Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Reinjection into a Fractured Reservoir – Induced Seismicity and Other Challenges in Operating Reinjection Wells in the Hellisheiði Field, SW-Iceland

Gunnar Gunnarsson, Bjarni Reyr Kristjánsson, Ingvi Gunnarsson, and Bjarni Már Júlíusson

Mailing address, Orkuveita Reykjavíkur, Bæjarhálsi 1, 110 Reykjavík, Iceland

E-mail address, gunnar.gunnarsson@or.is

Keywords: Hengill, Hellisheiði, reinjection, induced seismicity, seismic risk, temperature dependent injectivity, fractured reservoir

ABSTRACT

The Hellisheiði Power Plant was commissioned in 2006. It is located in the southern part of the Hengill Volcanic System, 25 km southeast of Reykjavík, Iceland. The system consists of hyaloclastite formations intersected by a NE-SW oriented fissure swarm. The Hellisheiði Geothermal Field is located in the southern part of the area. Another geothermal field under operation, Nesjavellir, is in the northern part of the area.

The most productive part of the Hellisheiði Field is relatively small and therefore it is necessary to reinject in order to maintain reservoir pressure. The reservoir is water dominated and around 50% of the produced fluid is steam at separator pressure. All the separated water is reinjected into the reservoir along with some condensate water. Two reinjection zones are operated for that purpose; Gráuhnúkar and Húsmúli.

There are mainly three challenges in operating the reinjection zones of the Hellisheiði Power Plant. Firstly, the productivity of the reinjection zones has been decreasing slowly – especially that of Húsmúli. Secondly, the permeability of the wells is highly dependent on the temperature of the reinjected water. The permeability increases with lower temperature. The third challenge is induced seismicity in the Húsmúli Reinjection Zone.

It is not clear why the productivity of the reinjection zones has been decreasing. Individual wells behave differently. In one well the injectivity is increasing while in others it is constant or decreasing. The temperature dependent injectivity is, however, relatively well understood. It is a property of the facture dominated permeability. The injectivity of the reinjection zones can be tuned to certain extent by changing the temperature of the injected water.

Intense induced seismicity followed the commission of the Húsmúli Reinjection Zone. The intensity was highest in the beginning and the biggest events were two quakes of magnitude ML 4.0. The seismicity has been fading out slowly indicating that the reinjection has released stresses that were present in the crust. The tectonics of the Hengill Area is complicated. The NE-SW oriented normal fissures intersecting the area are normal faults. N-S oriented strike-slip faults, which are part of the South Icelandic Seismic Zone (SISZ) are also found in the area.

Some seismicity due to the reinjection is still present in the area. It is dependent on the flow rate into the reinjection wells and the temperature of the reinjected water. In order to mitigate seismic risk the policy is to keep all injection parameters as constant as possible.

1. INTRODUCTION

The Hellisheiði Power Plant is located in the southern part of the Hengill volcanic region, Southwest Iceland. A topographical map of the Hellisheiði Geothermal Field is shown in Figure 1. Geological features in the area are characterized by NE-SW oriented fissures. Three Holocene eruptions are known in the system, 2000, 5800, and 10.000 years ago. Hot springs and fumaroles are widely found in the area (Sæmundsson 1967, 1995).

The Hellsheiði Power Plant was commissioned in 2006. It is used for producing electricity and hot water for space heating in Reykjavík and vicinity. The install capacity of the power plant to date is 303 MW in electricity produced in six high 45 MW pressure units and 33 in low pressure unit, and 133 MW of thermal energy.

The geothermal reservoir is water dominated and the average enthalpy of the produced fluid is 1750 kJ/kg. This means that at present separation pressure of 8.5 bar-a, half of the fluid is steam and the other half water. The Steam is used for electricity generation in the high pressure units. The separated water is flashed to 2 bar-a and the steam from the low pressure boiler is used for electricity generation in the low pressure unit. The flashed separated water is then used for heating up fresh groundwater, which is used for space heating. The separated water is then reinjected into the reservoir. In Figure 2 a simplified schematics of the Hellisheiði power plant is shown (Hallgrímsdóttir et al. 2012, Kjartansson 2010).

Two reinjection zones are operated in the Hellisheiði Geothermal field: Gráuhnúkar and Húsmúli. The Gráuhnúkar is the original reinjection zone of the power plant and it was commissioned in year 2007. Gráuhnúkar are located SW of the drilling field and the targets of the reinjection wells were the NE-SW faults intersecting the well field (see Figure 1). It came as a surprise that very high temperatures (>300) were measured in wells there, which makes the area interesting for future production. A new reinjection zone was planned in the so-called Húsmúli Area on the North-Western edge of the well field. The first well in the Húsmúli Area (HN-09) was drilled early 2008. Pumping tests looked promising and more wells were drilled. To date total of seven wells have been drilled in the Húsmúli Area, of which five are connected to the reinjection system of the powerplant. The targets of the wells are faults in the Húsmúli formation (see Figure 1).

