Geothermal Implications of Rift Zone Mini-Grabens—Geological and Geophysical Structure of the Reykjafell Mini-Graben, Hengill Geothermal Field, SW Iceland

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Keywords
Iceland, Hengill, Hellisheidi, rift zone, mini graben, central volcano, high-temperature geothermal field, fault, fissure, tectonics, geophysical, 1-D inversion, TEM

ABSTRACT

The active volcanic zones in Iceland are characterized by high heat-flow and extensive geothermal activity. Iceland is unique in its location being not only astride the diverging Mid-Atlantic Ridge, but also above 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 powerful 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 15-50 km wide and 170 km long. The Hengill low resistivity region covers about 112 km², and presently Reykjavik Energy operates two power plants in the area with installed capacity of about 420 MWe and 430 MWt. We present preliminary results on structural mapping of a mini-graben, the Reykjafell graben, which is located at the western flank of the Hengill geothermal system and thereby flanking the WVZ. The mapped graben strikes NE-SW, it is about 7 km long, up to 400 m wide and has a down-throw of up to 200 m. Production wells which penetrate the Reykjafell mini-graben are amongst the most powerful in the area. 1D inversion of TEM resistivity data strongly suggests an up-flow zone.

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. Blue areas indicate Tertiary rocks (16-2, 6 My), green areas Pleistocene (2,6 My-11,7 ka) and purple areas indicate the Holocene, forming most of the volcanic zones, which are outlined (modified from Johannesson and Sæmundsson, 1999).
Harðarson, et al. along the Reykjafell mini-graben. These results may have significant implications for other high-temperature geothermal areas which are located in a similar tectonic setting, for example, the East African Rift System. The paper illustrates the importance of detailed structural mapping during the initial phases of geothermal exploration, as such mapping is the most cost effective of all the following research techniques.

1. Introduction

Iceland is unique in its location astride the diverging Mid-Atlantic Ridge sitting on top of a mantle plume. Such dynamic systems combine significant 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) (Fig. 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, at which point the focus of extension in S Iceland will transfer from the WVZ to the EVZ (e.g. Sæmundsson, 1980, Hardarson et al., 1997, 2008). Since the Mid-Atlantic ridge system first migrated WNW over the Iceland plume about 24 m.y. ago (e.g. 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 (Sæmundsson, 1980, Hardarson et al., 1997).

The active volcanic zones in Iceland are characterized by high heat-flow and extensive geothermal activity. The high-temperature reservoirs (>200°C at 1 km depth) are mainly confined to the volcanic zones (Fig. 1), in particular to 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 and 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 most 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 (e.g. Einarsson 2008, LaFemina et al., 2005).

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 cuts the Hengill system and extends about 170 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, oriented E-W, is about 10-15 km wide and 70-80 km long and takes up the transform motion between the RR and the EVZ (e.g. Einarsson, 2008). The overall left-lateral transform motion is accommodated by

Figure 2. Satellite image of the Hengill central volcano showing the location of the Nesjavellir, Helliheidi, Hverahlid and Hveragerdi Fields. The western flank of the Western Volcanic Zone graben can be seen on the figure as the fissure/fault swarm terminates to the west and the surface becomes flat.
right-lateral faulting on many parallel transverse faults and counterclockwise rotation of the blocks between the faults, namely bookshelf faulting (e.g. Einarsson, 2008). 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 use, 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 (2013) about 29% of the electricity generated in Iceland is of geothermal origin, the rest being from hydro-resources. However, roughly 86% of primary energy used in Iceland is derived from indigenous renewable sources (68% geothermal, 18% hydropower) (National Energy Authority, 2013). The rest of Iceland’s energy sources come from imported fossil fuel used for fishing and transportation. Reykjavík Energy already operates a geothermal power plant at Nesjavellir, north of the Hengill volcano (Fig. 2), with installed capacity of 120 MWe and 300 MWt. Further power plants have been constructed at Hellisheiði, SW of the Hengill volcano (Fig. 2). They have installed capacity of 303 MWe and 130 MWt. At present 57 deep (1300-3300 m) exploration and production wells have been drilled at Hellisheiði. This includes 17 reinjection wells, numerous cold groundwater exploration wells and several shallow exploration wells. Exploration high-temperature wells have also been drilled at locations near Bitra and Hverahlid (Fig. 2). The first exploration well was drilled in 1985 at Kolvidarholl at the west boundary of the Hellisheiði field, followed by a well at Ölkelduhals (Bitra) east of Hengill (Fig. 2) in 1995. Subsequently this was followed by extensive exploration and exploitation at the Hellisheiði geothermal field.

