Temperature Dependent Injectivity and Induced Seismicity—Managing Reinjection in the Hellisheiði Field, SW-Iceland

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Keywords

Reinjection, induced seismicity, reservoir management, fractured reservoir, injectivity, temperature dependence, Hellisheiði, Hengill

ABSTRACT

Two reinjection zones are operated for the Hellisheiði Power Plant. One is the Gráuhnúkar, on the southern edge of the Hellisheiði Geothermal Field. The other is the Húsmúli at the northern edge of the field. The injectivity of the wells drilled in the Húsmúli Area has turned out to be temperature dependent. This effect differs from well to well, but over all the injectivity index is more than six times higher for water 20°C than for water of 120°C. This effect has to be taken into account when operating the reinjection zone in the Húsmúli Area. Temperature dependence has also been observed in the operation of the Gráuhnúkar Reinjection Zone. Accurate measurements of the temperature dependence have, however, not been undertaken in wells there.

The commission of the Húsmúli Reinjection Zone in September 2011 caused considerable induced seismicity. The biggest earthquakes, which occurred in the middle of October that year, reached a magnitude of M_L 4.0. Induced seismicity was observed in the area during drilling and well testing in the Húsmúli formation. The observed seismicity, when the operation started, was however, much more intense than expected. The induced seismicity did not cause significant damages. It did, however, cause considerable disturbances in the near by village of Hveragerði, which is located ~10 km from the reinjection wells. The induced seismicity in the Húsmúli Area has faded out during the reinjection suggesting that the reinjection released stresses already present in the area.

The Geothermal system in Hellisheiði is in fractured bedrock. The temperature dependence of the injectivity can be understood from the fractured nature of the permeability of the reservoir. The induced seismicity was partly dependent on the temperature of the injected water. This suggests that the thermal effects of the injected water on fractures does also play a significant role in the induced or triggered seismicity.

1. Introduction

The Hellisheiði Power Plant was commissioned in year 2006. Installed capacity is 303 MW in electricity, which is generated in six 45 MW high pressure units and a 33 MW low pressure unit. Additionally 133 WM of heat for space heating is generated in the district heating utility. A map of the Hellisheiði field is shown in Fig. 1. The Hellisheiði Field is located in the southern part of the Hengill Volcanic System. The area is characterized by hyaloclastites formations and SW-NE oriented fissure swarm. Two Holocene eruptions are known in the Hengill volcano; 2,000 and 5,000 years ago (Sæmundsson, 1967, 1995).

Reinjection has been a major challenge in the operation of the Hellisheiði Power Plant. Regulations and operation permits

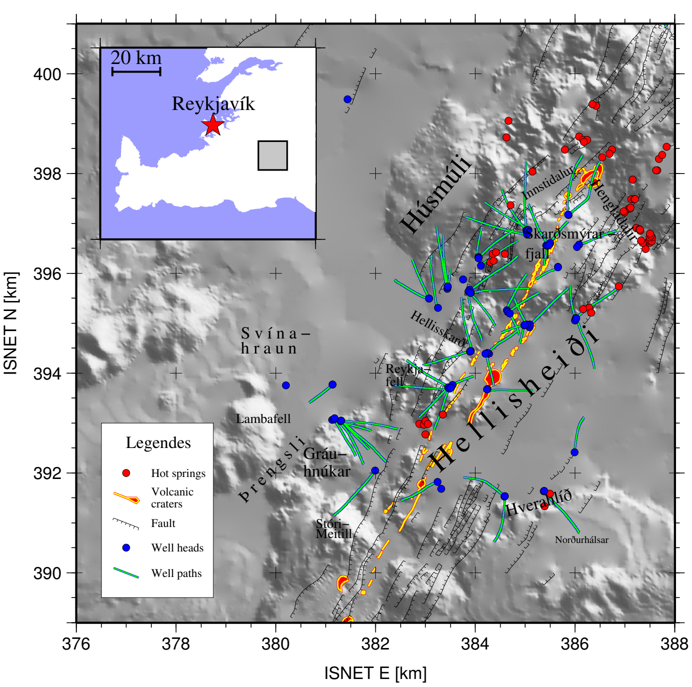

Figure 1. A map of the Hellisheiði area. Two reinjection zones are operated; Gráuhnúkar in the south and Húsmúli in the north.

require that all of the geothermal brine is reinjected back into the geothermal reservoir. This has been difficult to achieve. The performance of the injection wells has been difficult to control and induced seismicity has caused considerable problems. Two reinjection zones are operated for the power plant. The Original site is located in Gráuhnúkar on the southern edge of the geothermal field. The formation temperature in the Gráuhnúkar Area turned out to be very high (>300°C) when wells were drilled there. In Fig. 2 the formation temperature at 1000 m below sea level in the Gráuhnúkar Area is shown. The high formation temperature makes the Gráuhnúkar Area more feasible for production rather that than for reinjection. Thus, a new reinjection zone was planned in the Húsmúli area on the northern edge of the Hellisheiði field. That zone was supposed to replace the Gráuhnúkar which was to be converted into a production field.