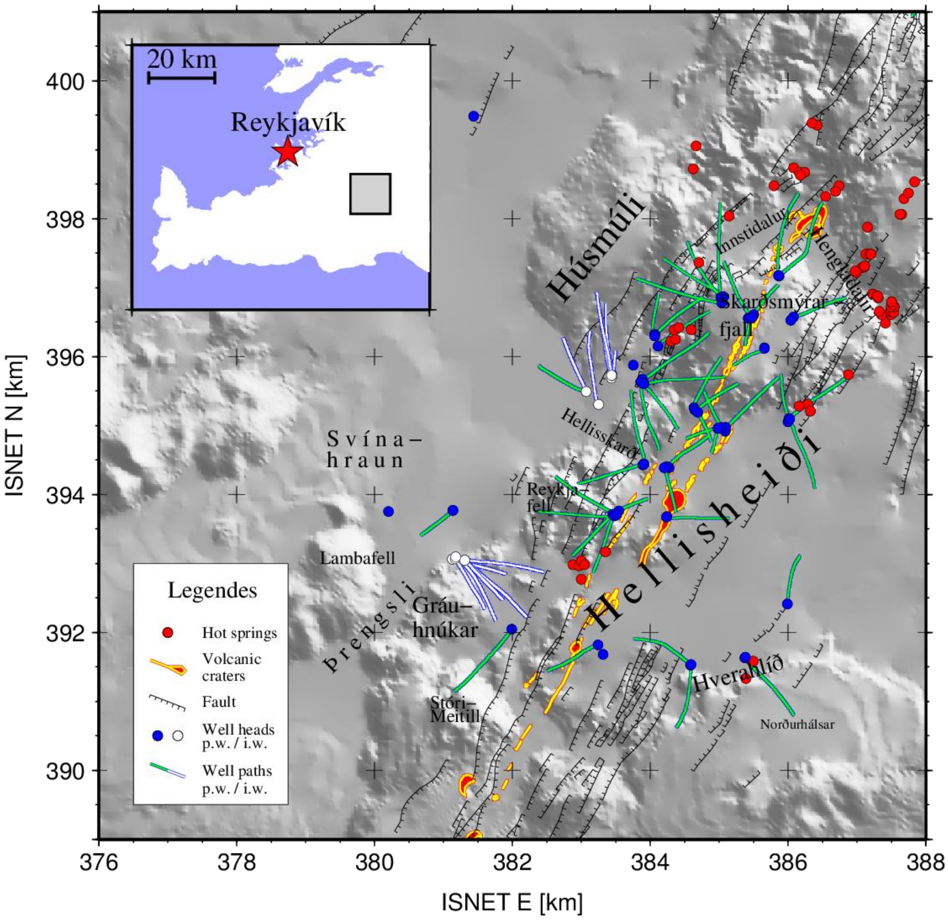

Figure 1: Topographical map of the Hellisheiði Geothermal field. Well heads of production wells (p.w.) and injection wells (i.w.) and trajectories of directionally drilled wells are shown.

The production in the center of the Hellisheiði field is very intense, making it necessary to reinject in order to maintain reservoir pressure. In order to investigate how well the reinjection supports the production and to estimate the risk of thermal breakthrough between production and reinjection wells, extensive tracer tests were started in both of the reinjecion zones in 2013. Water tracers were injected into two wells in each zone and the production fluid in the production wells was monitored. Preliminary results of the tracer tests suggest that the reinjection in the Húsmuli Area gives an important support to the production in the northernmost part of the drilling field. The reinjecion in Gráhnúkar does also support the production in the southern part of the field even though the support there does not seem to be as important. However, this support has to be considered if the reinjection in the Gráuhnúkar area is to be stopped and the area converted into production field. Powerful production wells are in the vicinity of Gráuhnúkar and they might decline more than production in the Gráuhnúkar Area would yield.

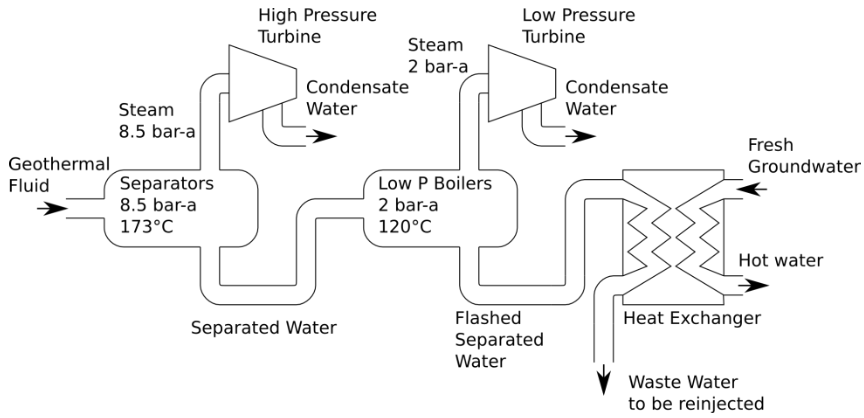

Figure 2: A simplified schematic of the Hellisheiði Power.

It has been a challenge to operate the reinjection wells, especially in the Húsmúli Reinjection Zone. The injectivity of the wells was considerably lower than pumping tests after drilling indicated. Moreover, the injectivity of most wells decreased during the first months of operation. It was discovered that the injectivity of the wells is highly dependent on the temperature of the injected water. The injectivity is considerably higher for colder water (Gunnarsson, 2011). Thinning the separated water with condensate water from the cold end of the turbines improves performance of the reinjection zones so much that the net flow of condensate water is higher when it is thinned than when it is reinjected directly. The thinning of the injected water with condensate water has the additional benefit of lowering the risk of clogging due to silica scaling (Sigfússon and Gunnarsson, 2011).

