

Geothermal Reinjection at the Hengill Triple Junction, SW Iceland

Björn.S. Hardarson¹, Gunnlaugur M. Einarsson¹, Bjarni R. Kristjánsson², Gunnar Gunnarsson², Helga M. Helgadóttir¹, Hjalti Franzson¹, Knútur Árnason¹, Kristján Ágústsson¹ and Einar Gunnlaugsson²

1. Iceland GeoSurvey, Grensasvegur 9, 108 Reykjavík, Iceland, 2. Reykjavík Energy, Bæjarhals 1, 110 Reykjavík, Iceland

Bjorn.S.Hardarson@isor.is

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ABSTRACT

Reinjection of waste geothermal fluid into geothermal systems has been recognized to play a very important role in present-day reservoir management and is most often environmentally necessary. Reinjection is a complex process, firstly it is a multi-parameter method and secondly it is critical to evaluate its possible effects on production wells in the geothermal field. Reykjavík Energy has had twelve injection wells drilled for the Hellisheidi power plant which is located by the Hengill central volcano in SW Iceland. The capacity of these wells varies significantly. Eventual production of the power plant will be 303 MW of electricity, 400 MW of thermal energy and some 500 L/s of waste water which has to be disposed off. The Hengill region covers about 110 km² 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. Consequently, fissures and faults are very common in the area. We believe that it is crucial to delineate this tectonic arrangement in relation to the location of injection wells, both regarding their capacity and possible effects on production wells in the field. Here we present new well data from the injection area for the Hellisheidi power plant and on the structure of fissures and faults.

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, 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 whereupon the focus of extension in S Iceland will transfer from the WVZ to the EVZ (e.g. Sæmundsson, 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 (Sæmundsson, 1980).

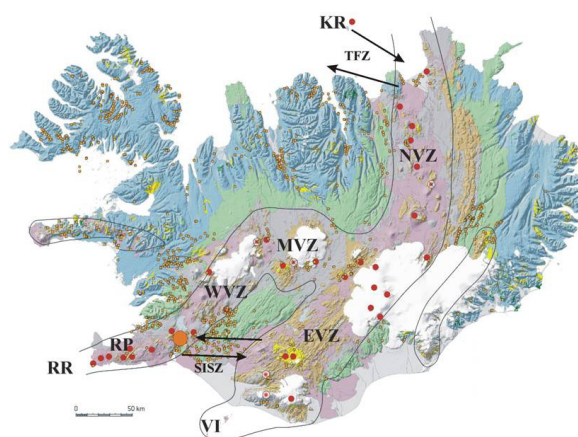


Figure 1: Geological map of Iceland showing the location of the active volcanic zones and transforms discussed in this paper. RR = Reykjanes Ridge; RP = Reykjanes Peninsula; WVZ = Western Volcanic Zone; MVZ = Mid-Iceland Volcanic Zone; NVZ = Northern Volcanic Zone; EVZ = Eastern Volcanic Zone; VI = Vestmanna 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 (modified from Johannesson and Sæmundsson, 1999).

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 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 (e.g. Einarsson 2008, LaFemina et al., 2005).

The Hengill region (Figs. 1 and 2) covers about 110 km² 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 (Fig. 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 the Hengill system extends about 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 10-15 km wide and 70-80 km long and takes up the transform motion between the RR and the EVZ (Einarsson, 1991). The overall left-lateral transform motion is accommodated by right-lateral faulting on many parallel transverse faults and counterclockwise 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.

