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The Hengill Geothermal System, Conceptual Model and Thermal Evolution

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ABSTRACT

The Hengill volcanic system in SW-Iceland is a central volcano that produces basaltic and subordinate amount of more evolved rock types and is cut by an active NE-SW fissure swarm. Recent seismic activity indicates that the South Iceland Seismic Zone (SISZ) intersects the eastern part of the fissure zone forming a triple junction with the volcanic zone. The main geological features include a fissure zone and a graben into which most of the volcanic products (lavas and hyaloclastites) accumulate forming highlands in its central part. Three basaltic fissure eruptions of 9, 5 and 2 thousand years before present are found within the fissure swarm. Reykjavik Energy has explored and exploited the huge geothermal resource developed in this volcanic system, first in Nesjavellir in the northern sector and then Hellisheiði in the south. Extensive geophysical surveys including resistivity (TEM) and MT have been done to delineate the geothermal anomaly. A total of about 90 deep exploration, production and re-injection wells have been drilled into the geothermal resources at Hengill, and a few exploration wells have also been drilled in the Bitra and Hverahlíð fields to the east and south of Hengill central volcano respectively. Temperatures within the Hengill geothermal resource varies from about 200°C to about 320°C. In one well at Nesjavellir, probable superheated conditions prevail at about 2100 m depth. The dominant hydrothermal alteration indicates that the geothermal system reached a peak during the last glaciation, but has since then been gradually cooling. The evidence suggests that Holocene volcanic fissure eruptions opened up new flow paths and locally intensified the geothermal system. This postglacial episode has not changed the overall alteration pattern in the reservoir, and may not be seen in the resistivity, but becomes visible by comparing formation and alteration temperature in the wells.

1 INTRODUCTION

The Hengill volcanic system lies about 30 km east of Reykjavík. Reykjavik Energy started exploring the Hengill geothermal resource some 50 years ago. An early resource assessment in 1986 predicted the size of the geothermal area to be around 110 km^2 with a capacity of about 5500 GWh/y or 690 ME$_e$ for 50 years. The company has built a power plant at Nesjavellir producing 120 MWe and 290 MWth for space heating. Another power plant has been built in Hellisheiði presently producing 210 MWe.

This paper summarizes some of the results of the exploration that is used to define the geothermal resource, such as surface geology, resistivity and borehole studies. A comparison is made between temperatures measured in the formations and the temperature inferred from alteration to show the evolutionary trend of the geothermal system.

2 SURFACE EXPLORATION

2.1 Geological Background

The Hengill volcanic system lies within the western volcanic zone of Iceland, as shown in Figure 1, at a location where South Iceland Seismic Zone (SISZ) intersects the riftzone forming a triple junction.

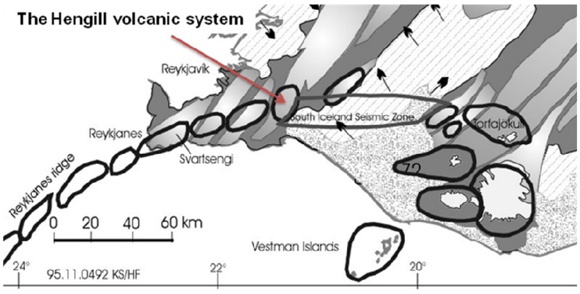

Figure 1: Geological map of SW-Iceland showing the eastern and western volcanic zones (grey colour), volcanic systems (elongated patches within the volcanic zones), the location of Hengill volcanic system and the South Iceland Seismic Zone.

2.2 Surface Geology

The geology of the Hengill volcanic system has been intensely studied (Sæmundsson, 1967, 1995a, 1995b; Árnason et al., 1987). The main component of the volcanic system is a 3-5 km wide and about 40 km long fissure swarm where rifting is most active and with maximum volcanic accumulation in the central part of the Hengill volcano (Figure 2). The fissure swarm is a depression or a graben structure with large graben faults that have a total throw on the western side of more than 300 m. The faults on the eastern side have not been located as accurately but are assumed to have an overall similar throw taken up by a greater number of step-faults. The largest part of the volcano is built up of hyaloclastite formations erupted during glacials, while interglacial lavas erupted in the highlands flow to the surrounding lowlands. Intermediate and felsic rocks are found in the western edge of the volcano, but have also been found as intrusives in the drillholes throughout the geothermal fields. Three lava eruptions have been recorded in Holocene time, nine, five and two thousand years ago. The latter two are shown in Figure 2 and play an integral role in the explored part of the Hengill geothermal system as discussed below. Surface thermal alteration is extensive, being most common in the Hengill table mountain in the centre of the volcano, but is evident throughout the volcano. Most of the alteration patches show a clear relation to tectonic faults and fissures. They are though mostly fossil indicating a more active system in the past. Surface geothermal activity is common as shown in Figure 2. Majority of these, however, lies on a northerly line extending from Hengill/Nesjavellir in the north through the subsidiary Ölkelduháls volcanic system called Hrómundartindur/Ölkelduháls to Hveragerði in the southeast.

