



## **GEOHERMAL EXPLORATION OF THE HENGILL HIGH-TEMPERATURE FIELD**

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### **ABSTRACT**

The active volcanic zones in Iceland are characterized by high heat flow and extensive geothermal activity. Iceland is unique in its location astride the diverging Mid-Atlantic Ridge and, furthermore, on top of a mantle plume. These two dynamic systems combine fundamental factors that promote magmatism, tectonics and geothermal activity. The high-temperature geothermal areas are mainly confined to volcanic systems, in particular central volcanoes, and are subject to strong tectonic control. The Hengill central volcano hosts one of the most powerful geothermal fields in Iceland, dominated by NE-SW striking faults. It is located at the western flank of the West Iceland Volcanic Zone (WVZ), which represents the Mid-Atlantic Ridge on land forming a graben-like structure approximately 10-15 km wide and 100 km long. The Hengill low resistivity structure covers about 112 km<sup>2</sup> and presently Reykjavik Energy operates two power plants in the area with installed capacity of about 420 MWe and 430 MWt. 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 Hellisheidi in the south. Extensive geophysical surveys including resistivity (TEM) and MT have been executed 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 Hverahlid 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.

### **1. INTRODUCTION**

Iceland is unique for its location astride the diverging Mid-Atlantic Ridge and, furthermore, on top of a mantle plume. These two dynamic systems combine fundamental factors that promote magmatism and tectonics. Today the Mid-Atlantic Ridge is represented on land by the Western and the Northern Volcanic Zones (WVZ and NVZ, respectively) (Figure 1). The WVZ and NVZ are offset along a region known as the Mid-Iceland Volcanic Zone (MVZ) which may be viewed as a 'leaky' transform fault. The NVZ is connected to the Kolbeinsey Ridge (KR) in the north by the Tjörnes Fracture Zone (TFZ). The Eastern Volcanic Zone (EVZ) is currently propagating to the south with the Vestmanna Islands (VI) representing the tip of the propagator. The EVZ is connected to the WVZ by the South Iceland Seismic Zone (SISZ) and the WVZ is connected to the Reykjanes Ridge (RR) in the south by the Reykjanes Peninsula (RP). Eventually, a ridge-jump is expected whereupon the focus of extension in S Iceland will transfer from the WVZ to the EVZ (Saemundsson, 1980; Hardarson et al., 1997 and refs. therein). From

the time when the Mid-Atlantic ridge system migrated WNW over the Iceland plume about 24 m.y. ago (Vink, 1984), the plume has repeatedly refocused the location of spreading with the necessary adjustments being accommodated by transform displacements of the ridge. Relocation of the spreading axis through ridge jumping is a prominent process in the evolution of Iceland and is the primary cause for the tectonic configuration as seen on the island and for the arrangement of high- and low-temperature geothermal areas (Saemundsson, 1980).