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 is still active seismically, hosting geothermal reservoirs (Fig. 2) and forming the base of the Hengill system with a thick lava sequence. Three well-fields have been developed within the greater Hengill area, including Nesjavellir, Hellisheiði, where resource utilization is well underway, and Hveragerdi, where the geothermal resource is utilized by the local community for direct use. Furthermore, exploration drilling has been launched at Bitra and Hverahlid adjacent to the Hengill system (Fig. 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 which may play a role in the permeability of the geothermal field (e.g. Árnason and Magnusson; 2001). The Hengill volcano is mainly built up of hyaloclastite formations erupted underneath the ice sheet of the last glacials, forming a mountain complex rising up to some 800 m (Fig. 2). Interglacials lavas on the other hand, flowed down and accumulated in the surrounding lowlands. 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 250 m (Franzson et al., 2005, Hardarson et al., 2009). 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 (Sæmundsson 1995, Franzson et al., 2005). The volcanic fissures of the latter two can be traced to the north, through the Nesjavellir field (Fig. 2) and into Lake Thingvallavatn (Sæmundsson, 1995). At Nesjavellir these volcanic fissures act as the main out-flow channel of the geothermal system and the fissures are also believed to act as major out-flow zones in the Hellisheiði field (e.g. 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 have also been targeted, since 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 (e.g. Árnason and Magnusson 2001; Gunnlaugsson and Gislason, 2005). The southern part of the Hengill area rises up to approximately 600 m elevation at Skardsmýrarfljót (Fig. 2). A large geothermal high-temperature anomaly has been shown to exist in the area by means of extensive geological mapping and geophysical exploration (e.g. Árnason and Magnusson 2001). The Hengill system is dominated overall by NE-SW strike of major fractures and faults. In some places, however, the fractures are intersected by easterly striking faults, indicated by seismic data, which may affect the permeability of the Hellisheiði field (e.g. Árnason and Magnusson 2001). Volcanic fissures of 5 and 2 thousand years seem to play an important role as major out-flow zones in the field (e.g. Sæmundsson 1995, Björnsson 2004, Franzson et al., 2005).

3. Fissure Swarm and Faults

The Hengill fissure swarm forms a graben-like structure, which extends 60-70 km to the north and south of the central volcano, and is 5-10 km wide, in general striking NE-SW. Large NE-SW faults are a prominent geological feature at the western side of the Hengill system field with a total throw of about 250 m towards the east. These large faults can be traced about 15-20 km to the northeast, and they represent the western margin of the Hengill fissure/fault zone (e.g. Sæmunds-
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Other major faults in the area have not been mapped but minor faults are fairly common on the surface, usually with an eastern down-throw in the western half of the graben and throw to the west in the eastern half. However, along the western flank of the Hengill fissure swarm, a narrow, but significant, mini-graben, with down-throws to the east and west on either side, has been identified as a potential geothermal up-flow zone.

Faults at the western margin of the Hengill system are shown in figure 3. The faults tilt to the east, except the fault labeled “E” which tilts west and we estimate the throw on the surface to be at least 40 m. However, analysis of drill cuttings and drilling data from wells that intersect these faults indicate a down-throw of up to 200 m at 1300 m b.s.l. Consequently, a mini-graben, the Reykjafell mini-graben, (Hardarson et al., 2009) is found between faults “W” and “E” (Figs. 2 and 3). It is of interest that aquifers often appear to be largest at locations of highest temperatures and production wells that cut the Reykjafell graben are amongst the most powerful (>6 MWe) at Hellisheiði. Permeability along the faults and the two postglacial eruptive fissures at the western margin of the Hengill system is believed to be high, causing a strong out-flow towards the south from the Skardsmyrarfjall hyaloclastite mountain and north from the Reykjafell mountain (Fig. 2). At least some of the aquifers encountered in the

Figure 3. Faults at the western margin of the Hengill system. The faults dip to the east, except fault labeled “E” which dips west. Consequently a graben is found between faults “W” and “E”. The Husmúli fault (labeled “H”) is flanking the western rim of the Hengill fissure swarm. The view is from SW to NE.

Figure 4. Geological map of the Hengill area (Sæmundsson, 1995). The research area is within the red box (cf. Fig. 7). The volcanic accumulation consists of postglacial lavas (blue-purple colors), hyaloclastites from glacial times (brownish colors) and interglacial lava flows (greenish colors). Chemically evolved volcanics are yellow.
wells can be directly related to margins of intrusions indicating the importance of fracture permeability in the geothermal reservoir (Franzson et al., 2005). However, our preliminary results indicate that permeability at the western margin of the Hengill system is primarily related to the major faults and these faults have been the target for both production and reinjection wells.

3.1 The Reykjafell Mini-Graben

Detailed surface mapping of the southern part of the Reykjafell mini-graben has recently been executed and drill-cuttings, where available, were analysed to map the sub-surface. Resistivity data was acquired in 2006 and 1D inversion of TEM resistivity data was published by Árnason (2007). Figure 4 shows a geological map of the Hengill volcano and the mapped area is boxed. Figure 5 shows resistivity at 850 m b.s.l. from the TEM survey.