Induced seismicity has been a considerable problem during the operation of the Húsmúli Reinjection Zone. No considerable seismicity has, however, been measured in the Gráuhnúkar area. The Húsmúli Area is not known to be in particular seismically active. In 2003 few earthquakes were observed during the drilling of production well HE-08, which is 2800 m deep located near to the Húsmúli formation (Björnsson, 2004). During drilling and testing of the reinjection wells in the Húsmúli seismicity was also observed (Gunnarsson, 2011). This seismicity, which was detected on the national seismometer network run by the Icelandic Meteorological Office, was never considered to be a problem. On the contrary, it was viewed positively because it was believed that the new permeability was being created. The drilling of the last well in the Húsmúli area caused, however, considerable induced seismicity. Those earthquakes were not taken seriously and the reinjection zone in the Húsmúli was commissioned in September 2011 without taking any measures to mitigate seismic risk. Intense inducted seismicity followed the commission of the Húsmúli Reinjection zone. The activity peaked by the middle of October when two events of local magnitude 4 occurred (Bjarnason et al., 2012). Since then the seismicity has been lower and has been partly correlated with the flow into the wells.

The temperature dependent injectivity and the induced seismicity is a property of the fractured reservoir. The evolving of the injectivity of the injection wells probably also connected to this fundamental property. Thus, it is necessary to understand the fracture network of the field and its behaviour in order to manage the reinjection properly and mitigate seismic risk.

2. RESERVOIR PROPERTIES OF THE HELLISHEIÐI FIELD

The Hellsheiði field is water dominated fractured reservoir. The bedrock consists of basaltic lava layers, hyaloclastites and intrusions, mainly dykes. There are big variations in the porosity of the rocks. In the hyaloclastites it is 15-60% (Frolova et al. 2005), but it is lower in the lava layers and lowest in intrusive rocks. It has been useful to assume that the active average porosity of the reservoir rock is 10%. That is the number has been used in reservoir modeling of the Hellisheiði geothermal field (see e.g. Gunnarsson et al. 2011). In Figure 3 is the formation temperature at the depth of 1000 m below sea level shown. The formation temperature is characterized by sharp structures. The hottest regions are > 300°C and are mainly concentrated on a SW-NE oriented 1 km wide strip running from the Gráuhnúkar Area in towards the southern part of Skarðsmýrarfjall. The average enthalpy of the produced fluid is about 1750 kJ/kg, which is considerably higher than the enthalpy of the water phase at reservoir temperature. The enthalpy of individual wells range from water enthalpy ~1200 kJ/kg to dry stream enthaly of 2700 kJ/kg. Boiling due to pressure drop caused by the production along with separation of the water and steam phases in the vicinity of the wells, cause this higher enthalpy. Most of the production is focused on this hottest part of the system where the enthalpy of produced fluid is high. There is also dense production in the northern part of the field in Skarðsmýrarfjall from wells that are highly permeable and yield great amounts of fluid with low enthalpy (1200 – 1300 kJ/kg). The production in these areas is more than 300 kg/s/km2. This is a considerable production and it would cause the water level to drop 125 m annually assuming that there is no natural recharge or reinjection, and that the porosity is 10% and the average temperature 275°C. Due to this high production per square km, it is necessary to reinject in order to maintain reservoir pressure. It has been a challenge to find a solution to the problem of reinjecting into the Hellisheiði reservoir in order to provide the necessary pressure support.

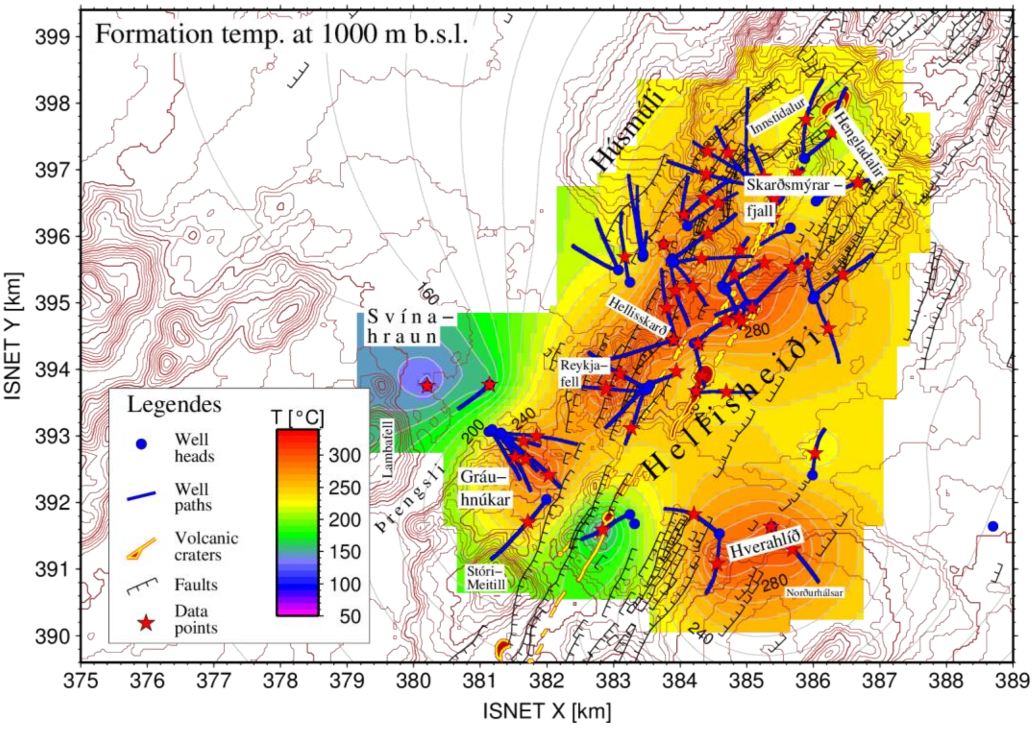

Figure 3: Formation temperature at 1000 m below sea level in the Hellisheiði Area.