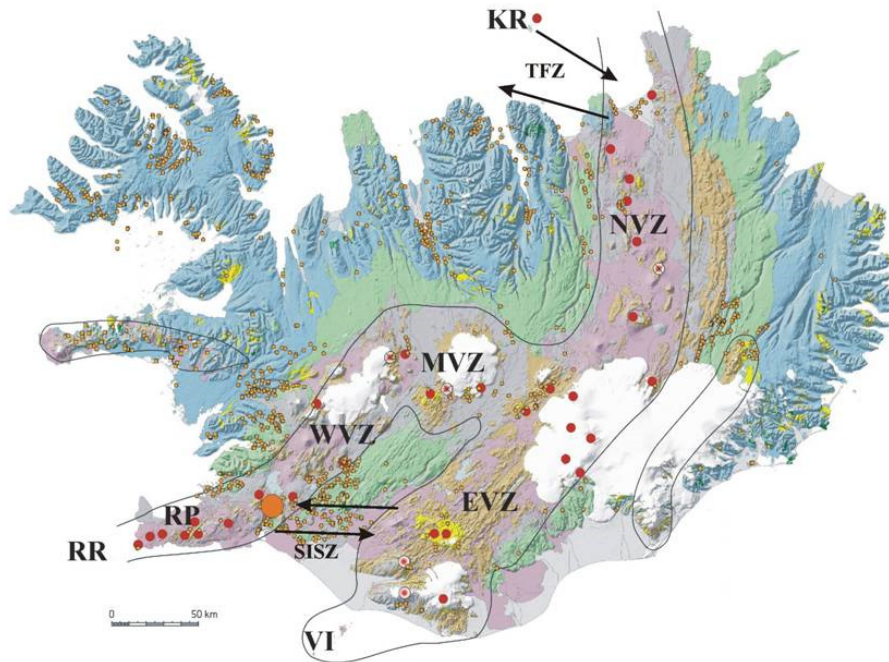


FIGURE 1: Geological map of Iceland showing the location of the active volcanic zones and transforms discussed in this paper. RR = Reykjanes Ridge; RP = Reykjanes Peninsula; WVZ = Western Volcanic Zone; MVZ = Mid-Iceland Volcanic Zone; NVZ = Northern Volcanic Zone; EVZ = Eastern Volcanic Zone; VI = Vestmanna Islands; SISZ = South Iceland Seismic Zone; TFZ = Tjörnes Fracture Zone. Red dots indicate high-temperature areas. Orange circle represents the approximate location of the Hengill volcanic system (Hardarson et al., 2010)

The active volcanic zones in Iceland are characterized by high heat flow and extensive geothermal activity. The high-temperature reservoirs ( $>200^{\circ}\text{C}$  at 1 km depth) are mainly confined to the volcanic zones (Figure 1), in particular the central volcanoes, and are subject to strong tectonic control. The heat source is considered to be magmatic associated with shallow level crustal magma chambers or dyke swarms. The prevalent permeability, in general, seems to be affiliated with intrusive bodies and sub-vertical faults and fractures. Seismic activity in the active volcanic zones is primarily related to volcanoes and magmatic movement resulting in rather small earthquakes, whilst all major earthquakes in Iceland have originated within the TFZ and SISZ. The transform motion is commonly achieved by strike-slip on faults that are transverse to the zone (LaFemina et al., 2005; Einarsson, 2008).

The Hengill region (Figures 1 and 2) covers about  $112\text{ km}^2$  and is one of the most extensive geothermal areas in Iceland. It is located at a triple junction where two active rift zones meet a seismically active transform zone (Figure 1). The Hengill triple junction is a complex of fissure swarms and volcanoes located between the southern part of the WVZ (the Reykjanes Peninsula, RP), the WVZ and the SISZ. The Reykjanes peninsula is a highly oblique, en echelon extensional rift zone about 70 km in length. The WVZ north of Hengill system extends about a 100 km NE to the Langjökull glacier. Normal faulting is prominent throughout this system. The fissure swarms are almost parallel to the trend of the zone itself, indicating a spreading direction perpendicular to the zone. The SISZ is oriented E-W, is about 10-