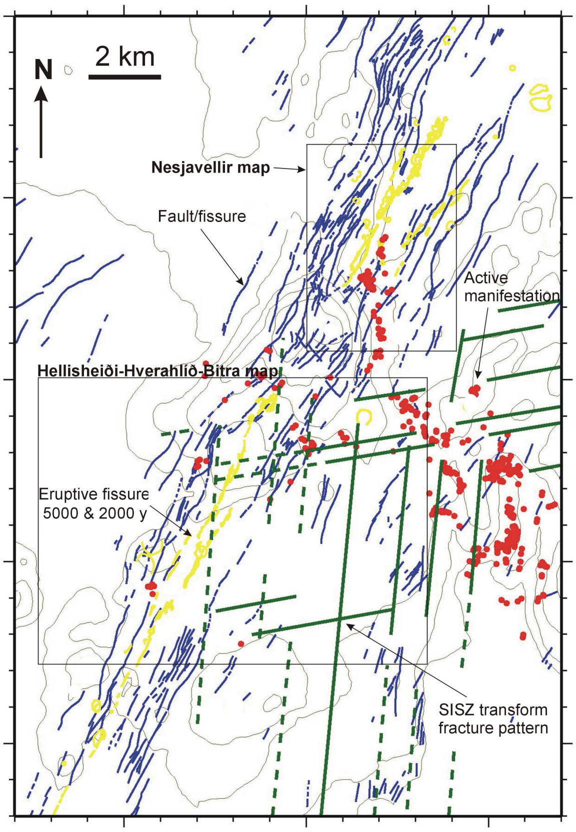

Figure 2: The Hengill volcanic system showing the topography, the faults related to the transform system (SISZ), and the post-glacial eruptive fissure swarm cutting the central volcano. The Hellisheiði-Hverahlíð-Bitra and Nesjavellir maps refer to figures 11-16.

2.3 Geophysical Exploration

Several geophysical exploration methods have been used to define the structures and the characteristics of the geothermal system in Hengill, including Bouguer gravity survey (Þorbergsson et al., 1984; Árnason et al., 1987), aeromagnetic survey (Björnsson and Hersir, 1981), seismic refraction and passive seismic surveys (Pálmason, 1971; Fougler, 1984). The most informative exploration method in defining the geothermal reservoir prior to drilling is, however, resistivity. The methods used in the Hengill area include Schlumberger and dipole-dipole survey (Hersir, 1980; Björnsson and Hersir, 1981). In 1987 the TEM method was applied, and to date some 280 TEM soundings have been made. Árnason et al. (2000) related the resistivity structures to variations in hydrothermal alteration, which appear to be of greater importance than the temperature variation. The low-temperature clay-rich outer margin of a high-T reservoir is characterized by low-resistivity and the underlying higher resistivity is associated with the formation of chlorite and less water-rich alteration mineral assemblage. Figure 3 shows a resistivity map at 850 m b.s.l. in the Hengill area where the high-resistivity core is shown as the cross-hatched area.

Although the high-resistivity shows some relation to the dominant NNE-SSW alignment of the fissure swarm, a broad WNW-ESE structure crosses Hengill from Húsmúli in the west to Bitra and Hveragerði in the east. These structures have been confirmed by the zonation of temperature dependent alteration minerals in drillholes, but the formation temperatures have though been variable as is discussed below.

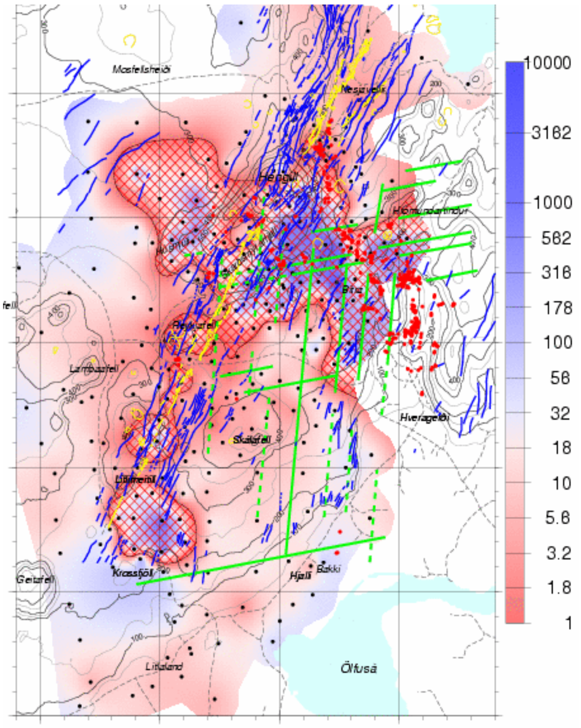

Figure 3: A resistivity map of the Hengill central volcano at 850 m b.s.l. showing variations in resistivity. The cross-hatched areas define high resitivity cores below low resistivity, and are interpreted to indicate alteration temperatures of over 230°C.

Hengill is a very seismically active area, as would be expected from the dense fissure swarm and recent eruptions. Two kinds of tectonic activity seems to prevail in the Hengill area; dilationary rifting as exemplified by the fissure zone, and a transform component concentrated in the eastern part of Hengill and related to the SISZ. The last major earthquake episode associated with the Hengill fissure swarm occurred in 1789 with a significant subsidence along the graben faults. Intense seismic activity occurred in 1991-2001 which appeared to associate with transform tectonic activity related to the South Iceland Seismic Zone (SISZ). The activity appeared to concentrate along N-S and ENE-WSW lines, mostly in the eastern part of the Hengill area, as seen in Figure 2. A study of fracture pattern from aerial photographs has shown a similar combination of fracture directions (Khodayar and Franzson, 2007). The Hengill volcanic system can therefore be considered to be located at a triple junction. This must affect permeability in the crust as discussed later.

MT soundings were first employed in the area in 1976 (Hersir, 1980), and then more comprehensively in more recent INTAS, I-GET and ISOR projects. These data have been integrated with the available TEM data in order to construct a comprehensive map of resistivity from surface down to over 15 km depth (Árnason et al., 2009). Figures 4 and 5 show the emergence of two conducting layers below 4 km depth which lie in a WNW-ESE direction. The shallower one extends from Hengill mountain towards Bitra. The true meaning of these low resistivity bodies are not clear, but some kind of fluids or even minor partial crustal melting is inferred. The presence of these shallow

low resistivity bodies have raised hopes for a zone of supercritical fluids that could be reached by conventional drilling.