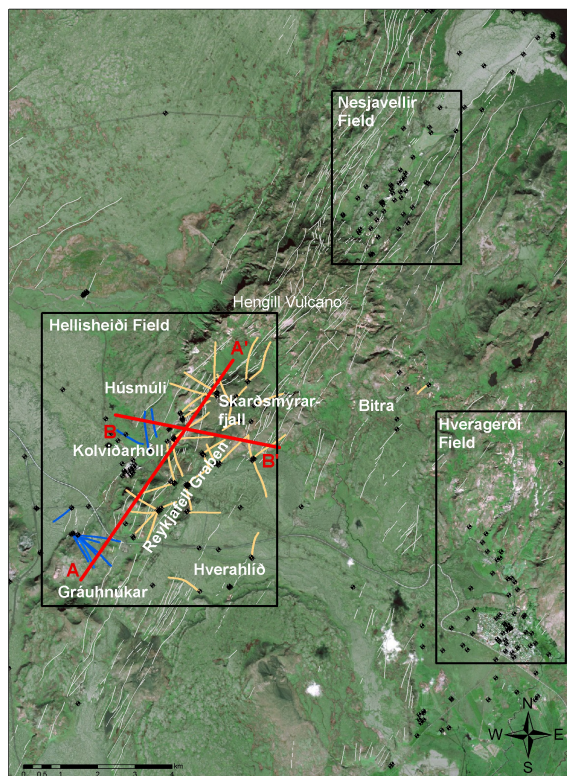


Figure 2: Satellite image of the Hengill central volcano showing the location of the injection sites at Gráuhnúkar and Kolvíðarhöll (reinjection wells shown with blue lines). White lines express faults and fissures and yellow lines indicate production wells. Red lines show the location of cross sections A-A' and B-B'.

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 (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 (National Energy Authority, 2009). Reykjavik Energy already operates a geothermal power plant at Nesjavellir, north of the Hengill volcano (Fig. 2), with installed capacity of 120 MWe and a 290 MWt for a hot water plant. Further power plants are being constructed at Hellisheiði, SW of the Hengill volcano. Eventual production of these will be about 300 MWe and 400 MWt but current production capacity is 213 MWe. At present 46 deep (1300-3300 m) exploration and production wells have been drilled at Hellisheiði, 12 reinjection wells, numerous cold water wells and several shallow exploration wells. Exploration wells have also been drilled at locations near Bitra and Hverahlíð (Fig. 2). The first deep exploration well was drilled in 1985 at Kolvíðarhöll at the west boundary of the Hellisheiði field, followed by a well at Ölkelduhals east of Hengill in 1995. Subsequently this has been succeeded by vigorous exploration and exploitation at Hellisheiði.

Geothermal reinjection began as a method of disposing of wastewater from power plants in order to protect the surrounding environment. It was initialized as early as 1969 and 1970 at the Geysers area in California and in the Ahuachapan field in El Salvador, respectively. Presently there are a number of geothermal fields worldwide where reinjection is already a part of the operation. In Iceland most high-temperature power plants dispose of liquid effluent by reinjection (since 1982) and at the Hellisheiði power plant all of the waste water is reinjected. Reykjavik Energy has to date drilled 12 injection wells in the Hellisheiði field, 9 of which are operational, 6 at Gráuhnúkar and 3 at Kolvíðarhöll (Fig. 2) but further reinjection wells are being designed. Eventual waste water that has to be disposed of is in the order of 500 l/s. The remaining three reinjection wells are not operational but are being used in a revolutionary carbon capture project studying the feasibility of sequestering the green-house-gas carbon dioxide into basaltic bedrock and store it there permanently as a mineral (Sigurdardóttir, 2008, Matter et al., 2009).

2. GEOLOGICAL SETTING

The Hengill volcanic system is currently active while its predecessor, the Hveragerði system, is now extinct in terms of volcanic activity but still active seismically, hosts geothermal reservoirs (Fig. 2) and forms the base of the Hengill system with a thick lava sequence (Fig. 3). Three well-fields have been developed within the greater Hengill area, Nesjavellir, Hellisheiði, where resource utilization is well underway, and Hveragerði where the geothermal resource is utilized by the local community (Fig. 2). Furthermore, exploration drilling has been launched at Bitra and Hverahlíð 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 (Fig. 4) which may play a role in the permeability of the geothermal field (e.g. Arnason and Magnusson, 2001). The volcano is mainly built up of hyaloclastite formations (Fig. 3) erupted underneath the ice sheet of the last glacials, forming a mountain complex rising up to some 800 m at Hengill (Fig. 2). Interglacial lavas on the other hand flow down and accumulate in the surrounding lowlands. The fissure swarm associated with the volcano is a depression or a graben structure with large graben faults with 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, Helgadóttir et al., 2009). 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 outflow channel of the geothermal system and the fissures are also believed to act as major outflow 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, 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 (e.g. Arnason and Magnusson, 2001; Gunnlaugsson and Gislason, 2005).