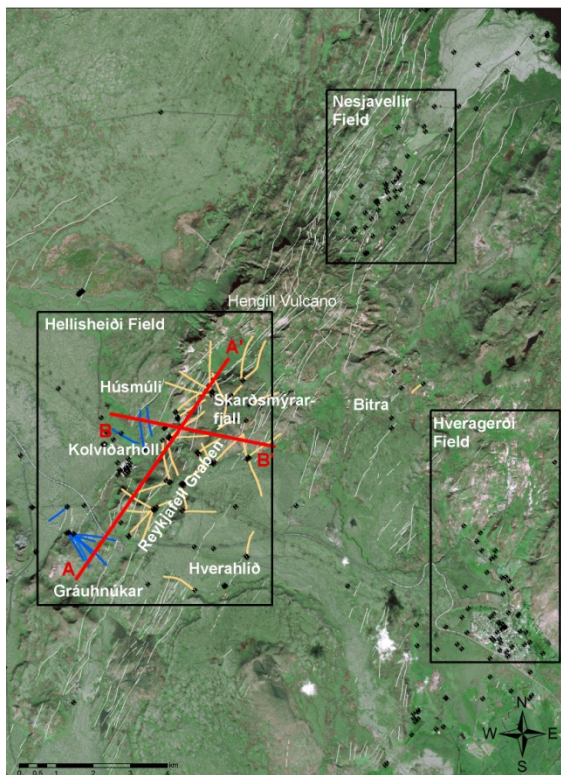


FIGURE 2: Satellite image of the Hengill central volcano showing the location of the injection sites at Grauhnukar and Kolvidarholl (reinjection wells shown with blue lines). White lines express faults and fissures and yellow lines indicate production wells. Red lines show the location of cross sections A-A' and B-B' in Figure 3 (Hardarson et al., 2010)

shallow exploration wells. Exploration wells have also been drilled at locations near Bitra and Hverahlid (Figure 2). The first exploration well was drilled in 1985 at Kolvidarholl at the west boundary of the Hellisheiði field (Figure 2).

## 2. GEOLOGICAL SETTING

The Hengill volcanic system is currently active while its predecessor, the Hveragerdi system, is now extinct in terms of volcanic activity but still active seismically, hosts geothermal reservoirs (Figure 2) and forms the base of the Hengill system with a thick lava sequence (Figure 3). Three well-fields have been developed within the greater Hengill area, Nesjavellir, Hellisheiði, where resource utilization is well underway, and Hveragerdi where the geothermal resource is utilized by the local community (Figure 2). Furthermore, exploration drilling has been launched at Bitra and Hverahlid adjacent to the Hengill system (Figure 2). Structurally the Hengill system is dominated by a large NE-SW striking fault/fissure swarm which is, however, in places intersected by easterly striking features (Figure 4) which may play a role in the permeability of the geothermal field (Árnason and Magnusson, 2001). The volcano is mainly built up of hyaloclastite formations (Figure 3) erupted underneath the ice sheet of the last glacials, forming a mountain complex rising up to some 800 m at Hengill (Figure 2). Interglacial lavas on the other hand flow down and accumulate in the surrounding lowlands.

15 km wide and 70-80 km long and takes up the transform motion between the RR and the EVZ (Einarsson, 2008). The overall left-lateral transform motion is accommodated by right-lateral faulting on many parallel transverse faults and counter clockwise rotation of the blocks between the faults, namely bookshelf faulting (Einarsson, 2008). As all of these tectonically different zones meet at the Hengill triple-junction, the tectonic scenario of the area is very complicated and enigmatic.

The main geothermal utilization in Iceland until recently was for direct uses, with space heating being by far the most important. In recent years there has been a growing interest in electrical energy production from geothermal energy, and currently (2008) about 25% of the electricity generated in Iceland is of geothermal origin, the rest being from hydro resources. However, roughly 82% of primary energy used in Iceland is derived from indigenous renewable sources (62% geothermal, 20% hydropower). The rest of Iceland's energy sources come from imported fossil fuel used for fishing and transportation. Reykjavik Energy already operates a geothermal power plant at Nesjavellir, north of the Hengill volcano (Figure 2), with installed capacity of 120 MWe and a 300 MWt for a hot water plant. Further power plants are being completed at Hellisheiði, SW of the Hengill volcano. Production of these is about 303 MWe and 400 MWt. At present 48 deep (1300-3300 m) exploration and production wells have been drilled at Hellisheiði, 17 reinjection wells, numerous cold water wells and several

