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## EXPLORATION AND DEVELOPMENT OF THE HENGILL GEOTHERMAL FIELD

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### ABSTRACT

The Hengill geothermal field is one of the biggest geothermal areas in Iceland, its size is well over 100 km<sup>2</sup>. It is at the triple junction, formed by the Reykjanes peninsula, South Iceland Seismic Zone and the western volcanic zone. The Hengill area has been explored extensively by surface methods for the past five decades. Geological mapping, geochemical sampling and analysis, and many geophysical methods have been applied. Among them are various resistivity soundings, Schlumberger, dipole-dipole, head-on profiling, TEM and MT. Aeromagnetic and gravity surveys were conducted as well as both seismic refraction survey and passive seismic survey. GPS geodetic survey was performed and crustal deformation studies inferred from InSAR. Results from different measurements and geological investigations in boreholes have put constraints on the results of the surface explorations. The Hengill area has been exploited for several years, both for hot water production and electricity generation. Plans for further utilization of the geothermal energy have been made. Many of the results presented here are from an article, recently submitted for publication in *Geothermics* (Árnason et al., 2009).

### 1. GEOLOGICAL AND TECTONIC SETTING

The Hengill volcanic complex is located in the southern end of the western volcanic zone (WVZ) of Iceland (Figures 1 and 2). It is at the triple junction of the WVZ, the Reykjanes Peninsula (RP), which is the landward extension of the Reykjanes spreading ridge, and the South Iceland Seismic Zone (SISZ), which is a transform zone, transferring a part of the crustal spreading from the WVZ to the eastern volcanic zone (Figures 1 and 2). The great Hengill volcanic complex hosts three main volcanic centres, which are, listed from SE to NW and decreasing age, Graendalur (0.3-0.5 My), Hrómundartindur on the decline and Hengill at the peak of activity (Figure 3). The Graendalur volcano was substantially eroded during glacial time, but Hrómundartindur and Hengill consist mainly of relatively uneroded hyaloclastite. Mount Hengill itself is a tuya with remnants of a lava shield on top. The geology of the Hengill area has been mapped in details (Saemundsson, 1995), see Figure 3.

Both Hrómundartindur and Hengill have erupted in postglacial times. Hrómundartindur last erupted about 11 thousand years ago and Hengill 5 thousand and 2 thousand years ago (Árnason et al., 1987). The extrusive volcanic products are mainly basalts but with significant occurrences of acidic rocks SW of Mount Hengill.

The Graendalur-Hrómundartindur part of the Hengill volcanic complex is seismically very active. The Hengill central volcano is bisected by about 3-5 km wide and about 40 km long fissure swarm (Figure 2), extending N30°E, from the coast and to the NE towards lake Thingvallavatn. The fissure swarm was active in 1789, with extensive rifting and subsidence. In the period from 1991 to 2001 high seismic activity occurred in the eastern Hengill area but with different tectonics. Over 90 thousand earthquakes were recorded by the permanent seismic network (SIL) operated by the Icelandic Meteorological Office (Árnason and Magnússon, 2001). Similar active periods occurred around 1915 and 1950-1955 (Seismological Bulletin from these years).

Geothermal surface manifestations in the Hengill area are shown in Figures 3 and 4. Results from CO<sub>2</sub> gas geothermometers are given in Figure 4. According to the figure there are at least three upflow zones and the temperature seems to decrease to the southeast, towards Hveragerdi which is in good agreement with temperature-logs in the wells there. Notice the inconsistency between the temperature in the wells in Ölkelduháls and isolines of the gas geothermometers. This will be discussed later.

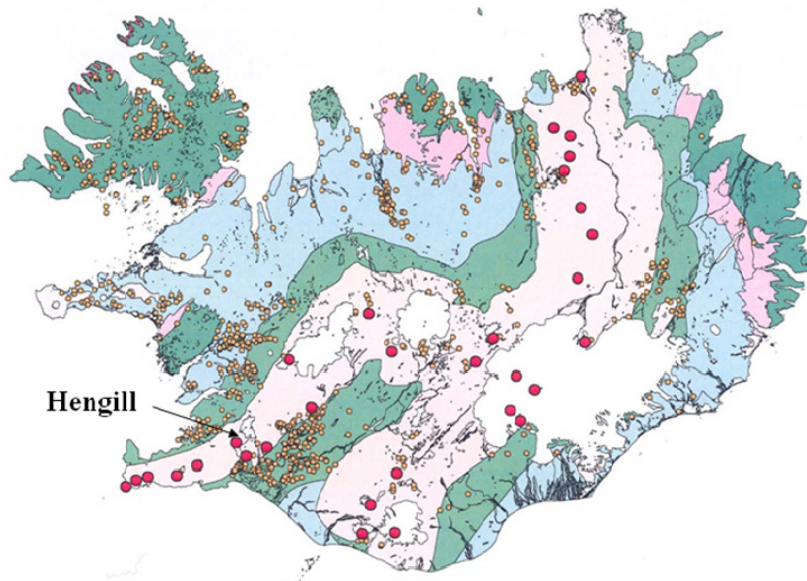


FIGURE 1: A simplified geological and geothermal map of Iceland.

The light pink area, which outlines the neovolcanic zone, is late Quaternary rocks, light green Plio-Pleistocene 0.8-3 My, light blue Tertiary 3-8 My, pink Tertiary 8-10 My and dark green Tertiary > 10 My. Red dots are high-temperature geothermal areas and yellow dots are low-temperature areas