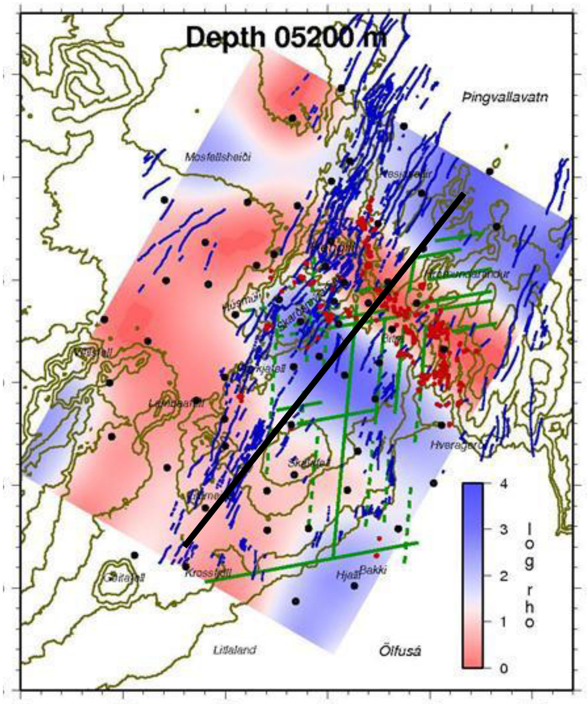

Figure 4: Resistivity at 5200 m b.s.l. as observed from TEM-MT surveys (Árnason et al., 2009). Black line indicates the alignment of cross-section shown in Figure 5.

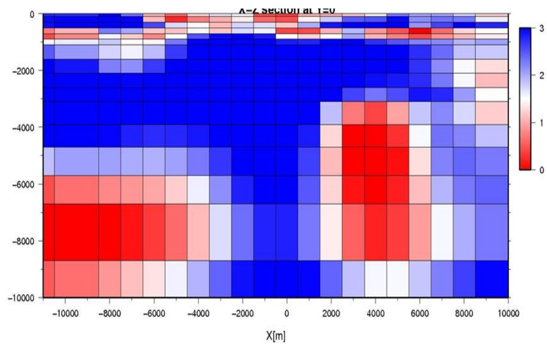

Figure 5: A NE-SW cross section showing low- and high-resitivity structures down to 10 km depth. North-east end is to the right on the picture.

3 SUB-SURFACE EXPLORATION

3.1 Introduction

The exploration drilling of the Hengill system started at Nesjavellir in 1965 with five wells and continued 1981-1985 with the drilling of 13 wells. Hot water production started in 1990 and power generation in 1998. Further 10 wells have been drilled as step out and make up wells, along with a few shallower reinjection wells.

Drilling exploration of the Hellisheiði field started with a well at Kolviðarhóll in 1986, and in 1990 a well in Bitra was drilled. A major exploration effort started in Hellisheiði in 2001 and to date 49 production type wells have been drilled in the area along with 14 reinjection wells, most of them deep (>2000 m). Three exploration wells have been drilled in the Bitra field and another five exploration wells in Hverahlíð. The location of the wells is shown in Figures 10-16.

The depths of wells range from about 1000 m down to 3322 m, the deepest well drilled in Iceland. While vertical wells dominate in the Nesjavellir field, directional wells are dominant in the newer geothermal fields, where up to four wells are drilled from each drill pad.

The methods used to study the subsurface character of the geothermal system include analysis of drilling data, cutting samples, lithological logs, temperature and pressure data, fluid sampling and productivity data.

A major effort is presently underway to study in more detail the geothermal reservoir in the southern part of Hengill.

3.2 Nesjavellir Field

The subsurface geology and geothermal condition of the Nesjavellir reservoir has been studied in some detail (e.g. Franzson 1998, 2000, et.al. 1986, Steingrímsson et al., 1990). The results from those studies can be summarized as follows: A simplified geological cross-section (Figure 6) shows a dominant hyaloclastite accumulation down to about 400 m b.s.l.. below which lava accumulation dominates. This level has been interpreted as the start of the Hengill central volcano. A similar feature, but slightly deeper, has been found in the southern part of Hengill volcano. A tentative age of 0.3 to 0.4 my has been put on this stratigraphic level, which constrains the age of the central volcano and provides a maximum age of the geothermal system. The intrusive rocks are basaltic dykes or sheets which become noticeable below about 800 m depth and increase up to 80-100% intensity below 2000 m depth. Shallow-dipping dioritic sheet-like intrusions are also found at various depths and they contribute substantially to the permeability in the field, along with the basaltic intrusions. Hydrothermal alteration has also been mapped in a considerable detail with respect to hydrothermal zonation, time evolution and fluid inclusions. The cross section in Figure 7 shows the shape of the temperature dependent alteration zones. These show a clear relation to faults, a feeder to a hyaloclastite ridge and possibly the feeders to the 5000 and 2000 y old volcanic fissures. The time relations of the hydrothermal mineral deposition into voids show a heating of the geothermal system and expansion to shallow levels culminating into the present alteration zones. However, calcite deposition is observed to overprint higher T alteration as the last mineral phase deposited in most parts of the area, especially in the upper region of the system. A number of fluid inclusion studies have been done on the alteration minerals, in particular the calcite. The calcite Th-temperatures show a range in most cases lower than expected from the alteration temperature zonation, which indicates that the geothermal system has been cooling in recent time. A comparison between the alteration temperatures and fluid inclusions on one hand and the present formation temperature on the other often shows a significant discrepancy.