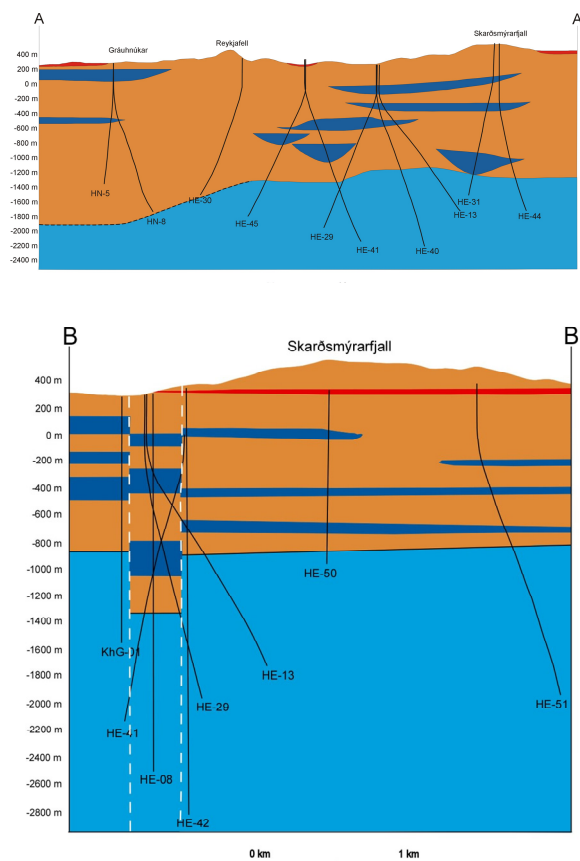


Figure 3: Geological cross section along lines A-A' and B-B' (Fig. 2). Blue formations are interglacial lava series and the light blue formation is interpreted as the base of the Hengill central volcano being erupted from the Hveragerdi system. Red formations are postglacial lavas. Brown formations are hyaloclastite formations. Dotted, black line represents areas where no data are available. White broken lines show the Reykjafell graben (from Helgadóttir et al., 2009).

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 (e.g. Arnason 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 (e.g. Arnason and Magnusson, 2001). Volcanic fissures of 5 and 2 thousand years seem to play an important role as major outflow zones in the field (e.g. Sæmundsson, 1995; Björnsson, 2004 and Franzson et al., 2005). In addition they have also been used as targets for the reinjection wells of the area.

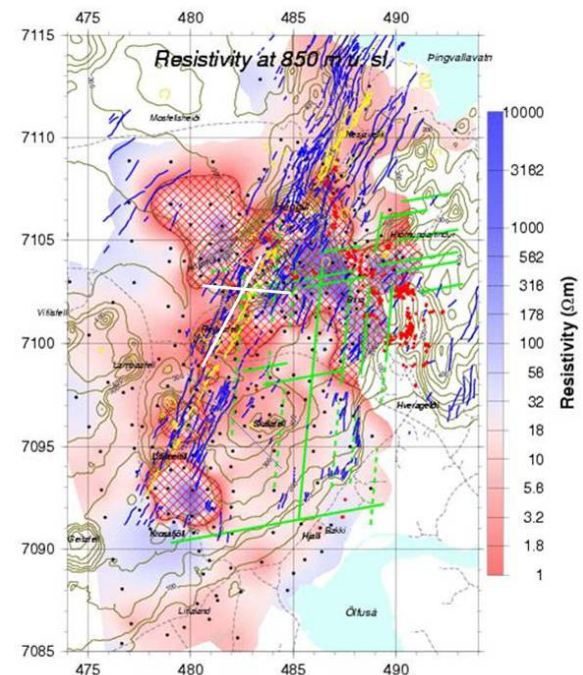


Figure 4: Resistivity at 850 m below sea level according to recent TEM surveys. High resistivity below low resistivity (< 10 Ωm) is shown as red, crossed lines. Surface geothermal springs as red dots. Surface fissures and faults as blue lines. Green lines are fissures and faults defined by earthquake locations and yellow lines are post glacial (< 12 ka) fissures. White lines show the location of cross sections A-A' and B-B' in Figure 2 (Arnason, 2006).

3. FAULTS

Large NE-SW striking faults are a prominent geological feature at the western side of the Hengill system with a total throw of about 300 m towards the SE. These large faults can be traced about 15-20 km to the northeast, and they are believed to represent the western margin of the Hengill fissure/fault zone (e.g. Sæmundsson, 1995; Franzson et al., 2005). Other major faults in the area have not been found from borehole data, and minor faults are more difficult to identify due to the lack of reliable horizontal marker horizons, such as lava series (Franzson et al., 2005).

Aquifers (feed points) in the wells are located using, for example, circulation losses, temperature logs and

hydrothermal alteration. A detailed analysis of these data and their exact relation to the geological factors is ongoing (e.g. Helgadóttir et al., 2009).