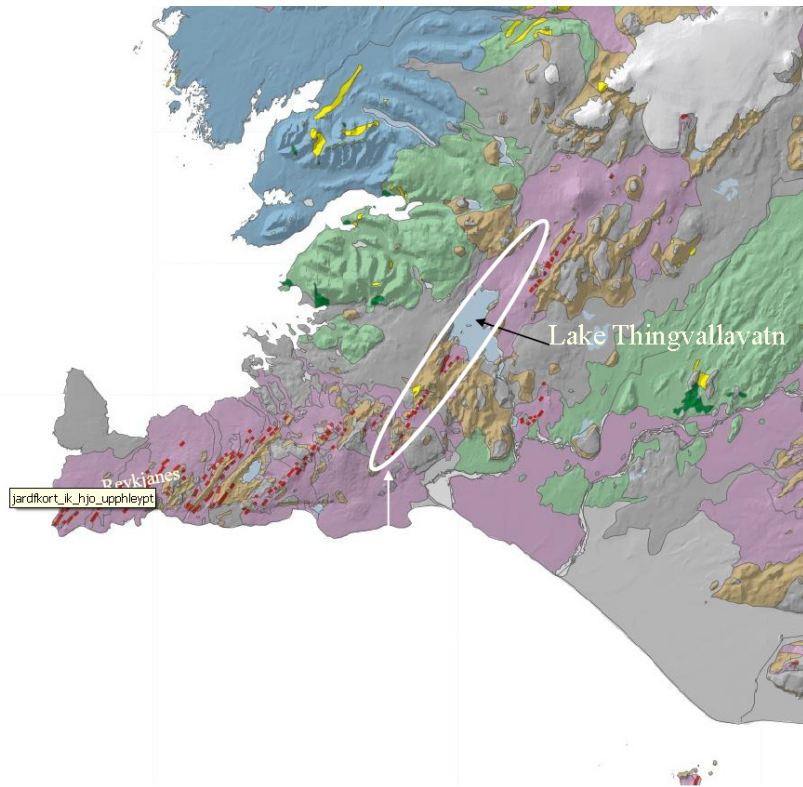


FIGURE 2: A simplified geological map of SW-Iceland, fissures on the Reykjanes ridge are shown as well as the Hengill fissure swarm, defined by the white curve

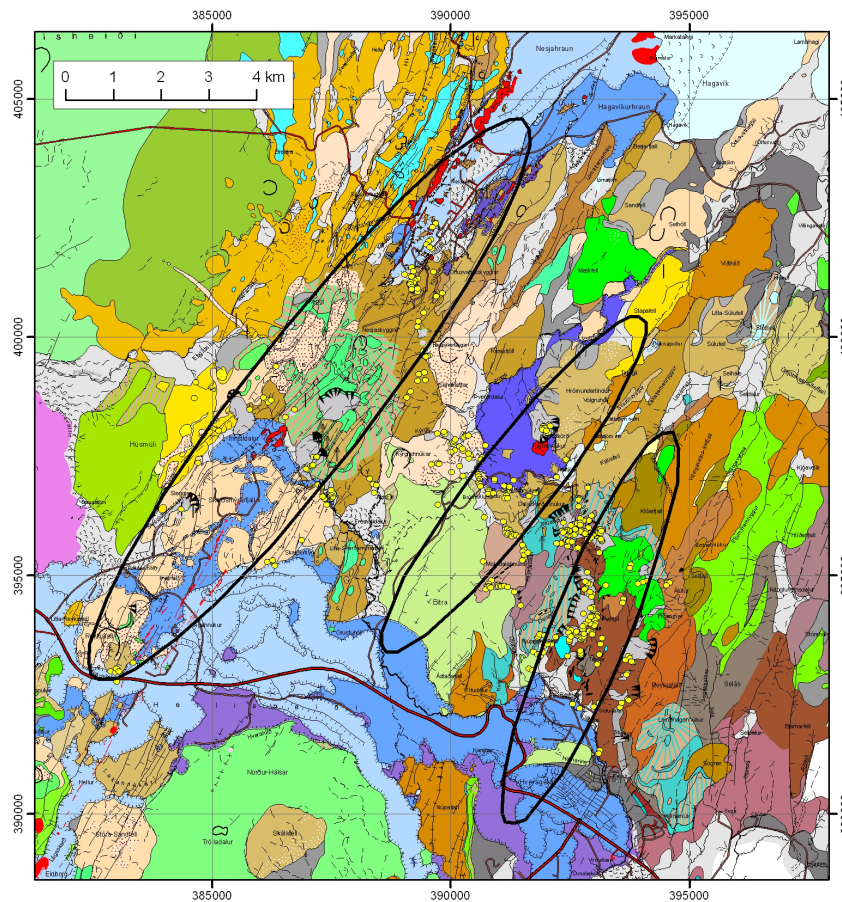


FIGURE 3: A geological map of the Hengill area, modified from Saemundsson (1995). The volcanic accumulation consists of hyaloclastites from glacial time and interglacial lava flows. The tectonic structures are mainly NE-SW. A volcanic system lies within a 10 km wide graben. The black curves show the three main volcanic centres, Graendalur, Hrómundartindur and Hengill. Yellow dots denote geothermal surface manifestation

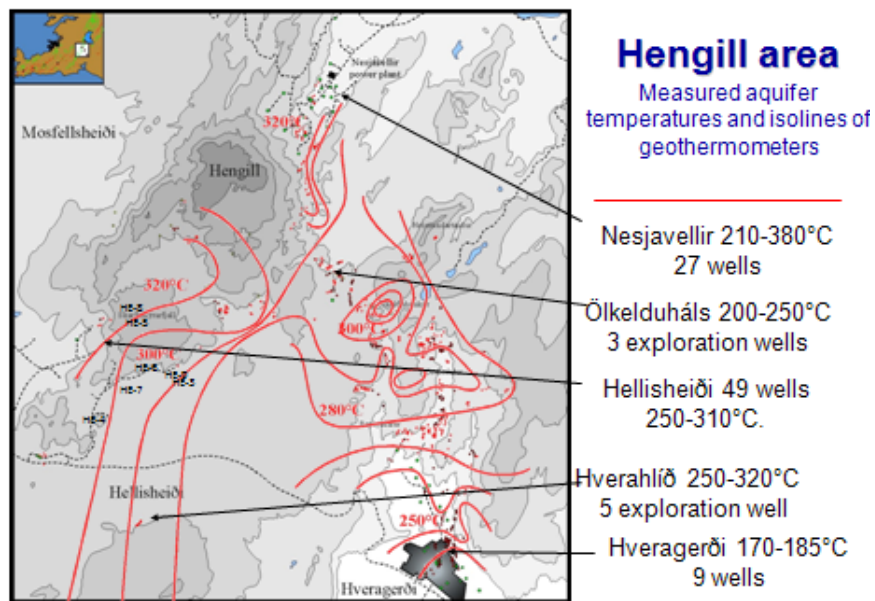


FIGURE 4: Measured aquifer temperatures and isolines of CO<sub>2</sub> gas geothermometers (modified from Ívarsson, 1998). Geothermal surface manifestations are shown as red dots. Numbers of wells and average temperature in the wells for the five known main subfields is given as well



## 2. GEOPHYSICAL SURVEYS

Approximately 100,000 micro-earthquakes occurred in the Hengill area between 1994 and 2000. Most earthquakes were located at 3-5 km depth, reflecting the locally very thin and hot crust. The earthquakes group together on lines striking either E-W or N-S, but surprisingly not to the NNE, as seen in the surface geology.