In places, the present formation temperature is significantly lower than inferred from the alteration and fluid inclusion data, with other locations being in equilibrium or giving higher temperatures than the alteration. This is shown schematically in Figure 7. It shows higher formation temperature along the same structures that controlled the highest alteration temperatures, and both are related to the location of the recent fissure eruptions. It is of interest to mention that an over pressurized aquifer was encountered at 2150 m depth in well NJ-11, (see Figure 7), with a temperature surpassing the critical temperature. The zone showing formation temperatures above alteration temperatures seems to extend horizontally towards east at a depth range of 600-1100 m b.s.l., and is controlled by aquifers connected to basaltic sills. Formation temperatures lower than alteration temperatures are at two depth levels on the eastern side; at 300-600 b.s.l. and 1400-1900 m b.s.l. Cooling is much more conspicuous in the western part of the area where temperatures are considerably lower than indicated by alteration in well NJ-12 down to 1400 m b.s.l. (c.f. Figure 7). The difference is even greater in the other two wells in Kýrdalur.

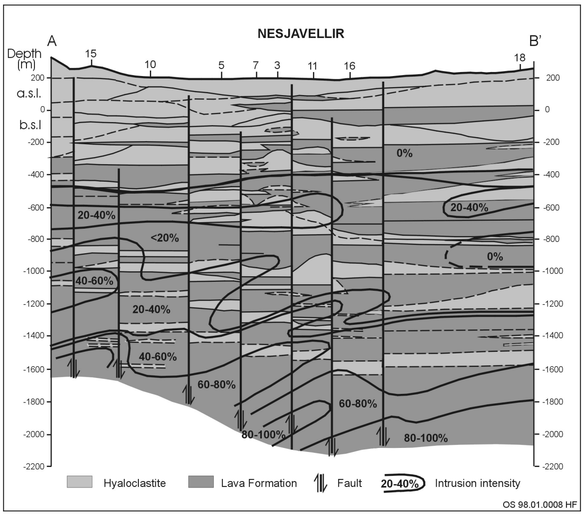

Figure 6: A simplified N-S geological cross-section through the Nesjavellir field, showing the distribution of lavas and hyaloclastite formations, and isolines of intrusion intensity (Franzson, 1998).

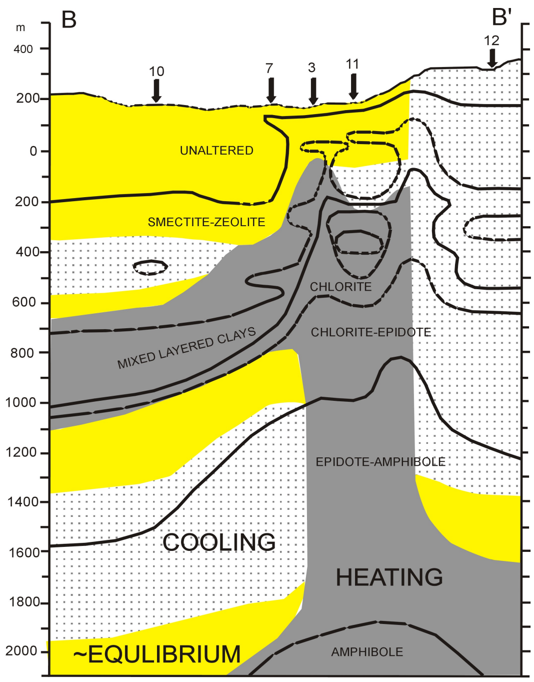

Figure 7: An E-W cross section across the Nesjavellir field showing the alteration zones (separated by isolines) and a comparison between formation and alteration temperatures showing cooling, equilibrium, heating (dotted, yellow and gray shades) (Franzson, 2000).

The interpretation of this data suggests strongly that the Nesjavellir system has been cooling gradually from the stage of maximum alteration, but geothermal activity intensified recently, probably related to the Holocene fissure eruptions of five and two thousand years.

3.3 Bitra Field

Three exploration wells have been drilled in the Bitra field which is located to the east of Hengill (e.g. Figure 14). The geological features in the wells show a dominant succession of hyaloclastites, which have been interpreted as belonging mostly to the Hveragerði central volcano, the precursor to the Hengill volcanic system (Steingrímsson et al., 1997). The Bitra formation, a small lava shield, overlies a large part of the field, and has been dated from the onset of Holocene or about 13000 y.

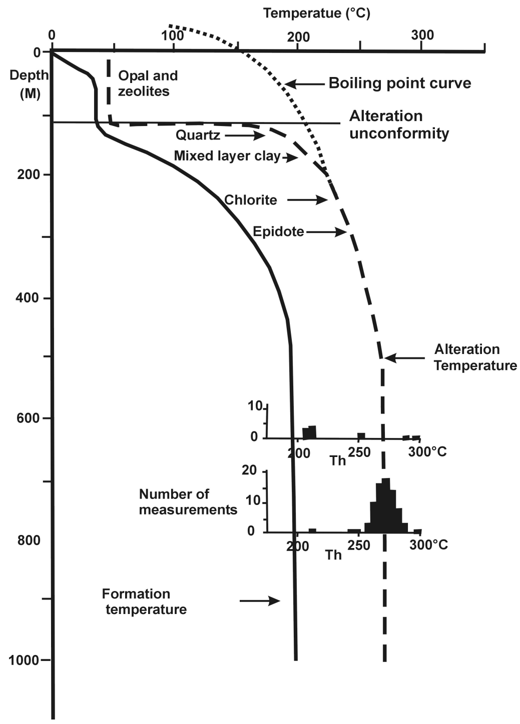

Figure 8: Formation-, alteration- and fluid inclusion temperatures in well ÖJ-1 in Bitra field (Steingrímsson et al., 1997).