Faults at the western margin of the Hengill system are shown in Figure 5. The faults tilt to the east, except the fault labeled “E” which tilts west and we estimate the throw on the surface at least 30 m. However, preliminary analysis of drill cuttings and drilling data from wells that intersect

these faults indicate a throw of at least 300 m at 1300 m b.s.l. Consequently a substantial graben, the Reykjafell graben, (Hardarson et al., 2009) is found between faults “W” and “E” (Fig. 5). 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 at Hellisheidi.

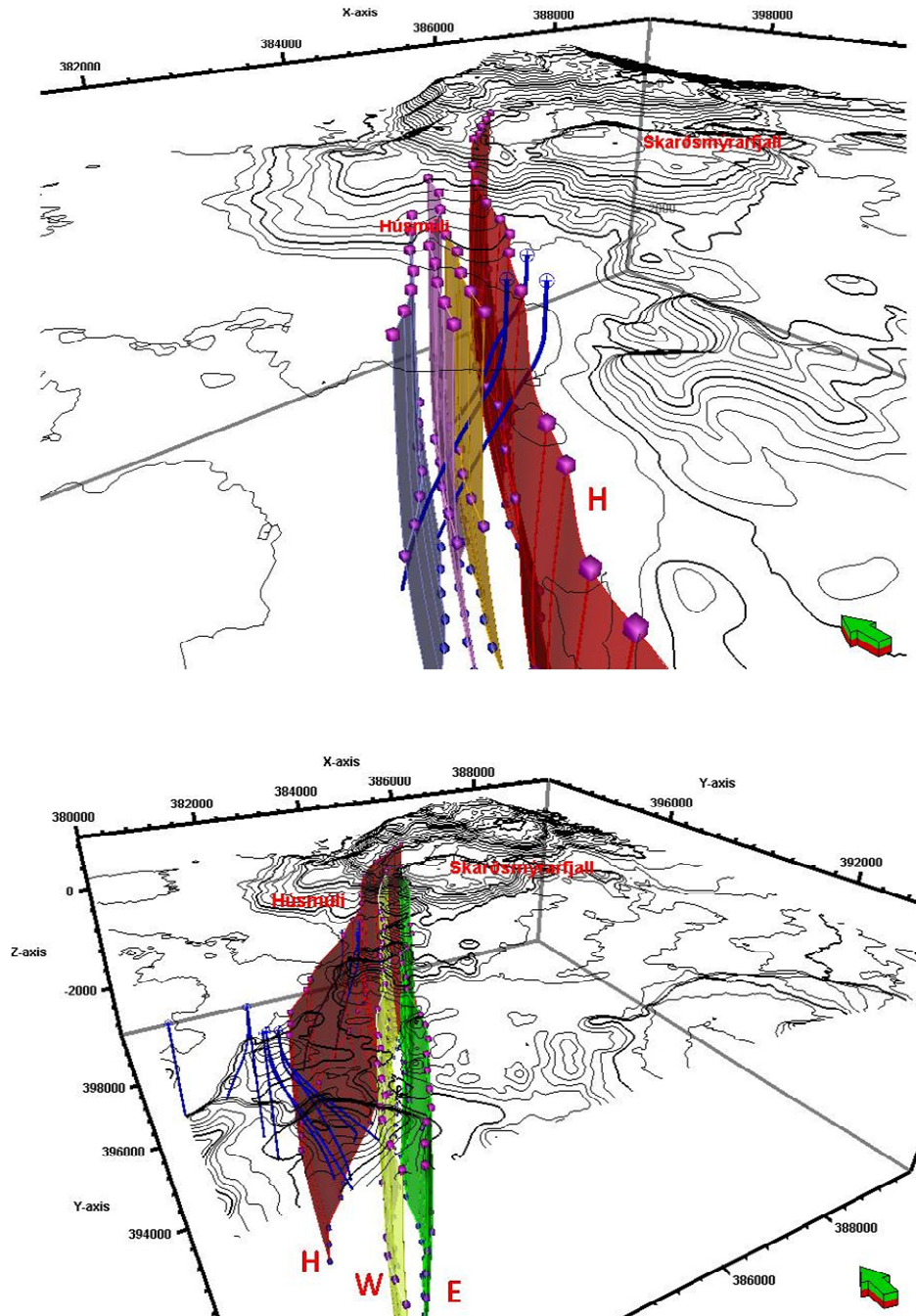


Figure 5: Faults at the western margin of the Hengill system (Fig. 2). The upper figure shows the Kolvidarholl reinjection site and the lower shows the Grauhnukar site. The reinjection wells are shown in blue. The faults dip to the east, except fault labeled “E” which dips west. Consequently a graben is found between faults “W” and “E”. The Husmuli fault is labeled “H”. The view is from SW to NE.