Figure 5 shows that the seismicity is mainly to the east of the fissure swarm. The inferred lineaments show that the tectonics is of a transform character. This was very clear in an episode in 1998. In June that year an intensive swarm started on an ENE-WSW lineament to the SE of Mount Hengill. This was then followed by an earthquake of magnitude above 5 and very high activity with epicentres along a SSW-NNE line (the longest solid line on Figure 5) (Rögnvaldsson, 2000). A GPS geodetic survey had been finished just before the episode (Sigmundsson et al., 1997). A repeated survey, right after the episode, showed substantial and consistent crustal movements. The NW and SE quadrants moved NW and SE, respectively and the NE and SW quadrants moved SW and NE, respectively. About five months later, in November 1998, a relatively big earthquake occurred further to the south followed by a big swarm of smaller quakes with epicentres around a WSW-ENE line as seen on Figure 5. It is well worth to note in Figure 5 that the transform tectonics terminates in the NW-part of the fissure swarm. Synthetic Aperture Radar Interferograms (InSAR) show that between 1993 and 1998 there was a considerable uplift going on (up to about 18 mm/year) with the centre of the uplift SE of Mount Hengill (Feigl et al., 2000). The uplift has been interpreted to be due to intrusion of magma in the uppermost crust (Feigl et al., 2000).

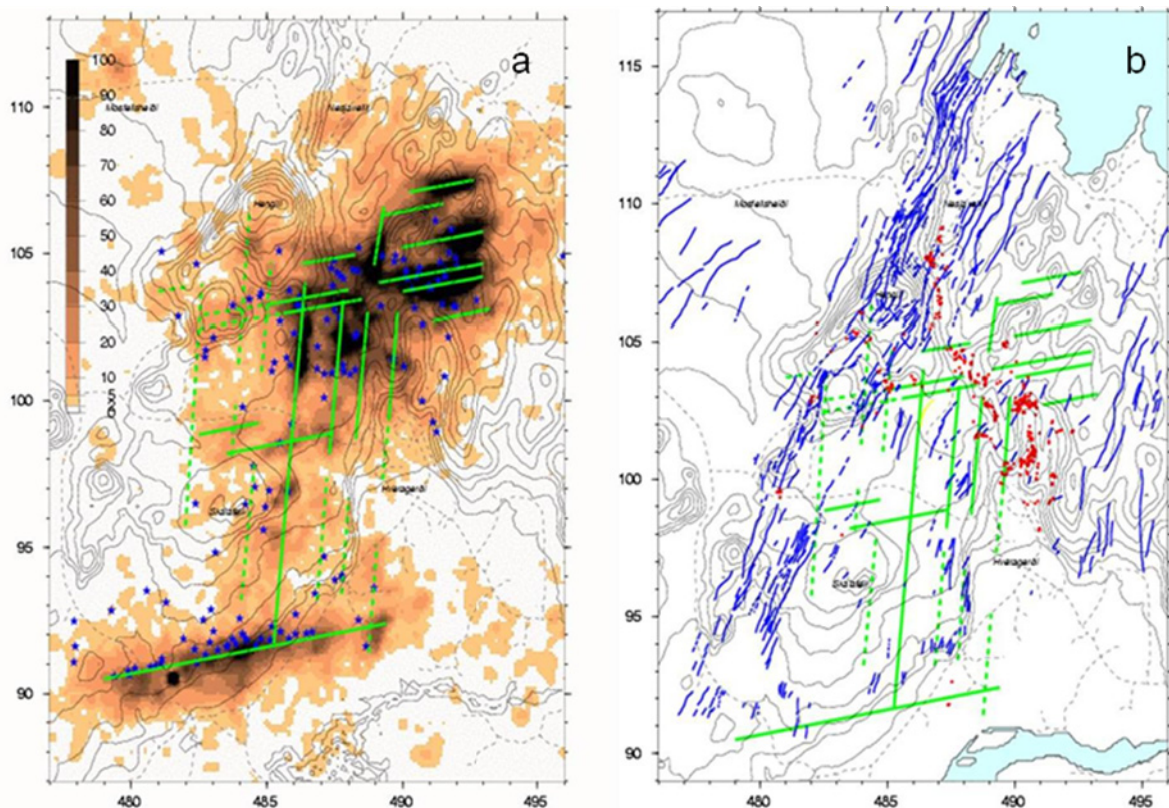


FIGURE 5: a) Density of epicentres (number within 250x250 m<sup>2</sup> squares) from 1991 to 2001 and inferred tectonic lineaments (green lines). The inferred tectonic lineaments are based on the overall distribution of the seismicity as well as careful analyses of individual episodes (earthquake swarms); b) faults and fissures mapped on the surface (blue lines), geothermal surface manifestations (red) (Saemundsson, 1995) and inferred transform tectonics revealed by seismicity (green lines) (Árnason and Magnússon, 2001)