Surface alteration is extensive in the Bitra area, some of it related to areas that are no longer hydrothermally active. Figure 8 shows the salient features of the alteration and thermal condition in the field. The formation temperature shows low temperatures down to below 120 m where it increases to just under 200°C at 500 m depth. This is a large contrast to the alteration minerals, which indicate much higher temperatures. The two temperature curves conform well within the Bitra formation, but diverge in the underlying glacial tillite where the alteration curve increases to over 180°C as indicated by the appearance of quartz, with mixed-layer clay, chlorite and epidote at slightly deeper levels, while the formation temperature increases more gradually up to 200°C at 500 m depth. It appears obvious from the contrast in alteration that the intense high temperature activity occurred prior to the eruption of the Bitra formation. Furthermore, the formation of the high-temperature assemblage, confirmed by the fluid inclusion analysis, would imply a hydrostatic pressure equaling to a water table at least 150 m above the surface prior to the Bitra eruption. Such an environment could only be attained during a glacial interval where the water table would reside within a thick ice cover. Similar results are found in the other two wells in Bitra, indicating that the geothermal system in this region has been gradually cooling during the glacial period and became moderately active when the Bitra lava shield erupted about 13000 y ago.

3.4 Hellisheiði Field

The main drilling in the Hellisheiði field started in 2001 and to date 46 exploration/production wells and twelve deep reinjection wells have been drilled (Figures 14-16). The very intense drilling of wells has resulted in a limited time to do detailed research into the geological factors controlling the geothermal system. Reykjavik Energy has, however, started numerous studies and the picture of the geothermal system is rapidly becoming clearer (Franzson et al., 2005; Gunnarsson and Kristjánsson, 2003; Helgadóttir et al., 2010; Hardarson et al., 2010; Haraldsdóttir et al., 2010; Kiflom et al., 2010, and references therein). The overall stratification in the field shows similar character as in Nesjavellir with hyaloclastite dominating down to 800-1000 m b.s.l. underlain by a more dominant lava sequence. This hyaloclastite/lava boundary lies somewhat deeper than found in Nesjavellir, which may indicate that the age of the central volcano is slightly older to the south, on the order of 0.4 my. Intrusions are mostly fine-grained basalts, with subordinate amounts of more evolved rock types. A comparison of intrusive frequency between Nesjavellir and Hellisheiði has not been done as yet, and may not be straight forward, as most of the Nesjavellir wells are vertical while the Hellisheiði ones are directional. Preliminary studies show, however, that intrusions become very common below about 2 km depth. There are two main drilling targets in the Hellisheiði field. Firstly, the 2000 and 5000 y old volcanic fissures; the same geological target as in the Nesjavellir field to the north. Secondly, the large fault structures at the western edge of the Hengill graben. These faults serve as major permeable structures of the hydrothermal system, and also as targets for reinjection wells. A similar fault system lies west of the explored part of the Nesjavellir system, but has not yet been drilled into. A few wells target the fault structures on the eastern margin of the Hengill graben.

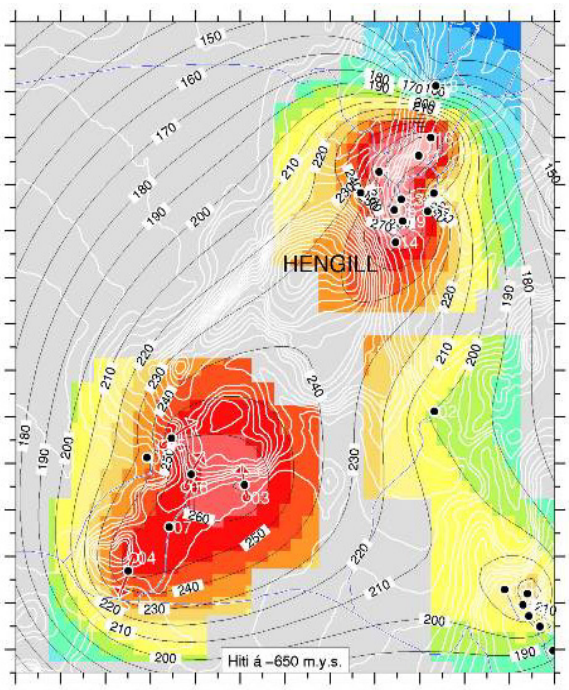

Figure 9: Temperature distribution in the Hengill area at about 1000 m depth interpolated from formation temperatures in wells (Björnsson, 2007).

The formation temperatures have been interpreted based on the well logs and on Figure 9 shows the temperature distribution at about 1000 m below sea level.

Figure 10 shows a NE-SW cross-section along the fissure zone (c.f. Figure 2). A model of a single up-flow zone underlying the Hengill mountain with an outflow from that towards south into Hellisheiði and north towards Nesjavellir has been postulated, along with inflow of colder water from the outer margins resulting in convective mixing. This model is still being developed and discussed as new data are rapidly emerging, which may suggest a more complex solution.

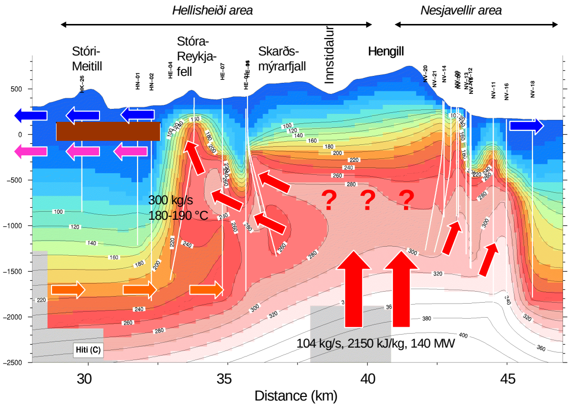

Figure 10: A NE-SW cross section of Hengill showing temperature distribution and an estimation of flow in the reservoir down to 2500 m b.l.s. (Björnsson, 2007).