In Fig. 3 a map of the Húsmúli Area is shown. Seven wells have been drilled there. Five of them are connected to the reinjection system of the Power Plant (HN-09, HN-12, HN-14, HN-16, and HN-17), one is impermeable (HN-11) and one is shallow and is used for monitoring (HN-13). The first well in the area (HN-09) was completed in February 2008. It was connected to the reinjection system in July same year. Testing of the well revealed that the its injectivity is very sensitive to the temperature of the injected water.

The targets of the wells in the Húsmúli Formation are the faults there. Results from well tests in the first well drilled there (HN-09) were encouraging and it was decided to proceed and drill more wells. The next well, HN-11, was impermeable, suggesting that the faults seen in the Húsmúli Formation are not permeable south of the formation. Other wells were more promising, especially HN-12, HN-16, and HN-17. Thorough well tests were undertaken in three of the wells, i.e. well HN-09, HN-12, and HN-16. Injectivity turned out to be dependent on the temperature of the injected water in all of them. The injectivity is much higher for colder water. This behavior has not been measured thoroughly in the wells in the Gráuhnúkar Reinjection Zone. However, during the operation of the Gráuhnúkar wells, similar temperature dependence of the injectivity has been observed. The temperature dependence is an important phenomenon when operating the reinjection zones and the reinjection systems of the power plant.

The Húsmúli Reinjection Zone was fully commissioned in September 2011. Well tests had suggested that a considerable amount of water could be reinjected there. In the beginning the capacity of the site was around 600 l/s pumped into 5 wells. The performance has decreased during the operation and is now around 400 l/s. The commission of the reinjection site was followed by swarms of induced earthquakes. the biggest events occurred in the middle of October 2011 when two earthquakes of magnitude $M_L 4$ happened the same day. Some induced seismicity had been observed during drilling and pumping test in the Húsmúli Area. The

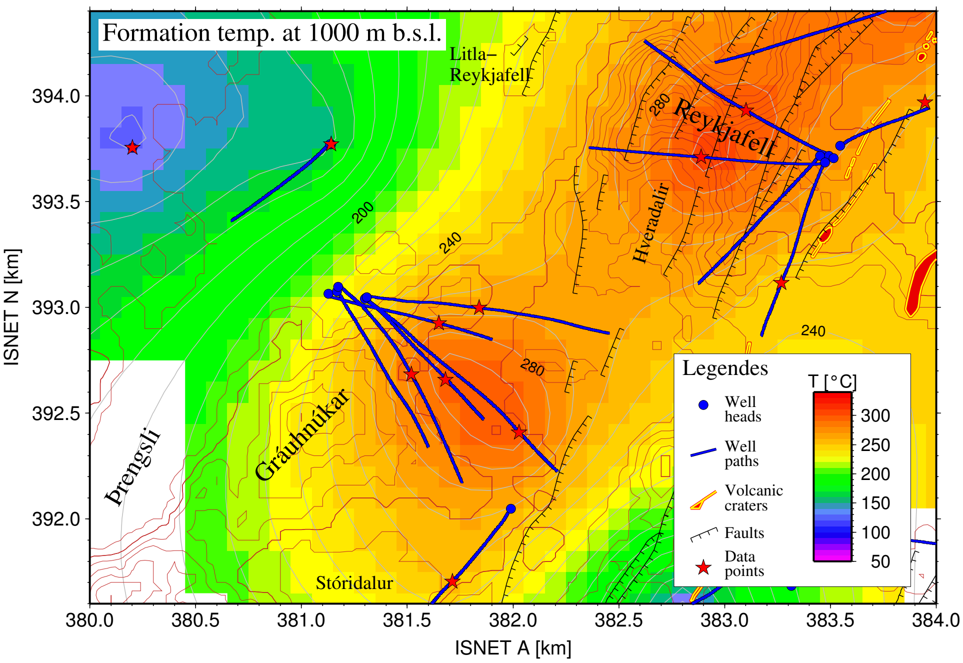

Figure 2. Formation temperature in the Gráuhnúkar Area at 1000 m below sea level. High formation temperature makes the area feasible for production.

