.l. as in the other surrounding wells.

5. DISCUSSION

At the time of writing this paper Reykjavik Energy is intensely drilling production wells in the Hellisheiði field, and data is continuously being added to the present conceptual model of the geothermal reservoir. This presentation must therefore be assessed as the first step towards making a geothermal model of the field.

5.1 Geological relations

The geological succession of the Hellisheiði is dominantly built up of hyaloclastites, which are formations of relative limited horizontal extent which makes them of limited use as marker horizons. Lava series on the other hand are seen to bank up against the volcano in the western part of the field. These lavas are an indication of the western boundary of the volcano, as lavas are features of valley infillings. The rapid thinning of three interglacial lava series seen in wells 1, 5 and 8 towards east confirms that the western boundary of the Hengill volcano has been stationary at that location through its lifetime of some 400,000 years. The unusually large faults in the same area would also indicate the rather prolonged termination of volcanic activity west of Hengill area. This may furthermore have the implication that the high temperature reservoir deepens sharply west of the faults. The eastern boundary of the graben has not been observed and may either lie further east of well HE-3, or be taken up by increased dip of the strata towards the Hengill volcano. The lava series that is found in well KhG-1 at 3-500 m b.s.l. is characterized by olivine tholeiite lavas in the upper part while tholeiite lavas dominate in the lower part. A lava series of similar thickness and character is observed at similar depth range in Nesjavellir to the north, and this gives an opportunity to connect the stratigraphic succession across Hengill through this marker horizon.

5.2. Hydrothermal alteration

High-temperature alteration extends to relatively shallow levels at three locations as discussed in chapter 3. Alteration around HE-3 appears to connect to extensive fault-related thermal manifestations north of the well. The area around Kolviðarhóll in the northeast also shows a strong relation to fault controlled thermal manifestations. The elevation of hydrothermal alteration around well HE-4 is in line with more extensive alteration in Stóra-Reykjafell. That may relate to the underlying fault zone that extends from the northeast. If so it may open up the drilling into the same fault zone north of well HE-4. However, the apparent diminishing surface manifestations northeast of Stóra-Reykjafell, may imply that the elevated alteration in Stóra-Reykjafell may be a separate upflow zone, possibly connected to the eruption of hyaloclastite in that mountain. Well HE-15 which is scheduled to be deviated into that zone will confirm that speculation. The overall distribution of hydrothermal alteration thus implies the existence og three local upflow zones within the Hellisheiði reservoir.

5.3 Comparison of alteration and formation temperatures

The cross sections in Figs. 11 and 12 show a comparison of the temperatures assigned to the hydrothermal alteration and the present formation temperatures. In cross sections A-A´ and B-B´ a clear difference is observed, where the measured temperatures are considerably higher than the alteration temperature in wells 6 and 7, while near equilibrium is observed in other wells. Comparison below 800 m b.s.l. is only possible in a few of the wells due to the lack of cutting samples. In wells KhG-1 and upper part of HE-5 in the western part of the field, and well HE-4 in the south, the alteration appears to compare relatively well with the formation temperature. However, evidence from a recently drilled well HE-10, which is situated about 300 m south of HE-7 and where cutting samples were attained down to 1900 m b.s.l., shows a progressive increase in hydrothermal alteration to the bottom, where the appearance of amphibole coincides with the disappearance of calcite, indicates temperatures of above 290°C below about 1000 m depth. A comparison with the measured temperatures at 1800 m depth in this part of the field, which are in the range of 220-240°C, implies that the geothermal system has cooled down relative to the dominant hydrothermal alteration assemblage. This central part of the Hellisheiði field therefore shows a conspicuous heating up in the upper part of the reservoir, while a notable cooling has occurred in the deeper part of the system. This appears to be related to the location of the two aforementioned eruptive fissures (c.f. Fig. 2).

A comparison with hydrothermal alteration at Nesjavellir is interesting. There, comparison of formation temperatures and hydrothermal alteration shows cooling, especially near the boundary of the reservoir, while other parts show a general conformity. Recent heating in parts of the Nesjavellir has been related to a renewed northward geothermal outflow along the eruptive fissures which are the continuation of the 2000 and 50000 year old fissures in Hellisheiði (Franzson 2000). It is proposed that the same applies to the Hellisheiði field in the depth range of 200-800 m b.s.l. where hotter geothermal fluids flow southwards along the same eruptive fissures.

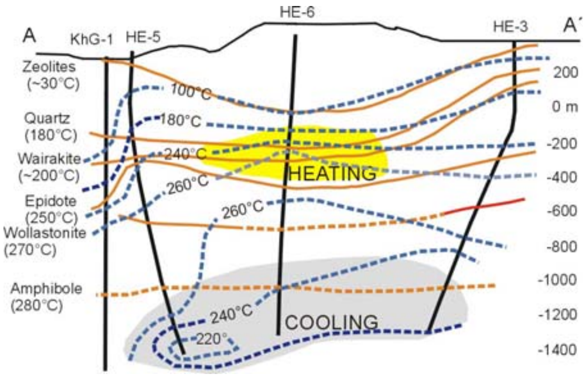

Figure 11. A comparison of alteration and formation temperatures in cross section A-A´ (c.f. Fig.2).