3.5 Hverahlíð Field

The Hverahlíð geothermal field lies to the south of Hellisheiði (figures 14-16). Five exploration wells have been drilled there ranging in depth from 2000 to 2800 m (Níelsson and Franzson 2010). The first well was sited near to the only surface manifestation, the second one was sited to the west and directed into the most active part of the fissure swarm, and the third one was to explore the northern sector of the field. Hyaloclastites interpreted as evidence of highlands and the existence of a central volcano, are dominant in the Hengill area. In Hverahlíð, on the other hand, lava successions are more dominant, indicating that the area is more distal to the central volcano. Temperature is among the highest in the southern part of the Hengill, where 320°C is observed at the base of the first well there, HE-21. The depth to the cap rock and temperature of the geothermal system increases towards west and north. The completion of three wells in 2009 has given more comprehensive answers to the extent of the field, but is not dealt with here.

4. THERMAL EVOLUTION

4.1 Introduction

The Hengill volcano is located, as are other active central volcanoes in Iceland, in a very dynamic environment. Magma is interpreted to provide the heat source to maintain the geothermal gradient and drive the geothermal system, and is periodically injected into relatively shallow crustal environment. There is no seismic evidence of an underlying volcanic magma chamber in the roots of the Hengill volcano at present. The fissure swarm is about 3-4 km wide in the Hengill area, but its activity shifts within these boundaries, causing permeability changes with time, both within the geothermal system, but perhaps more importantly, varying the ability of the overlying cold groundwater systems to intrude on the geothermal system. The South Iceland Seismic Zone (SISZ) is an additional tectonic element that must influence permeability in at least the eastern part of the Hengill region. Magmatic activity and a potential heat source may also associate with the SISZ (Feigl et al., 2000). The effect of glaciation on groundwater/geothermal systems may perhaps be greatly underestimated, and one must bear in mind that the country has been covered by a thick ice-sheet for about 90% of its lifetime.

4.2 Nesjavellir Field

The integrated surface and borehole studies at Nesjavellir explain a number of features of the geothermal system (Franzson 1998, 2000). Firstly, it has shown the evolution of the geothermal system with time, gaining strength and expanding to shallow levels, before showing effects of cooling throughout the system. Succeeding the cooling comes a renewed geothermal phase in a selected part of the geothermal system, evidenced by elevated temperatures at shallow to deep levels, possibly extending up to superheated temperatures. This renewed heating is not noticeably reflected in a change in the alteration zonation, which is an indication of its young age. The fact that the heating coincides with the location of the 5000 and 2000 year old fissure eruption sites strongly suggests that the renewed heating may be due to these eruptions, either because highly permeable fractures associated with the feeder dykes opened new up- and outflow-paths for the geothermal fluid, and/or that the eruption emplaced a new heat source at depth within the Hengill volcano. In either case, this provides a time frame for the formation of hydrothermal alteration, i.e. that it may require more than 5000 years to re-establish an alteration zone in equilibrium with in situ formation temperatures. The evidence from Bitra shows conclusively that the shallow and pervasive high temperature alteration was formed during the last glacial period, and prior to the eruption of the Bitra formation. One would therefore be tempted to speculate that the elevated high temperature alteration in Nesjavellir might also be derived from last glacial (15,000-120,000 y). If this conclusion is correct, it can be applied to the Hengill as a whole. Furthermore, because it has been established that resistivity structures are dominantly related to alteration zonation rather than purely temperatures, resistivity surveys may not detect subsurface changes occurring in the last 5000 y or so. It is therefore proposed here that comparing formation temperatures with alteration temperatures is the best means to detect changes that have taken place in postglacial time, which is a short time on geological scale, but very long in terms of geothermal utilization.

Figures 11 to 13 show an estimate of the temperature difference between formation (Tf) and alteration (Ta) in the Nesjavellir field at three depth levels; at caprock level, around 1000 m and at about 1500 m depth. These results are shown along with the location of the two postglacial basalt eruptions in the central part of the Nesjavellir.

The Nesjavellir system shows, as discussed above, a bimodal temperature difference with the western part showing pronounced cooling, while heating is occurring on the eastern side of the volcanic fissures. It is suggested here that this may be caused by down-flow of colder groundwater along the most active part of the fissure-swarm west of the volcanic fissures, as shown in Figure 11. The apparent cooling in the eastern part of the field at about 1500 m depth may be related to cooler inflow along shallow dipping dioritic intrusive sheets.

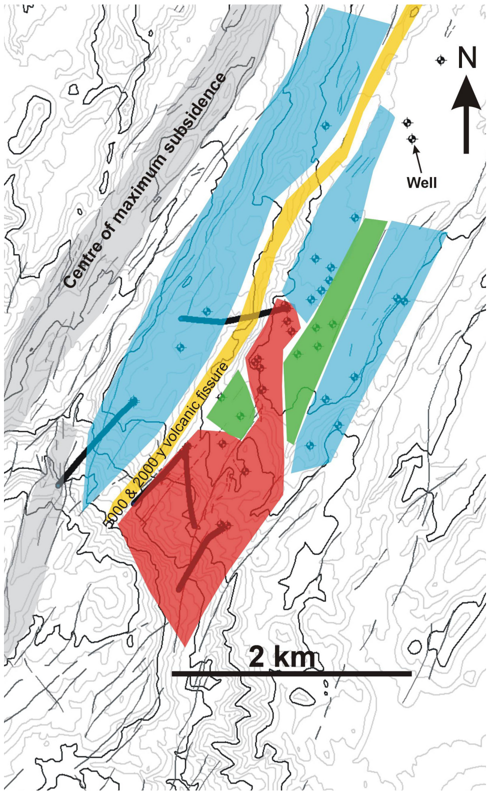

Figure 11: Nesjavellir field. A map showing the center of maximum subsidence, the 5000 and 2000 y old volcanic fissures and a comparison between formation temperature (Tf) and alteration temperature at caprock depth. (Ta) Red colour indicates Tf > Ta, green indicates Tf ~Ta and blue Tf < Ta.