The Reykjafell mini-graben was mapped north of Mt. Reykjafell to the SW through the Gráuhnúkar area, Mt. Stóri Meitill and past Mt. Litli Meitill (Fig. 6). However, it is believed to extend to the NE, possibly all the way to Nesjavellir (Fig. 2). The strike is generally NNE-SSW, the down-throw observed on the surface is 20-40 m and the graben is 150-400 m wide. Drill cutting analyses and drilling data from wells that intersect these faults (Fig. 7) indicate a down-throw of as much as 200 m at 1300 m b.s.l. The only surface manifestations are a few fumaroles which are present at the south margin of Mt. Reykjafell, and are located at the eastern rim of the graben. However, a few subglacial (>10 000 yrs old) craters are aligned, mostly along the eastern rim from NW to SW, and some are located within the mini-graben. The formation of Stóri Meitill and Litli Meitill (Fig. 6) placed at the western rim, may have been affected by the graben.

It is of interest that wells which penetrate the Reykjafell mini-graben are, in general, more powerful than most other wells in the Hellisheidi geothermal field (Fig. 7). Whilst the average yield of wells in the area is about 6 MWe, wells that cut the graben are usually more than 10 MWe and some, like

Figure 5. Resistivity at 850 m b.s.l. according to TEM survey 2006. High resistivity cores are shown with red, crossed lines. 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 (Árnason, 2007).

Figure 6. The Reykjafell mini-graben (thick red line) is located on the east flanks of Litli Meitill and Stóri Meitill and strikes NE from there through Mt. Reykjafell.
HE-30, HE-45 and HE-47 (Fig. 7), are around 20 MWe. It must be noted, however, that these are all directed through Mt. Reykjafell. Less is known about the area south of Mt. Reykjafell, for example HE-55 may not have penetrated the mini-graben and HN-5, which is a reinjection well, only managed to break the graben fault plane, but reached temperatures above 300°C. Further drilling is needed to confirm the nature of the graben south of Mt. Reykjafell.

### 3.2 Geophysical Data

TEM survey in 2006 revealed the resistivity structure of a geothermal high temperature system i.e. a low resistivity cap underlain by a high resistivity core. The resistivity reflects the high-temperature alteration of the rock. The low resistivity cap corresponds to a highly conductive layer dominated by smectite and zeolites formed at temperatures up to 230°C. At temperatures exceeding 230°C, the more resistive chlorite becomes dominant along with epidote (>250°C) comprising the high resistivity core (Fig. 5). Thus resistivity corresponds directly to temperature provided there is thermal equilibrium between the alteration and the rock (Árnason and Karlsdóttir, 2006; Árnason, 2007).

When scrutinized, the TEM soundings in south western part of Hengill area showed a special character indicating a vertical low resistivity layer. This feature had been encountered earlier in Geysir area (Karlsdóttir, 2004) and Hveravellir area (Karlsdóttir and Vilhjálmsson, 2006). Models were run with a vertical low resistivity and they confirmed characteristic features in TEM soundings above and near the low resistivity contact and hence revealed a potential up-flow zone along vertical fractures. The TEM soundings in Hengill area showing these features form a “line” from Reykjafell in the north all the way to Litli Meitill in the south (Figure 8).

Examples of the features encountered in the TEM soundings are displayed on figure 9. All TEM sounding marked as shaded stars show a narrow doming of the low resistivity cap or a small low resistivity anomaly above the low resistivity cap. This is the feature in question and thought to indicate up-flow of geothermal fluid along the line/fractures (Karlsdóttir, 2011).

At this point these findings were compared to the geology of this area showing that the alleged up-flow zone comprised by the TEM soundings corresponded directly to the Reykjafell mini-graben (Karlsdóttir, 2011).
4. Discussion

A central volcanic system consists of a central volcano and the associated fissure/fault swarm. Sometimes a geothermal system is related to the central complex, particularly at plate boundaries. Some mature central volcanoes experience one or more caldera collapses, which may indicate relatively shallow magma chambers and therefore a shallow heat source. Geothermal power companies often seek licenses and catchment areas of potential central volcanoes for geothermal exploration and exploitation. However, the fissure/fault swarms may also include geothermal resources, the Nesjavellir and Hellisheidi geothermal fields providing excellent examples of this. It is common to observe mini-grabens within the fissure/fault swarms, which may be large, i.e. with significant down-throws, although smaller and less significant grabens are more usual. Such grabens have been noted, and sometimes mapped, adjacent to several central volcanoes in Iceland and in the East African Rift System, for example by Eburr and Suswa (unpublished). However, they have not attracted much attention or detailed mapping, and are rarely mentioned in the literature.

In this paper we have shown that mini-grabens within larger grabens should be examined specifically in conjunction with geophysical data. In fact, the structural mapping can be useful in determining where resistivity stations should be most dense.

5. Conclusions

We have established by using combined structural and geophysical data that a mini-graben located within the Hengill fissure/fault swarm may potentially provide a high-temperature geothermal resource. Structural mapping and, in particular, geophysical data indicate up-flow zones along the mini-graben. Boreholes penetrating the graben in Mt. Reykjafell are in general more powerful than other wells in the Hellisheidi geothermal field. Until an exploration well has been drilled our knowledge of the extension of the heat anomaly to the south will remain inconclusive.

6. Acknowledgements

Permission from Reykjavik Energy to publish the data is acknowledged. Constructive comments by B. Steingrimsson, D. Boden and I.S. Macdonald are much appreciated.

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