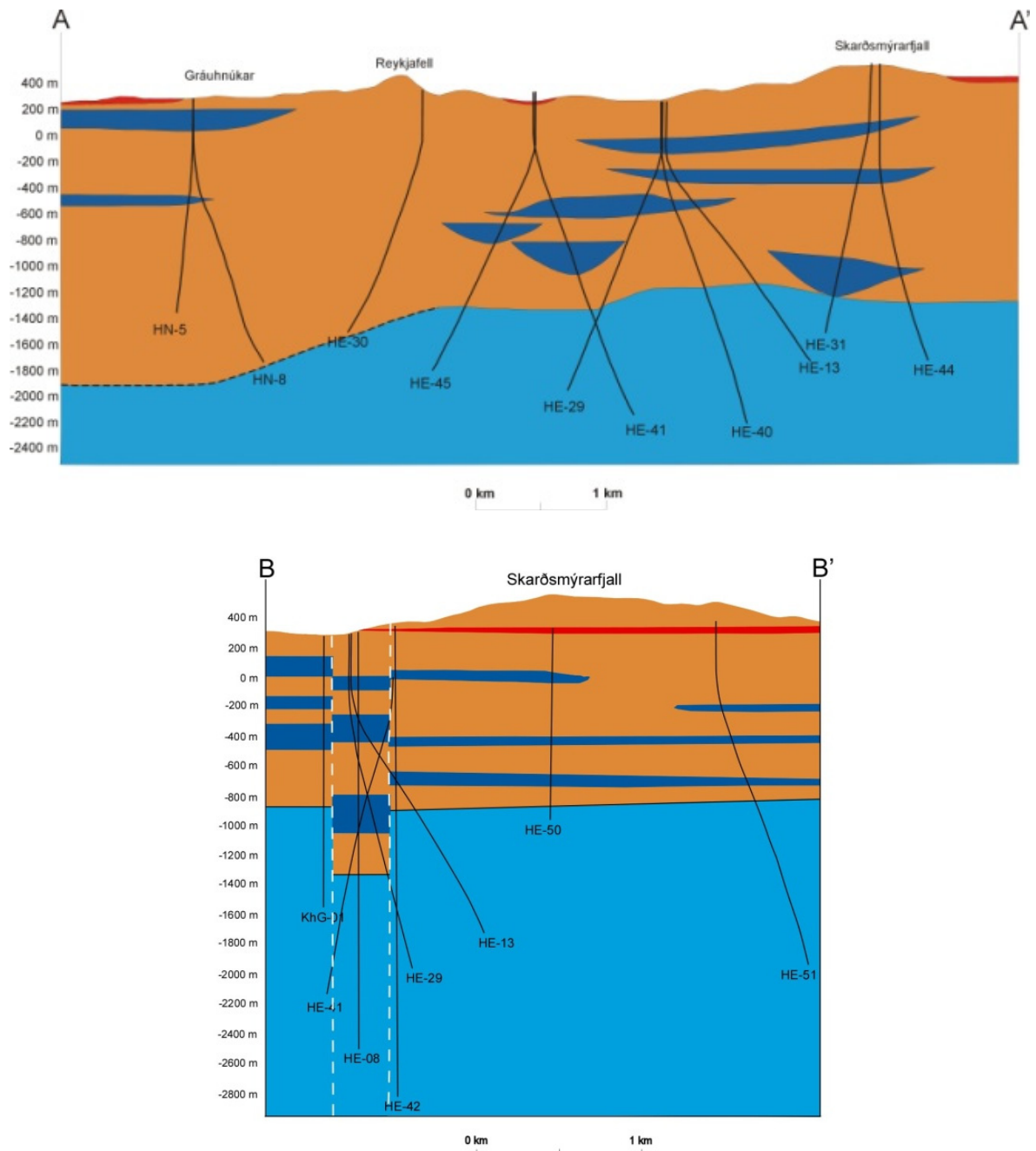


FIGURE 3: Geological cross section along lines A-A' and B-B' (Figure 2). Blue formations are interglacial lava series and the light blue formation is interpreted as the base of the Hengill central volcano being erupted from the Hveragerdi system. Red formations are postglacial lavas. Brown formations are hyaloclastite formations. Dotted, black line represents areas where no data are available. White broken lines show the Reykjafell graben (Helgadottir et al., 2010)