Various resistivity surveys have been conducted in the Hengill area. Close to 150 DC soundings were performed in the 70's and 80's, using both Schlumberger and dipole-dipole setups. They showed a conductive cap underlain by a resistive core (Björnsson and Hersir, 1981; Hersir et al., 1990). In the mid-80's a detailed multi-method DC resistivity survey was conducted in the Nesjavellir subfield north of Hengill using TEM and Schlumberger soundings and head-on profiling. The joint 2D interpretation of the different datasets showed a detailed picture of the resistivity structure in the uppermost 1 km under Nesjavellir that could be compared to data from nearby boreholes. The resistivity structure was compared to lithology, alteration mineralogy and temperature. The resistivity was not found to correlate with the lithology, but a fairly clear and consistent correlation was found with the alteration mineralogy. Figure 6 shows a simplified resistivity cross-section across Nesjavellir

subfield and the zones of dominant alteration minerals and temperature in nearby wells. The figure shows that the resistivity is high in the surrounding cold unaltered rocks. At temperatures of 50-100°C pronounced geothermal alteration sets in with smectite and zeolites as the dominant alteration minerals and the rocks become conductive. At higher temperature, in the range of 220-240°C, smectite and zeolites are gradually replaced by chlorite as the dominant alteration mineral in the so-called mixed layered clay zone (Kristmannsdóttir, 1979) and the resistivity increases again. At still higher temperatures epidote becomes abundant.

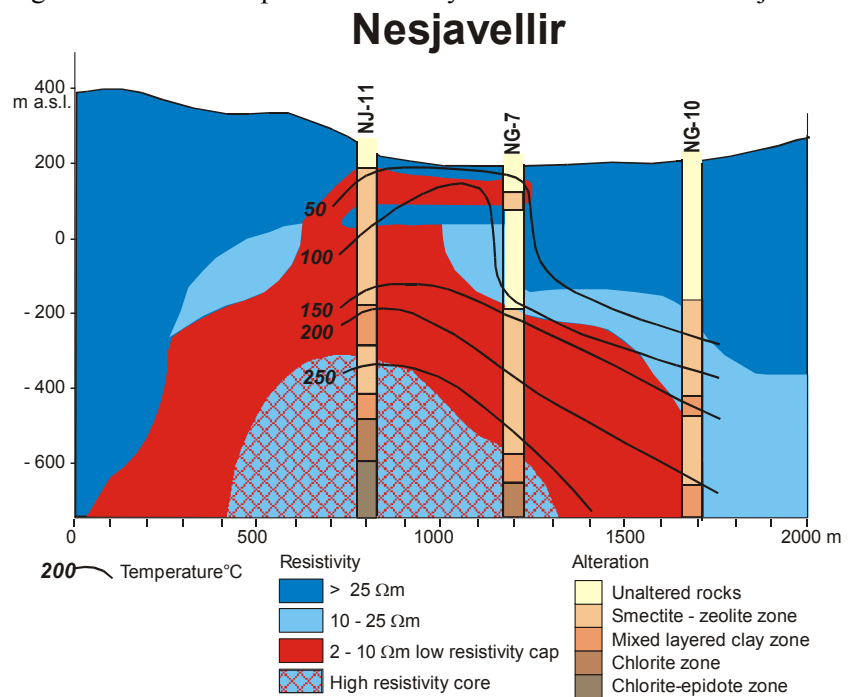


FIGURE 6: Resistivity cross-section across Nesjavellir subfield, alteration mineralogy and temperature in nearby wells (Árnason et al., 1987)

The smectite and the zeolites minerals have loosely bound cations that make these minerals conductive, while in the chlorite mineral these ions are bound in a crystal lattice, which makes the mineral more resistive. Similar correlation has been found in all the explored and drilled high-temperature geothermal fields in Iceland as well as in many high-temperature areas in other countries (Árnason et al., 2000). This was an important finding, because if the temperature that produced the alteration mineralogy prevails, the resistivity structure can be used to predict present reservoir temperature. But if cooling occurs, the alteration remains and so does the resistivity. The resistivity structure can therefore in most cases be regarded as a “maximum thermometer”. However, it has occurred that alteration minerals have indicated lower temperature than measured in the wells. This has been interpreted as being due to a young system being heated up and the alteration is lagging behind, still not in equilibrium with the temperature. At Ölkelduháls (see Figure 4) the resistivity structure suggests alteration minerals which in equilibrium with the temperature would indicate temperatures above 250°C. CO<sub>2</sub> and gas geothermometers show 290°C. However, the wells there show temperature 200-250°C. This has been explained as being due to cooling of the uppermost part of the system. The alteration minerals are not anymore in equilibrium with the temperature. The high temperature from CO<sub>2</sub> might be caused by another system lying deeper, capped by a horizontal dyke (Árnason and Magnússon, 2001). Resistivity of rocks are discussed in more details in another paper presented in this Short Course (Hersir and Árnason, 2009)



The Hengill area has been covered with 280 TEM soundings and 148 MT soundings. 1D joint inversion of 148 TEM/MT sounding pairs correcting for the static shift of the MT curves which can be severe, has revealed the resistivity subsurface structure (Árnason et al., 2009). The inversion showed a conductive cap underlain by a resistive core, both of them directly related to the geothermal reservoir. At a greater depth (several km) another low resistivity layer was found, the same layer that is found under most of Iceland.

There are many ways of representing the results of the 1D inversion, resistivity cross-section and iso-depth resistivity maps are one possibility. Here the elevation of the lower boundary of the uppermost conductive layer (top of the resistive core) and top of the deeper low resistivity layer are mapped (Figure 7). The figure shows that the resistive core domes up under and to the ESE of Mount Hengill. It also extends at relatively shallow depth to the west of Hengill and to the SSW along the fissure swarm. The resistive core dips down to greater depth in the NE and especially to the SW. Notice the correlation between the elevation of the resistive core and the geothermal surface manifestations.