3. OPERATIONAL CHALLENGES IN THE REINJECTION ZONES OF THE HELLISHEIÐI POWER PLANT

There have been three main challenges in operating the reinjection zones of the Hellisheiði Power Plant. Firstly the injectivity of the reinjection wells is highly dependent of the temperature of the injected water. Secondly the injectivity has been decreasing with time and thirdly is induced seismicity. The first and the last challenge are consequences of the fracture dominated nature of the reservoir. The reason for the second one is not clear but it is probable also connected to the properties of a fracture dominated system.

3.1 Temperature dependent injectivity

During pumping tests in the first wells in the Húsmúli reinjection zone it was observed that the injectivity in those wells is highly dependent on the temperature of the injected water. The injectivity was measured in three wells in step pumping tests using water of three different temperatures: 20°C, 80°C and 120°C. The water was pumped into the wells for a week before the step pumping test was undertaken in order to reach equilibrium. The result from these tests can be seen in Figure 4 and a map of the Húsmúli reinjection zone is shown in Figure 5.

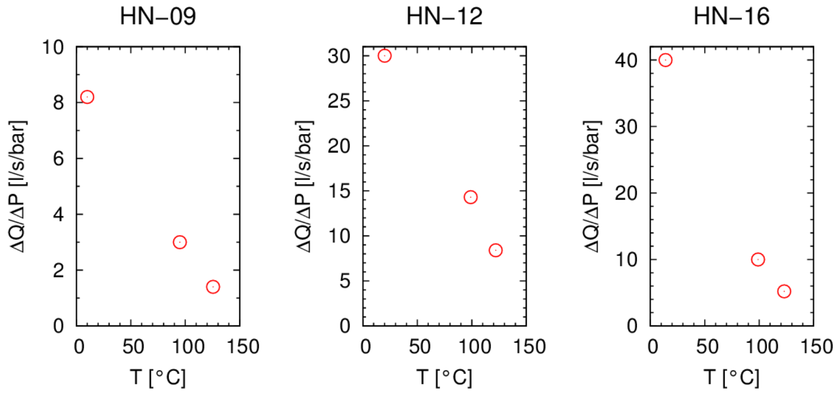

Figure 4: Injectivity in three wells in the Húsmúli Area measured for different temperatures of the injected water.

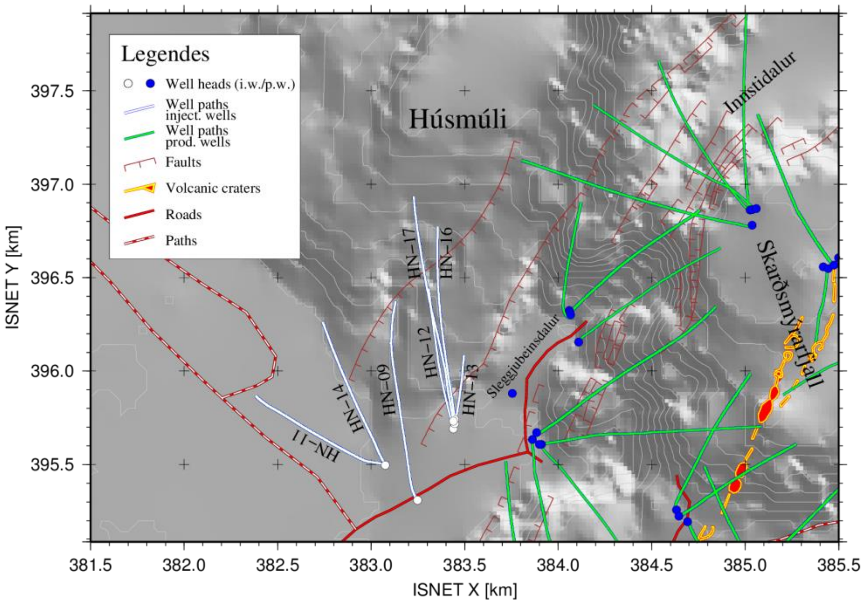

Figure 5: A closer view of the Húsmúli reinjection zone.

The injectivity of the wells is many times higher for cold water than for hot water. As mentioned above, this is a property of the fracture dominated flow. Lets assume that a flow though a fracture can be described as a flow between two plates. Then a laminar flow along a fracture obeys the following relation:

$$q = \frac{d^3 h}{12 \mu l} \Delta P \tag{1}$$

where d is the width of the fracture, μ is the viscosity of the fluid, l is the length (parallel to the flow) of the fracture, h is the height (perpendicular to the flow), and ΔP is the pressure difference driving the flow. Viscosity is dependent on temperature. 20°C water has five times higher viscosity than 120°C hot water. Thus, according to Equation 1 the injectivity for the 120°C should be five times higher than for the 20°C water. The measured injectivity for 20°C water is however 3-8 times higher than for 120°C water. The reason for this lies in the width of the fractures. The changes in the width of the fractures due to thermal expansion/contraction are big enough to compensate for the viscosity effects and more. A rough estimate gives that the width of the fractures has to triple from 120°C to 20°C in order to explain the difference in the injectivity for those temperatures. This effect is more or less reversible and has been used in operating the reinjection zones.