The fissure swarm associated with the volcano is a depression or a graben structure with large graben faults and 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 age of the volcano has been estimated to be around 400,000 years (Franzson et al., 2005; Helgadottir et al., 2010). Postglacial volcanism includes three fissure eruptions of ~9, ~5 and ~2 thousand years (Saemundsson 1995; Franzson et al., 2005). The volcanic fissures of the latter two can be traced to the north, through the Nesjavellir field (Figure 2) and into Lake Thingvallavatn (Saemundson, 1995). At Nesjavellir these volcanic fissures act as the main outflow channel of the

geothermal system and the fissures are also believed to act as major outflow zones in the Hellisheiði field (Franzson et al., 2005) and 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; Hardarson et al., 2009) have also been targeted as these serve as major feed zones of the hydrothermal system. Extensive geological mapping, fluid geochemistry and geophysical surveys have shown the existence of a large geothermal high temperature anomaly in the whole area (Árnason and Magnusson 2001; Gunnlaugsson and Gislason, 2005).

The southern part of the Hengill area rises up to approximately 600 m elevation at Skarðsmýrarfjall (Figure 3). A large geothermal high temperature anomaly has been shown to exist in the area by means of extensive geological mapping and geophysical exploration (Árnason and Magnusson 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 (Árnason and Magnusson, 2001). Volcanic fissures of 5 and 2 thousand years seem to play an important role as major outflow zones in the field (Saemundsson, 1995; Björnsson, 2004; Franzson et al., 2005). In addition they have also been used as targets for reinjection wells in the area.

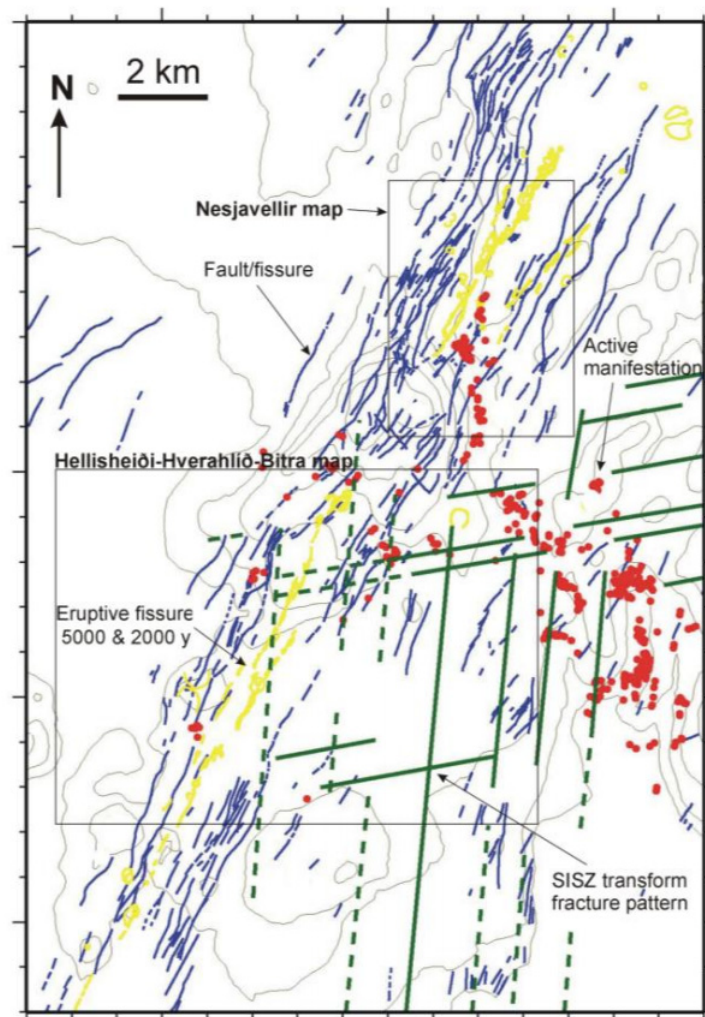


FIGURE 4: The Hengill volcanic system showing surface geothermal springs as red dots. Surface fissures and faults as blue lines. Green lines are fissures and faults defined by earthquake locations and yellow lines are post glacial (< 12 ka) fissures (Franzson et al., 2010)

### 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 (Thorbergsson et al. 1984, Árnason et al., 1987), aeromagnetic survey (Björnsson and Hersir, 1981), seismic refraction and passive seismic surveys (Pálmason, 1971, Foulger, 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 5 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.