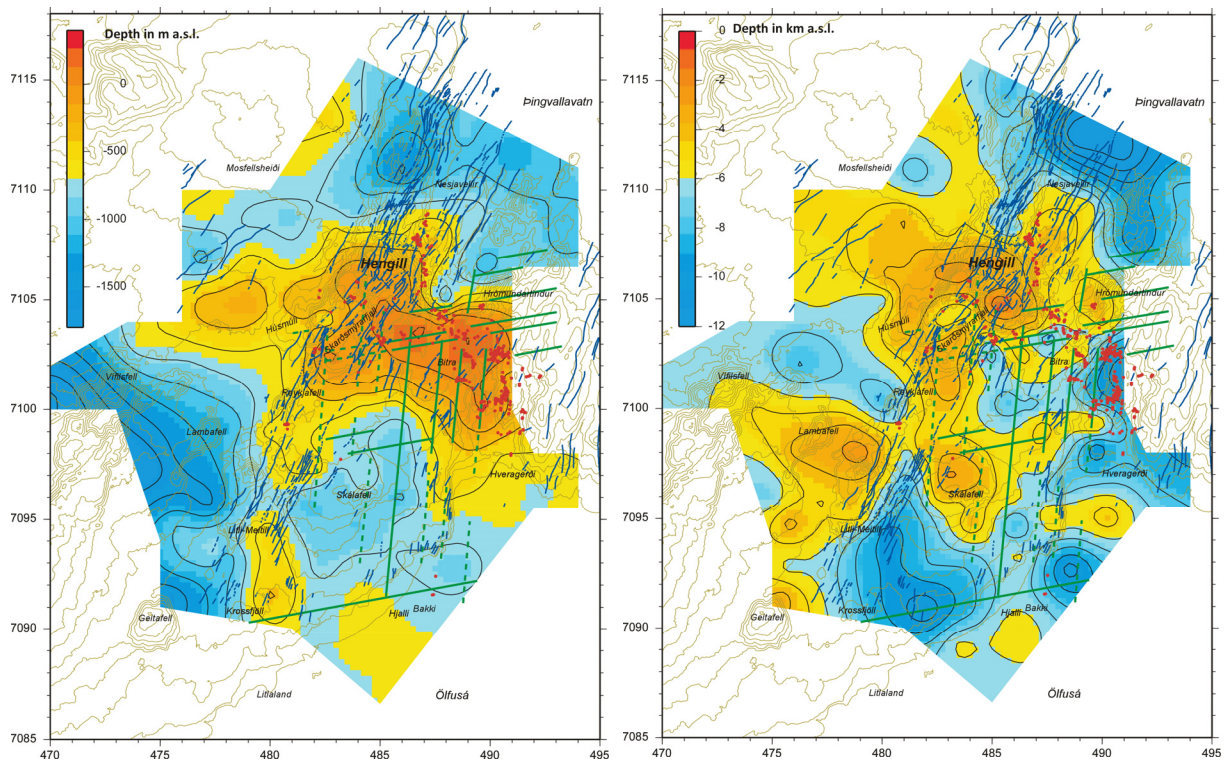


FIGURE 7: Elevation of the resistive core (left) and the top of the deep conductor (right) in the Hengill area. Geothermal surface manifestations are shown as red dots, faults and fractures mapped on the surface are shown in dark blue, faults inferred from seismicity are shown in green (Árnason et al., 2009)

Figure 7 shows that the deep conductor is at shallowest depth under a WNW-ESE elongated area centred under Hengill, similar to that of the resistive core. In addition, the figure shows conductors at relatively shallow depth, about 4 km b.s.l., on both sides of the fissure swarm around 10 km south of Hengill. The top of the resistive core is to some extent controlled by the fissure swarm, but the main anomalies at depth to both the resistive core and the deep conductor have a WNW-ESE elongation through Hengill. The figures show that this direction is the same as that of a zone where E-W oriented faults, inferred from seismicity, meet N-S oriented “seismic” faults. The region where the resistive core rises highest coincide with the area where the seismicity was most intense in the years 1991 to 2001 and the centre of uplift according to the InSAR (Feigl et al., 2000).

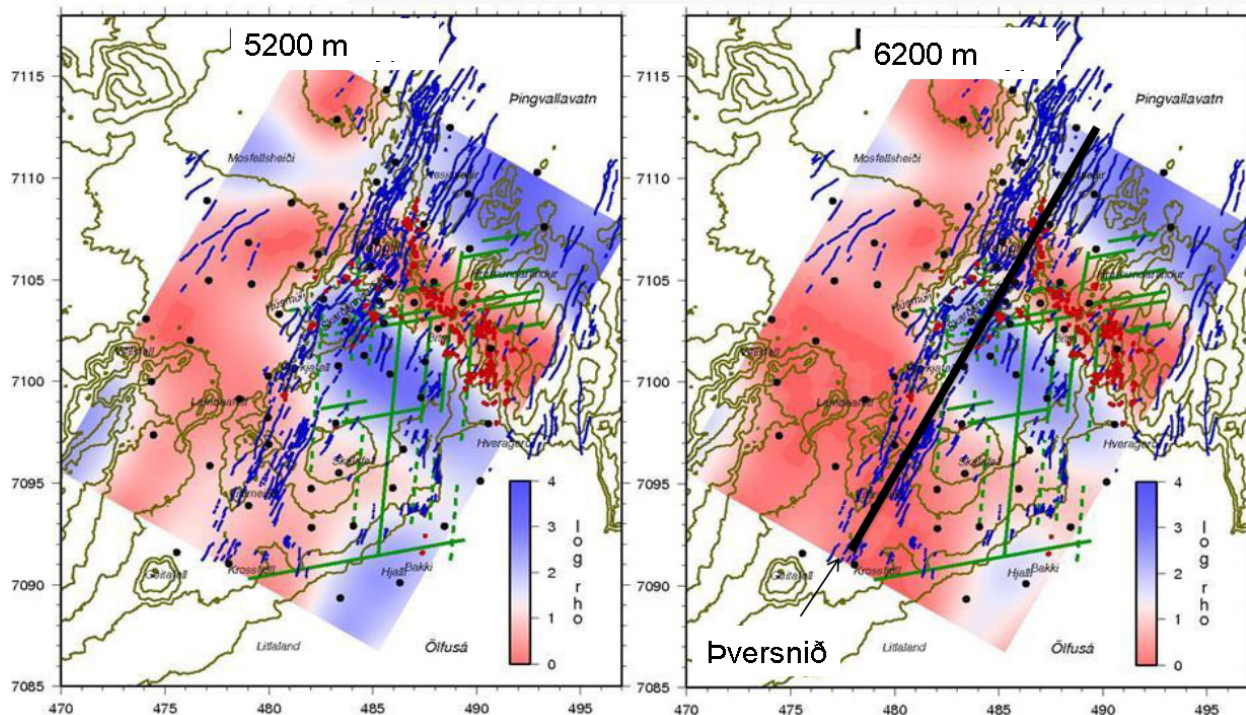


FIGURE 8: Resistivity at 5200 m depth (to the left) and 6200 m depth (to the right) below the surface based on 3D inversion of MT data (Árnason et al., 2009). The MT soundings are shown as black dots and the geothermal surface manifestations as red dots