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 outflow 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 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 reinjection.

3. REINJECTION

3.1 Introduction

The idea of injecting the effluent liquid back into the ground has been with the geothermal power industry for a long time (e.g. Stefansson, 1997). Initially the purpose was to get rid of the liquid effluent in a nicer manner than dumping it on the surface, into rivers, or ocean. However, soon it became clear that there were additional benefits such as improvement of the heat mining and stabilization of the production capacity of the geothermal field through the maintenance of the reservoir pressure. Reinjection counteracts pressure draw-down by providing an artificial water recharge (Stefansson, 1997). Water injection is also responsible for induced seismicity. The size, rate, and manner of seismicity are controlled by the rate and amount of fluid injected, the orientation of the stress field relative to the pore-pressure increase, the extensiveness of the local fault system, and the deviatoric stress field in the subsurface, i.e. how much excess stress is available to cause an earthquake (Majer et al., 2007).

However, there are several problems associated with reinjection, for example, clogging of injection wells, pipes and the formations close to the borehole but silica scaling is probably the most delicate operational problem in reinjection. Possible cooling of nearby production wells has also been addressed (Stefansson, 1997). Cooling of the reservoir caused by reinjection of colder fluid has been reported in a few high-enthalpy geothermal fields. For low-enthalpy geothermal fields, there have not been any such reports (Stefansson, 1997). Careful testing and research is necessary to avoid these problems. Tracer testing combined with comprehensive interpretation being the most important tool for this purpose.

3.2 Reinjection at the Hellisheidi Power Plant

Reinjection of the waste geothermal fluid at Hellisheidi was initiated as soon as the geothermal power plant was commissioned in 2006. Only the separated fluid has been reinjected but the condensate has been disposed of into shallow wells near the power plant (Kristjansson and Gunnarsson, 2009). The initial plan was to reinject the waste geothermal fluid into the lower part of the ground water system (below 400 m) alongside the geothermal area. A similar plan has been successfully applied at the Nesjavellir Power Plant (Fig. 2). After exploration drilling of three wells and well testing the initial plan was abandoned due to insufficient permeability. Consequently, six reinjection wells were drilled deep into the geothermal system at Grauhnukar (from 2006), south of the current production area and subsequently (from 2008) three to the west at Kolvidarholl (Fig. 2) targeting faults in the area (Fig. 5). However, as mentioned above, the first three failed reinjection wells now serve as an important part of carbon capture project studying the feasibility of sequestering the

green-house-gas carbon dioxide into basaltic bedrock and store it there permanently as a mineral (Sigurdardottir, 2008; Matter et al., 2009).

The two reinjection fields are dominantly built up of hyaloclastite, formations of limited horizontal extent but the few lava series which are present have been used as marker horizons. The reinjection areas are cut by the sub vertical, active NE-SW striking faults shown on figure 5. In some places, however, the faults are intersected by easterly striking features which may affect the permeability of the fields (e.g. Arnason and Magnusson 2001, Hardarson et al., 2007 and 2008). Temperature logs, circulation losses during drilling and drill data indicate that the primary aquifers, or feed points, are primarily related to the faults so that the permeability is vertical rather than horizontal between different formations. The reinjection wells are all directional, 1200-3000 m long (measured depth) but true vertical depth varies from 1000-2500 m. When drilling started at Grauhnukar it became apparent that the wells were much hotter than anticipated, up to around 300°C, which is interpreted so that there is a separate up-flow zone in the area. Consequently some of the wells are designed so that they can serve both as reinjection and production wells. Presently about 170 l/s is injected at 8-10 bar into the Grauhnukar area and 20 l/s into the Kolvidarholl area. Only one hole is operational at Kolvidarholl and its injectivity index has been seriously reduced, possibly because of scaling problems.

In November 2007 a low-pressure turbine (32 MW) was commissioned and lowered the temperature of the separated fluid decreased from 180°C to about 120°C. The temperature change increased the injection capacity of the reinjection wells (Kristjansson and Gunnarsson, 2009). Recent well tests at the Kolvidarholl area also indicate a significant temperature dependence of the injectivity of well HN-9. Currently, Reykjavík Energy is performing well tests with different fluid temperatures ranging from 10°C to 120°C to separate and quantify the thermal effect on the injectivity of the wells. Preliminary results indicate a near linear, negative correlation between temperature and the injectivity index (Kristjansson and Gunnarsson, 2009).