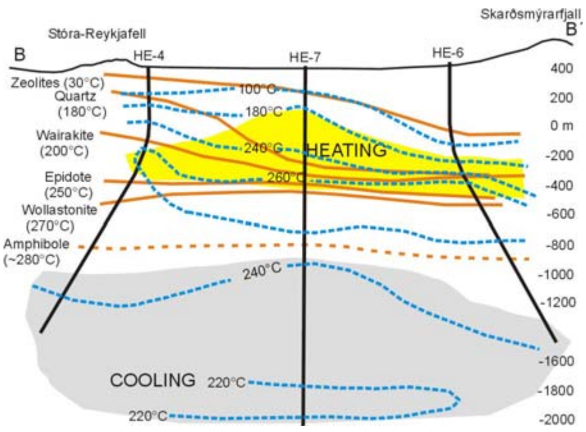

Figure 12. A comparison of alteration and formation temperatures in cross section B-B´ (c.f. Fig. 2).

The pronounced cooling occurring below that depth is interpreted as a colder inflow along the same fracture systems towards the geothermal system and forming in that way a convection system. The limited cooling that is observed in the western part of the field in the Kolviðarhóll area may be due to lower permeability in the reservoir, slowing down the encroaching cooling front of the surrounding groundwater. Similarities between Hellisheiði and Nesjavellir are thus considerable, though the outflow at the latter may be stronger and more localized and apparent amount of cooling may be more notable in the Hellisheiði. More detailed studies on alteration is undergoing in the Hellisheiði reservoir, but it is too early to establish whether the overall history of these systems match, confirming their common origin, or whether their history show contrasting evolution.

6. CONCLUSIONS

The exploration and production drilling so far in the Hellisheiði field have revealed several features relevant to the hydrothermal system.

1. The base of the stratification belonging to the Hengill volcano is estimated to be about 0.4 m.y., putting a constraint to the age of the geothermal system.

2. Large NE-SW faults of over 250 m total throw forms the western edge of the Hengill graben and fissure swarm. The relation of lava series and hyaloclastite formations indicate that this boundary has been stationary throughout the life of the Hengill system. Drillhole data suggests that the eastern boundary of the graben may be further east than well HE-3.

3. Intrusions become more abundant below about 1000 m depth b.s.l., but may not be as common as in the Nesjavellir reservoir to the north of Hengill. Postglacial basaltic eruptive fissures of 5 and 2 thousand years dissect the central part of the Hellisheiði, and are important in the field's permeability.

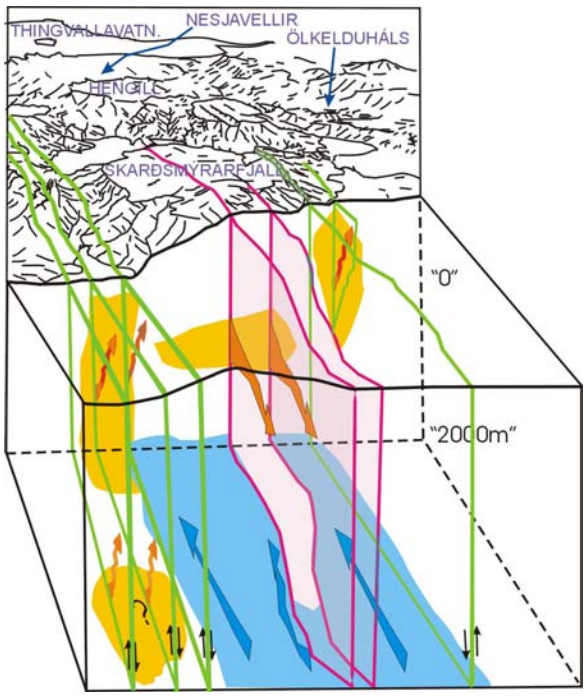

Figure 13. A conceptual model of the Hellisheiði high temperature system.

4. Figure 13 shows the salient features of the geothermal system. The major graben faults are seen in green lines and these contribute to the permeability of the reservoir there. More abundant hydrothermal manifestations in Stóra Reykjafell hyaloclastite along with shallower depths to hydrothermal alteration suggests that

these graben faults may cause a preferential upflow in that region. Surface alteration and high temperature alteration in HE-3, in the eastern part of the area (to the left in the Figure) is the highest found in Hellisheiði and suggests a neighboring upflow zone. The most important contributors to present high temperature permeability are believed to be the two postglacial volcanic fissures in the central part of the field (shown in pink). They are seen to open a high-permeability pathway, out of Skarðsmyrarfjall mountain towards southwest, of fluids of 260-280°C above 800 m b.s.l. depth. However, the lower formation temperatures at the base of the drilled reservoir compared to the alteration suggests that the same fissure structures are causing an inflow of colder waters towards the center of the reservoir to the north of the Skardsmýrarfjall mountain.

5. The geothermal system is a dilute system with dissolved solids less than 1500 ppm and low condensable gases. The enthalpy of the well discharge is ranging from 1200 to 1500 kJ/kg.

ACKNOWLEDGEMENTS

The Reykjavík Energy is thanked for the permission to publish the data. Reynir Fjalar Reynisson is thanked for drawing some of the figures.

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