3D inversion of 60 MT soundings was performed for the full static shift corrected MT tensors. The results are shown as iso-depth resistivity maps (Figure 8) and a resistivity cross-section (Figure 9). At 5200 and 6200 m depth a deep low resistivity extends to the west of Mount Hengill and spreads out to the south and SE. The low resistivity in the NW corner is also prominent. The low resistivity ridge to the SE of Hengill extends to the Graendalur central volcano (see Figure 3) coinciding with the geothermal surface manifestations and is bordered by high resistivity to the SW and NE. The resistivity cross-section (Figure 9) shows the conductive cap and the resistive core, both of them directly related to the geothermal reservoir. Below another low resistivity structure is seen.

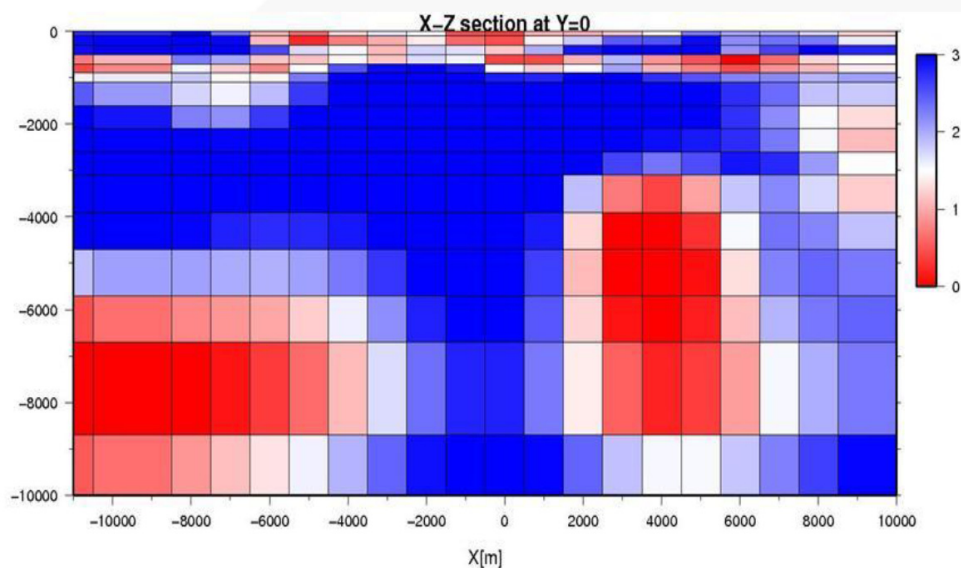


FIGURE 9: A NE-SW resistivity cross-section of the Hengill area based on 3D inversion of MT data (Árnason et al., 2009). The location of the cross-section is shown in the right part of Figure 8



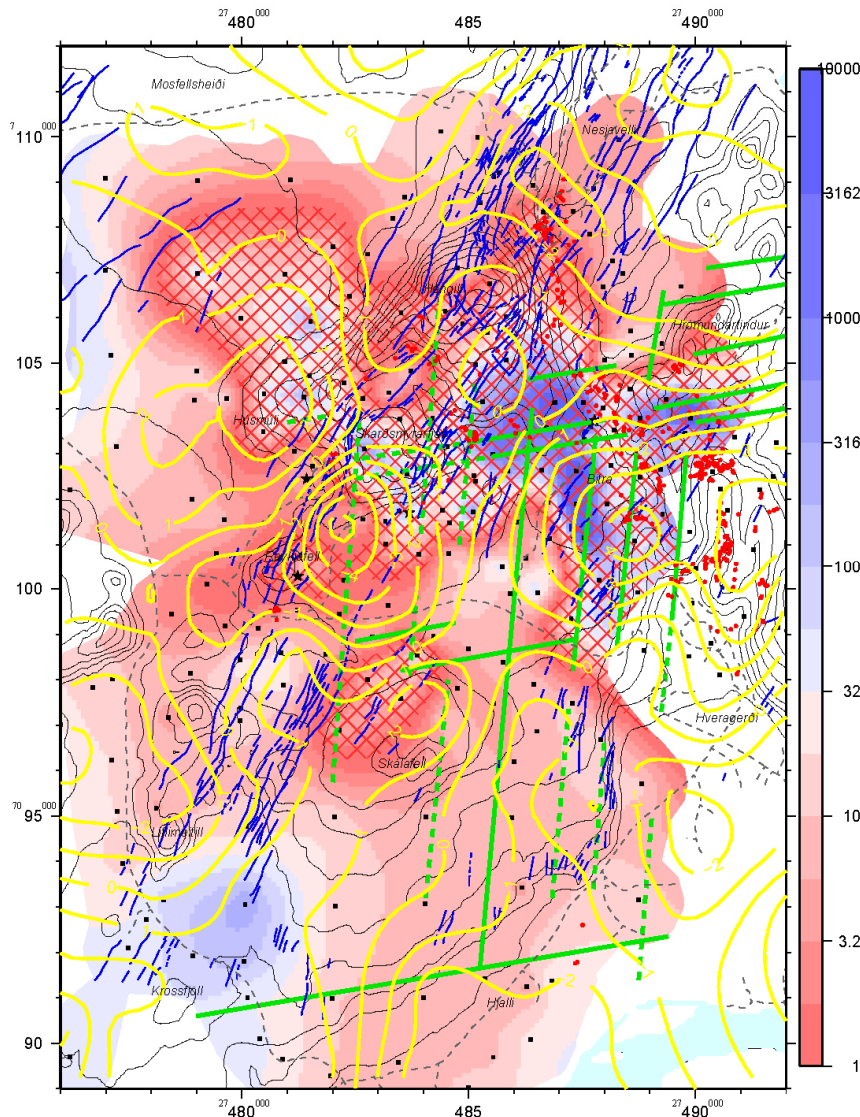


FIGURE 10: Resistivity at 600 m depth below sea-level according to 1D inversion of TEM data, faults and fractures mapped on the surface are shown in dark blue, faults inferred from seismicity in green, geothermal surface manifestations are shown as red dots and residual Bouguer gravity lines are shown in yellow colour (Árnason and Magnússon, 2001)