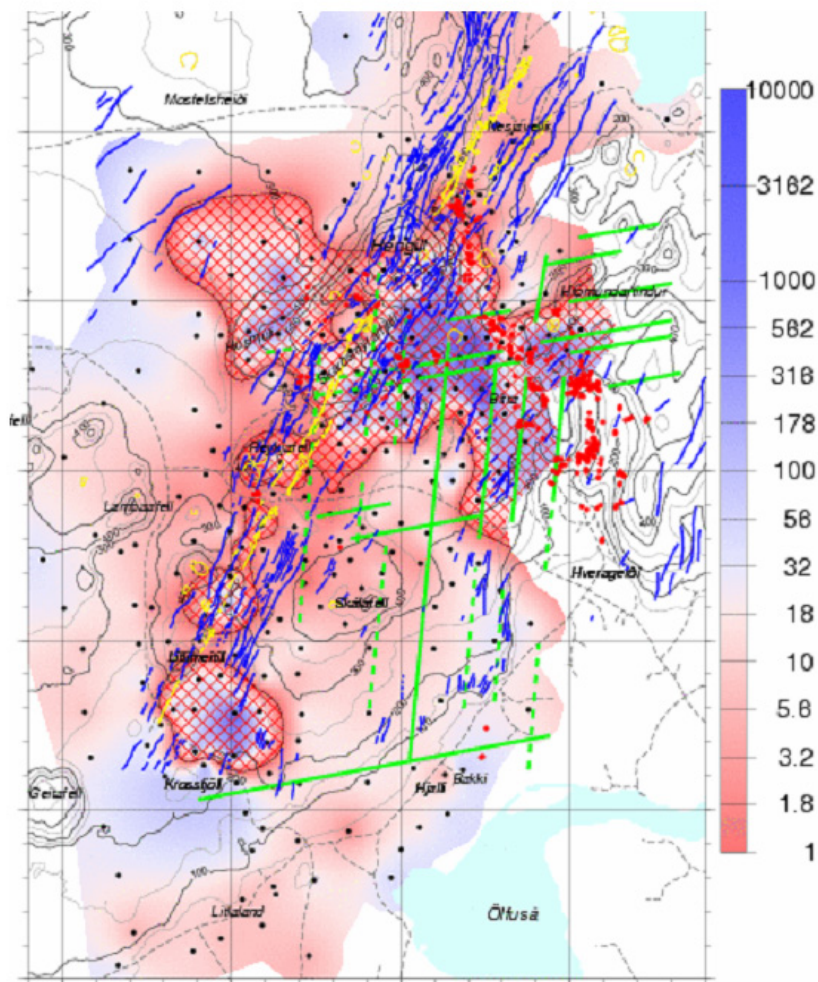


FIGURE 5: A resistivity map of the Hengill central volcano at 850 m b.s.l. showing variations in resistivity. The cross-hatched areas define high resistivity cores below low resistivity, and are interpreted to indicate alteration temperatures of over 230°C. Surface geothermal springs are shown as red dots, fissures and faults as blue lines. Green lines are fissures and faults defined by earthquake locations and yellow lines are post glacial (< 12 ka) fissures (Árnason, 2006)

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 (Figure 2). These structures have been confirmed by the zonation of temperature dependent alteration minerals in drill holes, but the formation temperatures have though been variable (Franzson et al., 2010). 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; dilatationary 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 SISZ (Franzson et al., 2010). 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 4. A study of fracture pattern from aerial photographs has shown a similar combination of fracture directions (Khodayar and Franzson, 2007). This supports the observation that the Hengill volcanic system may be considered to be located at a triple junction. This must affect permeability in the crust (Franzson 2010).

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., 2010). The results showed the emergence of two conducting layers below 4 km depth which lie in a WNW-ESE direction. The shallower one extends from Mt. Hengill 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.

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