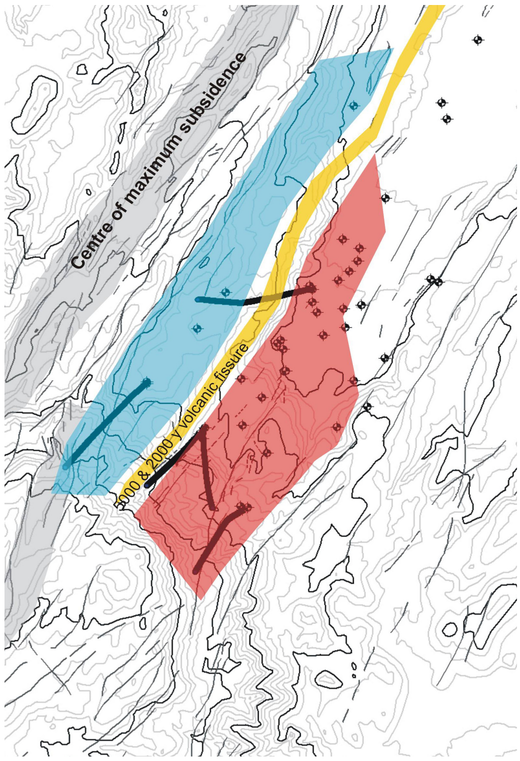

Figure 12: Nesjavellir field. A comparison between formation temperature (Tf) and alteration temperature (Ta) at ~1000 m depth. Red colour indicates Tf > Ta, green indicates Tf ~Ta and blue Tf < Ta.

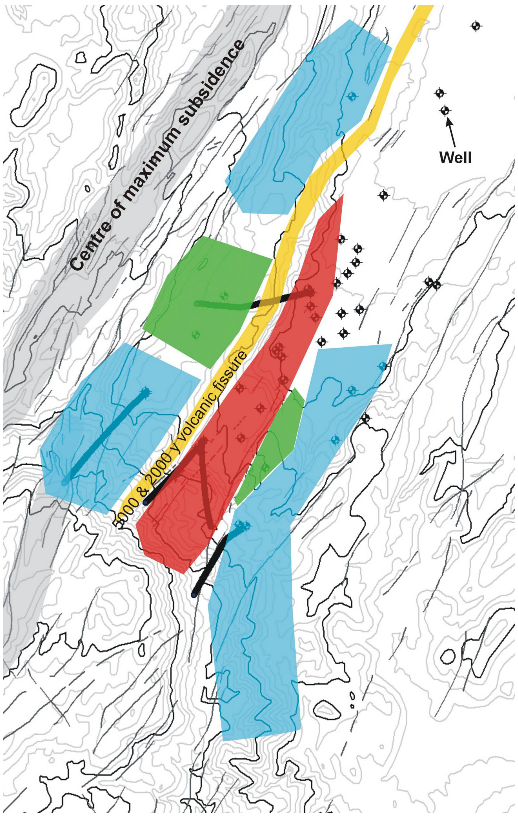

Figure 13: Nesjavellir field. A comparison between formation temperature (Tf) and alteration temperature (Ta) at ~1500 m depth. Red colour indicates Tf > Ta, green indicates Tf ~Ta and blue Tf < Ta.

4.3 Bitra Field

The much lower formation temperatures in Bitra, as compared to the alteration temperatures, are seen at all depths except in the easternmost well where the two temperatures are in equilibrium below 1500 m (Figures 14-16). It is tentatively suggested here that this very effective thermal mining is due to the combined permeability of the fissure-swarm and the superimposed fractures of the SISZ (c.f. Figure 2). It is also suggested that this thermal mining continues further west into the eastern part of Skarðsmýrarfjall.

4.4 Hellisheiði Field

Figures 14-16 show a similar relation between the differential temperature and the geological features in the Hellisheiði field. A recent heating occurs within the depth range of the caprock along the volcanic fissures (Figure 14). This heating is most pronounce at the southern slopes of Skarðsmýrarfjall, but is only vaguely detected in wells in central and eastern Skarðsmýrafjall. It is of interest that alteration temperatures at shallow levels seem to be higher than the present formation temperatures in the western part of the field. The deeper section in Figure 16 shows that a large part of the Skarðsmýrarfjall has suffered thermal mining (cooling), and only in a very localized part in between the 5000 and 2000 year old volcanic fissures do we still see evidence of formation temperatures higher than alteration temperatures. The thermal anomaly appears also to be present in Stóra Reykjafell further to the southwest. In general, thermal mining seems to be more pronounced in the eastern part of the Hellisheiði system and it is suggested that it may be due to higher permeability in that region compared to the area west of the volcanic fissures due to fracturing related to the SISZ. This thermal mining appears to be most effective at a depth range of ca 1400-2000 m.