The correlation between the gravity highs and the resistive core in Figure 10 is striking. The gravity high southwest of Hengill (the Graendalur central volcano) coincides with the high resistive core there. So does the gravity high at Húsmúli in the western part of the Hengill area and Hverahlíð in the southernmost area. Also there seems to be a general correlation between high gravity values and low resistivity at depth which lends support to the interpretation that the deep conductors represent dense intrusions and dikes.

The NW-SE oriented low resistivity anomaly under and to the SE of Mount Hengill is found where intense seismic activity has revealed transform tectonics. The area where this deep conductor is at shallowest depth coincides with the location of high P-wave velocity as found by seismic tomography (Jousset et al., 2009). Figure 11 right part, shows the very good correlation between the local up-doming of the deep conductor SE of Mount Hengill and the high P-wave velocity. Since no attenuation of S-waves is observed under the Hengill area, the deep conductors are believed to reflect hot but solidified intrusions that are heat sources for the geothermal system above.



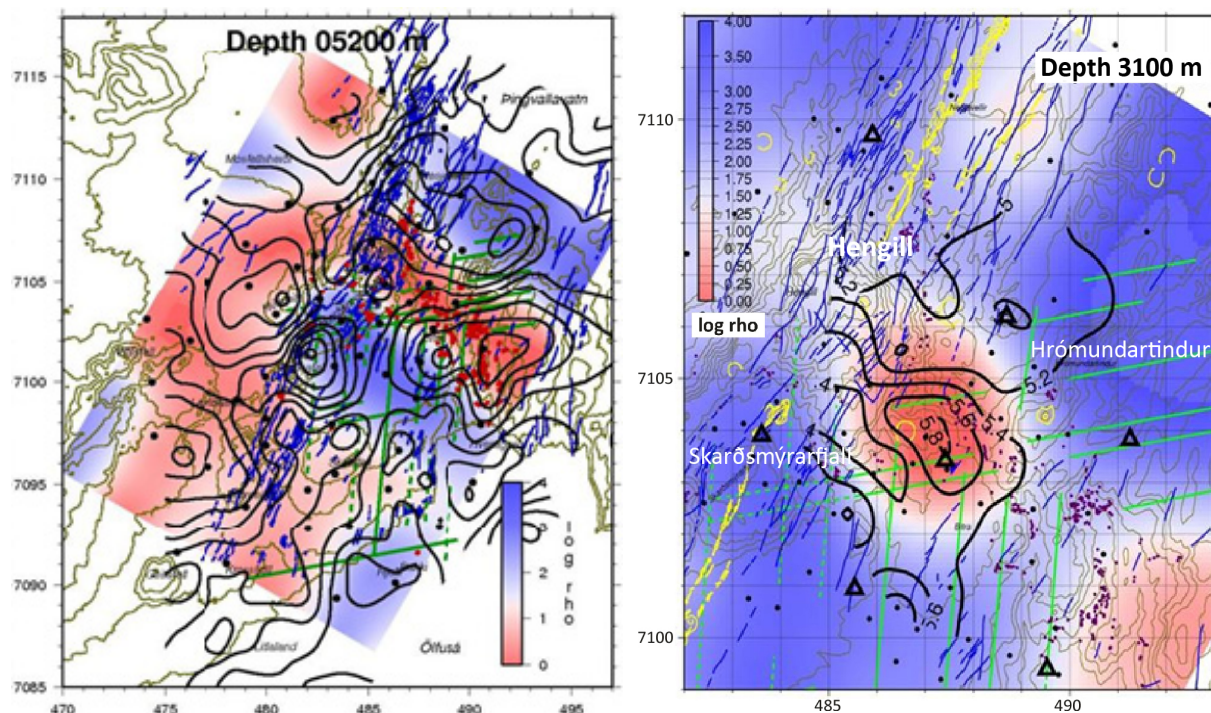


FIGURE 11: Comparison of residual Bouguer gravity anomalies (black contours) and resistivity at 5.2 km depth (left) (Árnason et al., 2009). P-wave velocity (km/s, black contours) and resistivity from 3D inversion of MT (colour scale is in log resistivity) at the depth of 3.1 km (right) (reproduced from Jousset et al., 2009 (Árnason et al., 2009))

The left part of Figure 11 shows that the low resistivity anomaly SE of Mount Hengill coincides with a gravity high and there seems to be a general correlation between high gravity values and low resistivity at depth. This lends further support to the interpretation that the deep conductors represent dense intrusions and dikes.

Both inversion approaches of the TEM/MT resistivity soundings give qualitatively similar results, but the 1D inversion gives a somewhat smeared model as compared to the 3D inversion. Both approaches reveal a shallow resistivity layer reflecting conductive alteration minerals at temperatures of 100-240°C. They also delineate a deep conductor at 3-10 km depth. The reason for this deep seated high conductivity is not fully understood. The distribution of the deep conductors correlates with a positive residual Bouguer gravity anomaly (see Figure 10), and transform tectonics, inferred from seismicity, as well as anomalously high P-wave velocity. The deep conductors are believed to reflect hot solidified but ductile, magmatic intrusions that are heat sources for geothermal systems.

To conclude the review on the exploration side of the Hengill high temperature geothermal field a temperature cross-section is shown, running from north to south and some kind of a conceptual model (Figure 12).