3.3 Seismicity

The plate-tectonic setting of the Hengill Volcano, being located at a triple junction, is one reason for its very high background seismicity. For example, in the period between 1994 and 1998 more than 80,000 small earthquakes were recorded in the Hengill and its surroundings (Vogtfjord et al., 2005). Some 50% of them had focal mechanisms consistent with normal and strike-slip faults related to plate movements in the area. The strike-slip faults form a conjugate system of NNE-striking dextral and ENE-striking sinistral faults. The remaining 50% of the earthquakes are concentrated in the high-temperature parts of the area and exhibited non-double-couple mechanisms characteristics of extensional failure due to circulating fluids (Foulger, 1988). The seismic activity is episodic on the time scale of decades whilst magmatic activity is also episodic, but on a much longer time scale. At a depth of 4-10 km below the Hengill area, velocity of P- and S-waves is reduced, more of the P-waves (low V_p/V_s). This is interpreted as heavily fractured volcanic fissure system and the low velocities caused by supercritical fluids, some of magmatic origin (Stefansson et al., 2006).

It is well known that seismicity plays an important role in geothermal systems located in seismically active areas by keeping aquifers open (fissures and faults) and forming new

ones. In many cases where permeability is poor, there is a need to increase the permeability and/or fluid content, i.e. to enhance the natural geothermal systems. One of the issues associated with Enhanced Geothermal Systems is the effect and role of the seismicity (or microseismicity) induced during the creation, or improvement in the properties, of an underground reservoir and subsequent extraction of geothermal energy (Majer et al., 2007).

Earthquakes in the Hengill area may affect production wells. This has, however, not been well documented. It was noted, during the drilling of the reinjection wells at Grauhnukar and Kolvidarholl and subsequent injection, that seismicity in the immediate area around the wells increased (Fig. 6). The magnitude of the earthquakes is generally small but the largest ones reach 2.5 at Grauhnukar and about 3 at Kolvidarholl. These results clearly indicate that the reinjection at Hellisheidi has induced seismic activity.

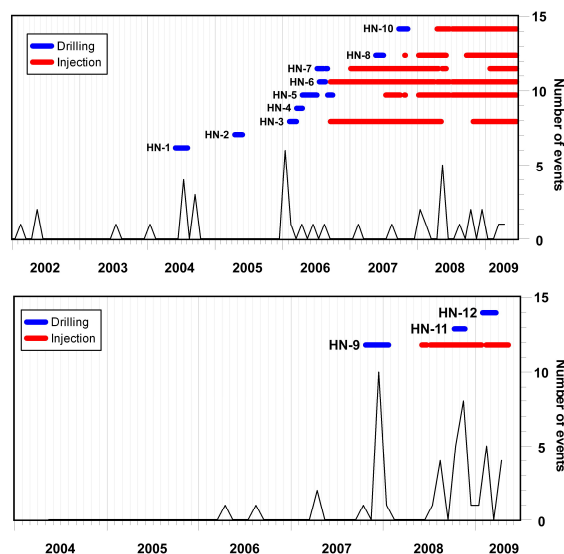


Figure 6: Frequency of seismic events at Grauhnukar (upper diagram) and Kolvidarholl (lower diagram) related to the drilling and injection into the reinjection wells at Hellisheidi. Seismic data is from the Iceland Meteorological Office.

5. CONCLUSIONS

This paper summarizes some of the results from the Hellisheidi reinjection fields by the Hengill volcanic system.

- 1) Reykjavik Energy has drilled 9 reinjection wells by the western margin of the Hengill volcanic system where it is dominated by large, NA-SW striking sub-vertical faults. Permeability is mostly confined to the faults and the wells intersect these structures.
- 2) Two reinjection fields have been exploited and the stratigraphy is dominated by hyaloclastites, formations of limited horizontal extent but the few lava series which are present have been used as marker horizons.
- 3) Preliminary results indicate a near linear, negative correlation between temperature of the reinjected waste water and the injectivity index.

- 4) During the drilling of the reinjection wells and subsequent injection seismicity in the area around the wells increased significantly indicating that the reinjection at Hellisheidi has induced seismic activity.

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