4.5 Hverahlíð Field

The three wells in Hverahlíð field in the southern part of Hengill also show contrasts in formation and alteration temperatures as shown in Figures 14-16. Well 21, which is located near to the only thermal manifestation, shows consistently higher formation temperatures than the alteration, while well 26 shows lower formation temperatures in the three depth levels. Well 36, on the other hand, shows equilibrium at the depth of the caprock, a slightly higher formation temperatures at 1000 m depth, but then a pronounced temperature reversal below 1500 m depth. It is tempting to suggest that the thermal mining at the base of the well is related to the most active part of the fissure swarm as shown in Figure 16, similar to what has been proposed for Nesjavellir. The higher formation temperatures in the upper part of the system compared to the alteration temperatures, however, raises hopes that a relatively recent heating episode has occurred in that area, unrelated to the aforementioned volcanic fissures. That upflow channel has not yet been identified.

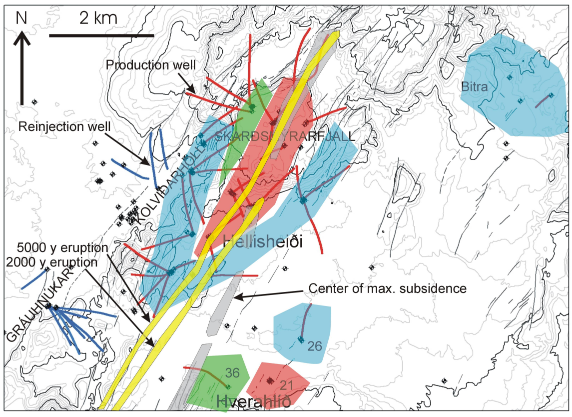

Figure 14: Hellisheiði, Bitra and Hverahlíð fields. A comparison between formation temperature (Tf) and alteration temperature (Ta) at ~cap rock depth. Red colour indicates Tf > Ta, green indicates Tf ~Ta and blue Tf < Ta.

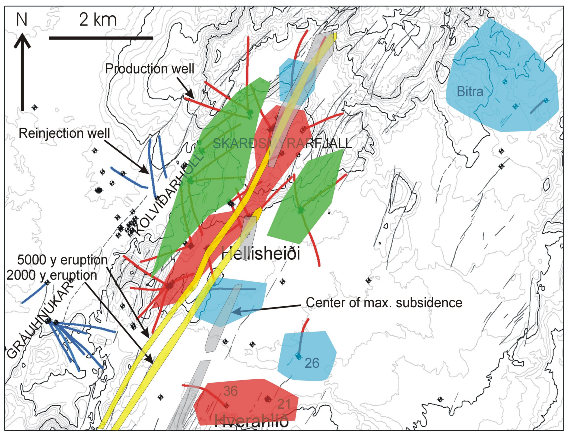

Figure 15: Hellisheiði, Bitra and Hverahlíð fields. A comparison between formation temperature (Tf) and alteration temperature (Ta) at ~1000 m depth. Red colour indicates Tf > Ta, green indicates Tf ~Ta and blue Tf < Ta.

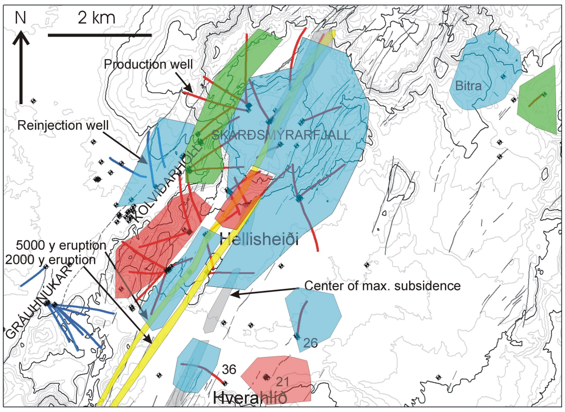

Figure 16: Hellisheiði, Bitra and Hverahlíð fields. A comparison between formation temperature (Tf) and alteration temperature at ~1500 m depth. (Ta) Blue colour indicates Tf > Ta, green indicates Tf ~Ta and red Tf < Ta.

4.6 Summary

The main conclusion of this discussion is that the high-temperature system at Hengill seems to be controlled by three factors: 1) thermal mining by down-flow of shallow cold groundwater system, 2) inflow of lower temperature hydrothermal fluid and thermal mining of hotter rocks at a depth level of 1500-2000 m depth, and 3) a hot upflow from a deeper reservoir which is connected to the 5000 and 2000 y old volcanic fissures. A separate upflow may exist in the neighborhood of well 21 in the Hverahlíð field. It is too early to postulate where that upflow lies, and this will have to wait until more drilling is completed in that area.

5. CONCLUSIONS

This paper summarizes some of the results of geothermal exploration in the Hengill volcanic system.

Surface geothermal manifestations in the Hengill area are closely related to the fissure zone, the central volcano and to the post-glacial volcanism.

Resistivity surveys have identified a 110 km^2 thermal anomaly at 850 m depth and a low resistivity structure below 4 km depth.

A comparison of the formation and alteration temperatures in the boreholes implies an evolution of the geothermal system where it apparently reaches a peak during the last glacial period and is succeeded by an overall gradual cooling during Holocene. This cooling is occurring either from above through the caprock of the system or along the tectonically most active part of the graben formation, preferentially at 1300-2000 m depth. Additional cooling is caused by the strong tectonic elements of the SISZ that enters the eastern part of the Hengill fissure swarm.

The cooling is locally interrupted by a heating episode in the area around the 5000 and 2000 year old fissure eruptions that dissect the Hengill central volcano. This heating is postulated to be the result of renewed upflow channels along these fissures from the roots of the Hengill geothermal reservoir and/or a replenished magmatic heat source for the geothermal system associated with the fissure eruptions.

A separate high-temperature system is located in the Hverahlíð area to the south of Hengill central volcano. This system shows higher formation temperatures than alteration in the upper part indicating a Holocene heating episode similar as found in Hengill. The source of that heating is still undefined.

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