In Figure 6 the total flow into the wells in the Húsmúli Reinjection Zone and the temperature of the injected water are shown from the commissioning of the zone in September 2011 till end of April 2014. It is evident that the temperature plays a major role in the injectivity of the system. Flow decreased during the spring and summer of 2012, when the temperature of the water increased. By the end of summer 2012 the district heating system of the Hellisheiði Power Plant was put back online after the summer break. Subsequently the temperature of the injected water to drop and the flow into the wells increased again. It did however not reach the same amount as in the fall of 2011. During the winter of 2012-2013 the flow of water into the Húsmúli reinjection zone was decreasing. It increased again in the fall of 2013 when the temperature of injected water was lowered further by thinning the separated water more with condensate water and by running the heat exchangers of the district heating utility at full power. Since then the flow into the Húsmúli zone has been more or less constant.

Temperature dependence of injectivity has not been measured systematically in wells in the Gráuhnúkar Area. Temperature dependence has, however, been observed in the operation of the wells there. The water that is injected in the Gráuhnúkar Area is not thinned with condensate water and is thus hotter than the water which is injected into the well in the Húsmúli Area. Temperature changes due to changes in the operation of the power plant cause changes in the flow of water into the wells there. There is, however, difficult to estimate and analyze these effects in the Gráunhúkar Area because of how the flow into the reinjection zones is controlled. The reinjection wells in the Húsmúli Area are always operated at full capacity while the rest of the waste water is injected into the wells in the Gráuhnúkar Area.

3.2 Decreasing injectivity

The decreasing injectivity of the Húsmúli reinjection zone, despite of constant temperature of the reinjected water as in the winter 2012-2013 is another challenge in the operation of the Húsmúli reinjection zone. It is not clear why the injectivity of the Húsmúli Reinjection zone is decreasing. It was believed that scaling in the reinjection wells and their vicinity might be the reason for the decreasing injectivity. The separated water was thinned by 30% with condensate water and chemical analysis of that mixture indicated that scaling should not be problem, when injecting it. Moreover, the injectivity of the Gráuhnúkar Area has been more or less constant during last years. The water there is, as mentioned above, not thinned with condensate water and therefore the risk of scaling should be higher in the wells in the Gráuhnúkar Area.

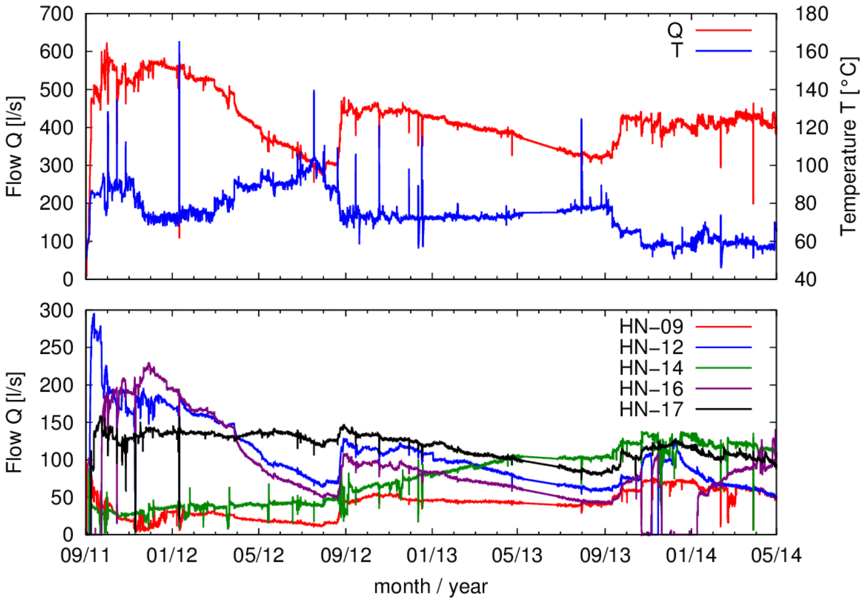

Figure 6: The flow into the Húsmúli Reinjection zone. The upper graph shows the total flow and the temperature of the injected water, the lower graph shows the flow into individual wells.

Rising reservoir pressure in the reinjection zone could also be responsible for the decreasing injectivity, but measurements in monitoring well did not show any clear indications that the reservoir pressure was increasing while the flow was decreasing. In this context, it is interesting to view how the flow into individual wells in the Húsmúli reinjection zone has evolved (see the lower part of Figure 6). There are considerable differences in the way that individual wells evolve. The performance of wells HN-12 and HN-16 has decreased. Well HN-17 has been more or less constant during the operation of the Reinjection zone, so has well HN-09. Well HN-14 has, however, increased in performance. In the beginning that well had very low permeability compared to other reinjection wells. After the heat exchangers were put online by the end of summer 2012 the flow into well HN-14 increased and by the end of summer 2013, when it stabilized it had become the most powerful reinjection well of the area. The locations of the wells can be seen in Figure 5.

There is no clear pattern in the evolving of the performance of the reinjection wells. Overall the performance of the Húsmúli Reinjecion zone is decreasing, but the individual wells behave very differently. What is also noteworthy is that the performance of the Húsmúli area seems to have stabilized in the fall of 2013 when the temperature of the injected water was lower to 60°C.

The different behaviour of the wells might be understood from their positions. Well HN-14, which lies west of the other well, has evolved differently than the other wells. It should also be mentioned that preliminary results of detailed mapping of fractures in the Húsmúli formation has revealed that the fracture structure is much more complicated than can bee seen in Figure 5. More complicated fracture structures than NE-SW oriented faults has also been revealed by seismic measurements. However, the key of understanding the behaviour of the reinjection zone lies in understanding why the wells behave differently.