### 3. UTILIZATION

The Hengill area hosts one of the largest high temperature geothermal fields in Iceland. It is located only 30-50 km from the city of Reykjavik and easily accessible for development. Plans to utilize the Hengill area date back to 1930's. The idea was to produce hot water for space heating in Reykjavik and also to generate electricity for the city. These plans were not realized at that time but in 1964 the Reykjavik Energy bought the Nesjavellir farm and started to develop the field to meet future demand of the space heating market in Reykjavik. The reason why Nesjavellir were chosen and not the southern part of the Hengill area which is closer to Reykjavik was the ground water resources at

## Hengill – Temperature cross section

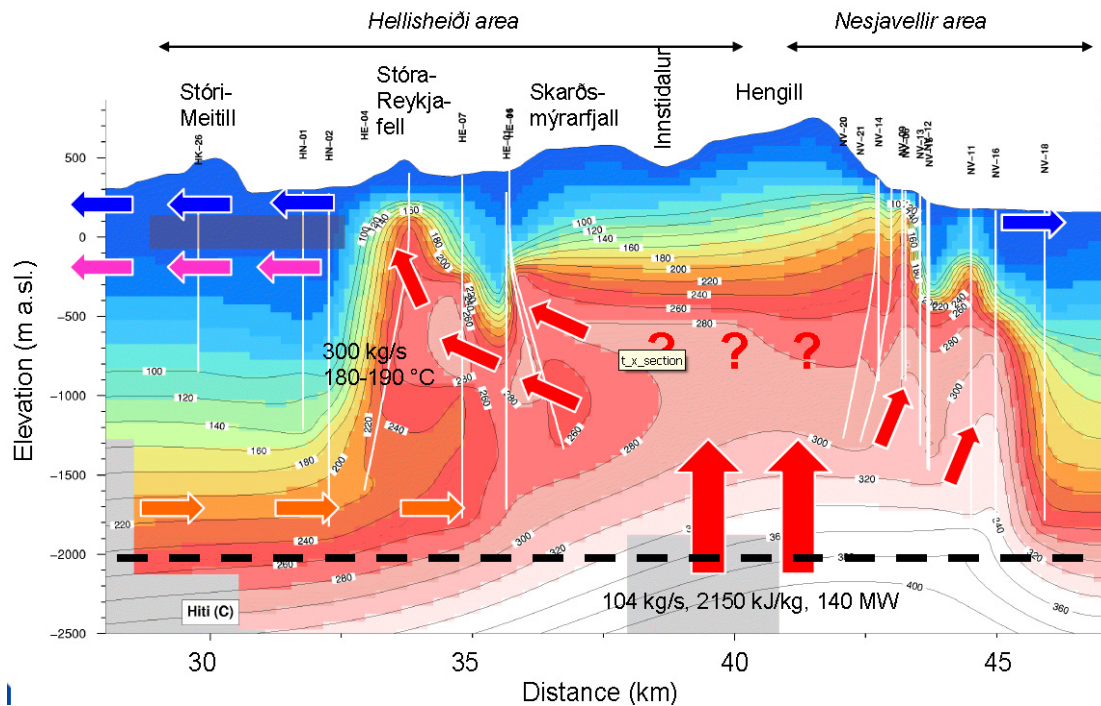


FIGURE 12: A south-north temperature cross-section between Hellsheiði and Nesjavellir. Arrows denote direction of proposed flow (Björnsson et al., 2006)

Nesjavellir. High temperature geothermal water is not suited for direct use due to high silica content of the water which will lead to scaling in the piping system.

Field exploration and drilling in Nesjavellir took place in the years 1965-1986 (see photo of the area in Figure 13). The first shallow (150 m) well was drilled in 1965 and the first deep (2 km) well was drilled in 1972. The main developments were, however, during 1982 to 1986 when it was clear that the low temperature fields in Reykjavik were fully utilized. At that time Reykjavik Energy had drilled 18 wells and the feasibility of the project confirmed. Reykjavik Energy started the construction of the power plant in 1987. The first phase was a 100 MW<sub>th</sub> hot



FIGURE 13: Nesjavellir subfield with the Hengill volcano in the background



water plant, 650 l/s of 83°C hot water, was commissioned in September 1990 and expanded to 150 MW<sub>th</sub> in 1992. The Nesjavellir Plant was designed for co-generation of hot water and electricity. In 1990 there was no demand of electricity to the national grid but that changed few years later and electricity generation started at Nesjavellir in 1998. The installed capacity was 60 MW<sub>e</sub>. The Nesjavellir co-generation plant produces now electricity with a capacity of 120 MW<sub>e</sub> and hot water with a capacity of 300 MW<sub>th</sub>. In the area there are 27 boreholes, 800-2500 m deep with temperatures up to 380°C. The maximum flow rate of hot water to Reykjavik is 1640 l/s of 83°C temperature. There are no plans for further expansion in Nesjavellir.

The second subfield of Hengill to be developed was Hellisheidi to the south of Mt. Hengill. Reykjavik Energy purchased land and geothermal rights in the area during the 1990's and started to develop the field in year 2000. The development has been very rapid and the power plant is built in several phases, the first ones are for electricity generation only but a hot water plant will be in operation within two years. The present status of the development is as follows (Steingrímsson, 2009):

- Hellisheidi I 90 MW<sub>e</sub> electric plant completed in 2006
- Hellisheidi II 33 MW<sub>e</sub> bottoming unit, completed in 2007
- Hellisheidi III 90 MW<sub>e</sub> electric plant completed in 2008
- Hellisheidi IV. 133 MW<sub>th</sub> hot water plant to be completed in 2009
- Hellisheidi V 90 MWe electric plant to be completed in 2011

Hellisheidi I to III were commissioned on time and the production drilling and construction work for Hellisheidi IV and V is underway but the commission of the hot water plant has been delayed until 2010.

Nesjavellir and Hellisheidi are the first subfield of the Hengill area to be developed. There are, however, several other exploitable geothermal subfields within the Hengill area and Reykjavik Energy is now developing two of them Hverahlid in the southernmost part of the Hengill area with an estimated capacity of 90 MW and Bitra in the easternmost part with an estimated capacity of 135 MW. Exploration drilling is ongoing but Reykjavik Energy has not started the construction of the power plants.

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