3.3 Induced seismicity

Intense induced seismicity followed the commission of the Húsmúli reinjection zone. Some seismic activity was observed on the national seismometer network of the Icelandic Meteorological Office when the wells were drilled and tested. That activity was never considered to be a problem. Induced seismicity has never before been a problem in a geothermal field in Iceland. The measured seismicity during testing was viewed positively and was believed to be due to formation of new fractures and thus increasing permeability. When the last well in the Húsmúli formation HN-17 was drilled, a swarm of earthquakes was measured. Those earthquakes were bigger than previously observed in the testing phase of the reinjection zone. In Figure 7 the magnitude and the number of events are depicted. It was evident that biggest events during the drilling operation occurred when the well intersected the main feed zones of the well. The induced activity during drilling of well HN-17 did, however, not raise any alarms. The Húsmúli formation was not known as a seismically active area and, as said above; induced earthquakes had never been a problem before in Iceland. Thus, nobody was prepared for the intense seismicity that occurred following the commissioning of the Húsmúli Reinjection Area.

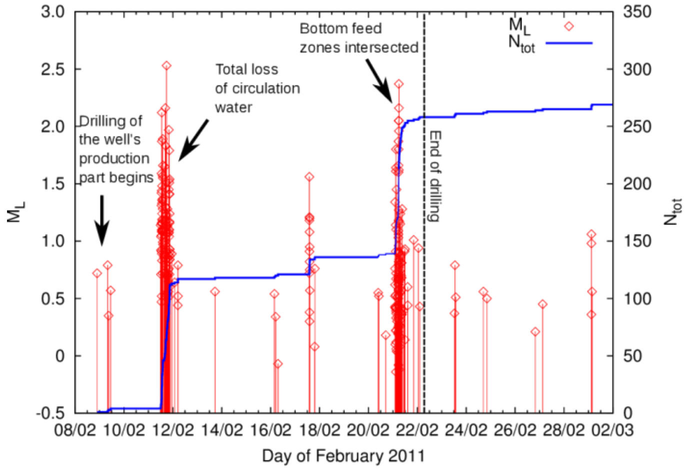

Figure 7: Seismicity during drilling of well HN-17 in the Húsmúli Area. The magnitude and accumulated number of events as measured by the national seismological network are shown.

In Figure 8 the flow and the temperature of the reinjected water is plotted with the local magnitude and accumulated number of measured earthquakes vs. time from September 2011 till the end of march 2014. As can be seen the induced seismicity started immediately after the reinjection started. It reached maximum in the middle of October 2011 when two events of the magnitude of 4 occurred. The seismicity slowly decreased and in the summer of 2012 it had almost faded out. The seismicity started again by the end of the summer of 2012, when the heat exchangers of the district heating utility were put online, the water was cooled, and the its flow subsequently increased. The seismicity was far from being as intense as the year before when the reinjection area was commissioned. As in 2012 before the seismicity slowly faded out and by the end of summer 2013 it was insignificant. The performance of the system had then decreased again, making it difficult to operate the power plant. By that time few experiments were undertaken in order to increase the performance of the reinjection system. One was to run the heat exchangers of the district heating utility at full capacity, another was to thin the separated water further with condensate water. Both measures resulted in colder water and thus more performance – i.e. more flow. Subsequently the seismicity increased again and it was the same on an average from September 2013 till the end of April 2014.

As mentioned above, induced seismicity had never been a problem before in a geothermal field in Iceland. Moreover, there is a fundamental difference in the reinjection in the Hellisheiði field and in injection into EGS systems, where the applied pressure is sometimes as high as 300 bar. The water level in the Húsmúli wells is approximately 200 m below the well head and the well head pressure is ~8 bar during operation. The maximal applied pressure is thus 28 bar which is too low for breaking the rock. The rock is moreover already broken. Thus, the induced earthquakes in the Húsmúli Area are triggered earthquakes. There are already stresses accumulated in the bedrock and the reinjection released those stresses by lowering the friction of the faults. What makes the Húsmúli Area prone to induced seismicity is also that it is located on the edge of the production field. The mass extraction causes subsidence in the center of the production field, which causes stresses on the faults on the edge of the production zone. The Gráuhnúkar reinjection zone is also on the edge of the production field. There is indeed an intensive mass extraction in their vicinity. However, the Gráuhnúkar Area is located along the fractures, which intersect the geothermal field. All pressure differences due to injection in the Gráuhnúkar Area and production near Reykjafell in the vicinity of the Gráuhnúkar are parallel to known faults in the area. There has been very little seismic activity observed in the Gráuhnúkar Area.

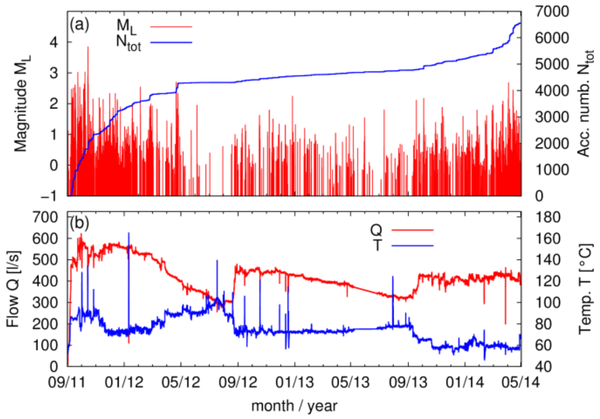

Figure 8: (a) Magnitude of earthquakes and their accumulated number as measured by the national seismometer network of the Icelandic Meteorological Office. (b) Total flow (Q) into wells in the Húsmúli reinjection zone and the temperature (T) of the water.

The evolving of the seismicity in the Húsmúli Reinjection Zone raises many questions on the nature of the seismicity and the permeability of the area. Tracer tests done in the Húsmúli wells indicate that the water flows to northeast along the fractures towards the production wells in Skarðsmýrarfjall in the north of the Hellisheiði Field. The earthquakes, however have been migrating westwards with time. Moreover, the faults that appear when the earthquakes are localized using relative methods are more N-S oriented, as can be seen in Figure 9, not NE-SW as the faults of the Hengill volcanic system (see Figure 1 and 5). This indicates that the Húsmúli Reinjection zone could be on the western edge of the South Iceland Seismic Zone (SISZ). The SISZ, which is shown in Figure 10, is a system of N-S strike-slip faults that are aligned much like books in a bookshelf on the big E-W oriented fault running from the Hekla volcano in Southern Iceland towards the Hengill volcano (see e.g. Hreinsdóttir et al. 2009). Big earthquakes (M>6) can occur on the SISZ. Due to historic records it happens approximate every century that few earthquakes occur in the system. They normally start in the eastern part and then shift to the west (Thoroddsen, 1905). This was also the case in the last events in the system. In year 2000 two earthquakes occurred, one in the eastern part and then one in the central part of the SISZ. In May 2008 two almost simultaneous events happen in the western part. There are records indicating that SISZ system could extend more to the west, even west of the Hengill Area. This could explain the N-S orientation of the faults that are located using the seismic data from the induced seismicity in the Húsmúli Area. It also could partly explain why this area was under stress when injection started in year 2011 (Bessason et al 2012).

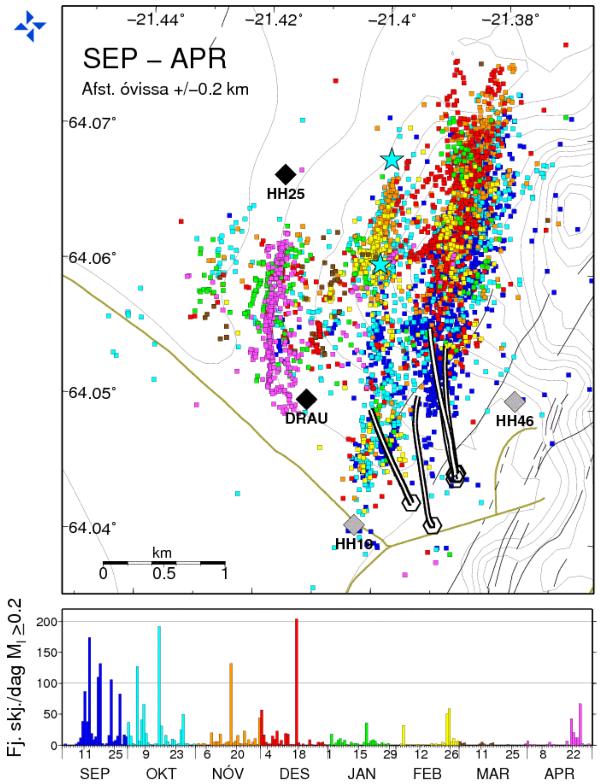

Figure 9: The epicenters of the induced from beginning of September 2011 till the end of April 2012 localized with accuracy of ± 0.2 km. The coloring of the dots corresponds to the month when they occurred. The blue stars show the biggest events, which occurred in October 2011. The lower part of the figure show the number of events pr. day in this period. (From Bessason et al. (2012)).

By comparing the frequency of the earthquakes and the flow rate it can be seen that there seems to be a connection between flow and seismicity. The number of events in four weeks periods is plotted vs. average flow in those periods in Figure 11. There seems to be some connections between the flow and the number of events though the data points are somewhat scattered. It should be noted that the well head pressure of the Húsmúli reinjection zone has been more or less constant since the beginning of its operation. Thus, the changes in the flow are solely due to changes in the permeability of the wells. It is still not clear how this causal relation between flow and seismicity works; whether higher flow rates are causing more seismic activity or the seismicity is creating and maintaining permeability.

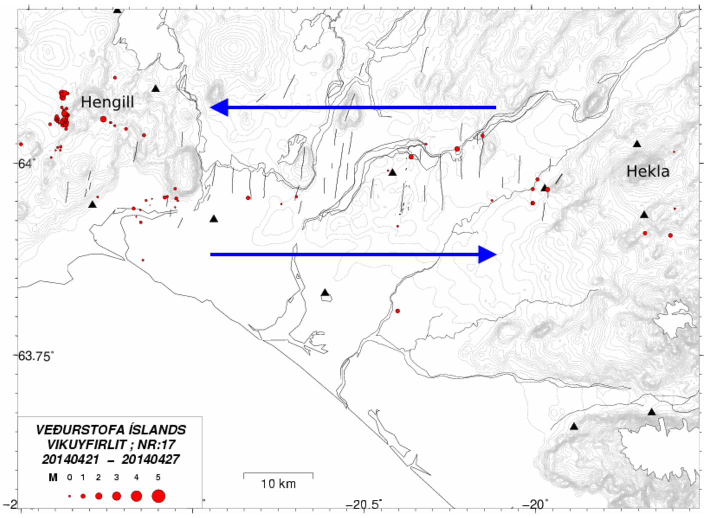

Figure 10: The South Iceland Seismic Zone (SISZ). It is an system of N-S oriented strike-slip faults which lies from Mt. Hekla in the east towards the Hengill Volcano in the west. The red dots in the figure are earthquakes observed by the Icelandic National Seismometer Network run by the Iceland Meteorological Office in the week from March 21 till March 27 2014. Swarm of earthquakes occurred in the Húsmúli Area (SW of Hengill) that week. (Adapted from Iceland Meteorological Office website www.vedur.is).

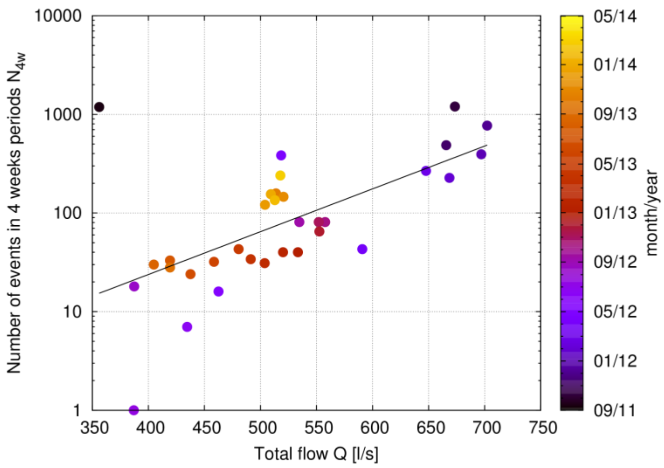

Figure 11: A semi log plot showing the number of measured events in a four week period vs. average total flow in the period. The color code shows the timing of each value.

4. CONCLUSIONS

The three main challenges in operating the reinjection system of the Hellisheiði power Plant, i.e. the temperature dependent injectivity, decreasing performance, and induced seismicity, have become more or less manageable. The temperature dependent injectivity and the induced seismicity are intrinsic properties of the fractured dominated reservoir. The decreasing injectivity might also be explained by the behavior of the fractures of the reservoir. The Hellisheiði Geothermal Field is located in the fissure swarm of the active Hengill Volcano. The rifting movements provide and maintain the fracture dominated permeability. The structure of the fractures in the Hellisheiði Field is, however more complicated than previously believed. Along with the NE-SW normal faults that are widely seen on surface, N-S strike-slip fractures seem to play an important role in the geothermal system. More accurate mapping of faults using both surface geology and by processing seismic data is also needed to be done. It is necessary to gain an understanding on how the injectivity of the wells evolves and how, if possible, the wells can be stimulated in order to enhance and maintain their injectivity. The fourth challenge in operating the reinjection should also be mentioned. That is to mitigate the risk of thermal breakthrough between production and injection wells. Ongoing tracer tests are going to be used for estimating that risk.

The main effort to date, when the induced seismicity seems to have been brought under control, is to ensure sufficient injection capacity for supporting the production of the field. The injectivity is highly dependent on the temperature of the injected water. Thermal expansion of permeable fractures is believed to explain the temperature dependent injectivity. In order to enhance the performance of the reinjection wells the injected water has been cooled. The injectivity of the Húsmúli Area has been slowly decreasing, while the injectivity of the Gráuhnúkar Area has been more or less constant. The reason for this decrease is not known. The injectivity of the Húsmúli area has however, been more or less constant since September 2013 when the water was cooled down to 60°C, by thinning the water 40% with condensate water and by running the heat exchanger of the district heating utility at maximum capacity. However, the combined reinjection capacity of the Gráuhnúkar and Húsmúli Reinjection Zones is barely enough for reinjecting all the separated water from the power plant. Moreover, there is presently no need for all the heat that is extracted from the separated water in the heat exchangers when they are operated at full capacity, so energy is being wasted.

More reinjection capacity is needed. To date no new reinjecting areas are being planned in Hellisheiði. There are, however, plans to enhance the capacity of the reinjection system by converting unsuccessful production wells into reinjection wells. Those wells are closer to the production wells than present reinjection wells and therefore there might be a higher risk of thermal breakthrough when injecting into them. In order to estimate the risk of thermal breakthrough and to estimate the importance of the reinjection for pressure support, tracer tests were undertaken. Preliminary results suggest that the reinjection is important for supporting the production in the Hellisheiði Field.

The induced seismicity has been the main public relations problem of the Hellisheiði Power Plant. After the magnitude 4 earthquakes that occurred in October 2011, a group of experts was commissioned to review the methodology of panning and operating reinjection in Geothermal Fields in Iceland. The main result was that all sudden changes in the reinjection, in flow rate and temperature, should be avoided at all cost. The expert group also came with suggestions on how to choose a reinjection site with respect to seismic risk and which research should be done for estimating this risk (Bessason et al. 2012). The suggestions on how to operate the reinjection areas of the power plant have been implemented. Since then, induced seismicity has not caused problems in the vicinity.

Induces seismicity in the Húsmúli Area was inevitable. The N-S faults of there are part of the SISZ and were probably under stress when the reinjection started. The reinjection lowered the friction of the faults causing them to slip. Moreover, the Húsmúli Area is located on the edge of production field. The mass extraction, due to production causes subsidence, which then induces stresses over the faults in the Húsmúli formation. Thus, the stresses released by the reinjection have been of both natural and man made causes. One can assume that the natural stresses were released in the initial phase of the reinjection. The recent seismicity is most probably due to man made stresses, caused by the mass extraction from the Hellisheiði field.

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