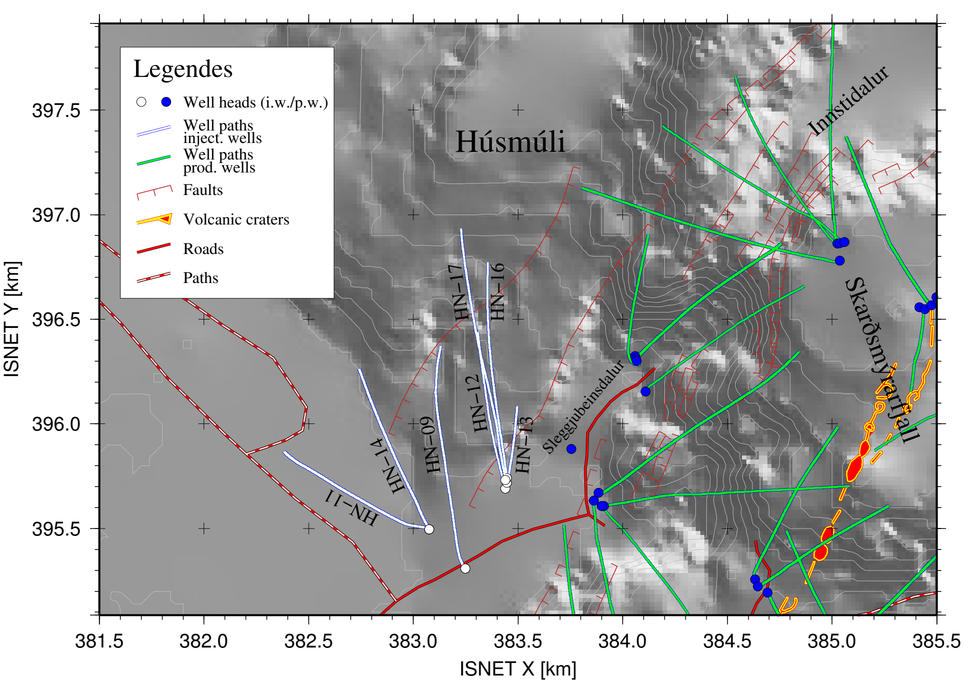

Figure 3. A map of the Húsmúli Area. Faults in the Húsmúli Formation were the targets when the reinjection wells were drilled.

unprecedented intensity of the activity after the commission of the area came as a surprise. The induced seismicity has faded out with time during the operation, suggesting that the earthquakes were triggered events, where stresses already accumulated in the crust were released. Even though the earthquakes did not cause any considerable material damages, they did cause disturbance in the nearby village of Hveragerði, which is located ~10 km from the reinjection site.

2. Temperature Dependent Injectivity

It became evident during the testings of the reinjection wells in the Húsmúli Area that the injectivity of the wells is dependent of the temperature of the injected water (Gunnarsson, 2011). The injectivity is measured in step pumping test, where pressure probe is placed in a well at the depth of the main feed zone. The pressure (P) is measured for different values of flow into the well (Q). The injectivity (ξ) is defined as

$$\xi = \frac{\Delta Q}{\Delta P}, \tag{1}$$

where $\Delta Q/\Delta P$ is the slope of the linear fit of the equilibrium values of P for given Q plotted v.s. Q. Thus, the injectivity measures how good the connection between the well and the reservoir is. This property was measured thoroughly for three different values of the temperature of the injected water in the three wells in the Húsmúli Reinjection Zone, HN-09, HN-12, and HN-16. The injectivity as a function of temperature can be seen in Fig. 4. The injectivity for the lowest temperature in wells HN-12 and HN-16 are not well defined. The wells seem to be very permeable for those low temperatures. The injectivity is, however, well defined for the other temperature values. Those temperatures are similar to the operating temperatures of the reinjection system of the power plant.

This temperature dependence can be explained by fracture dominated permeability. Changing aperture of fractures due to thermal expansion/contraction has a major effect on the permeability and outweighs the effects of viscosity (see Gunnarsson (2011) and Podgorney et al. (2011)). What is interesting from the operational point of view is that the injectivity almost doubles when the injected water is cooled from 120°C down to 80°C.

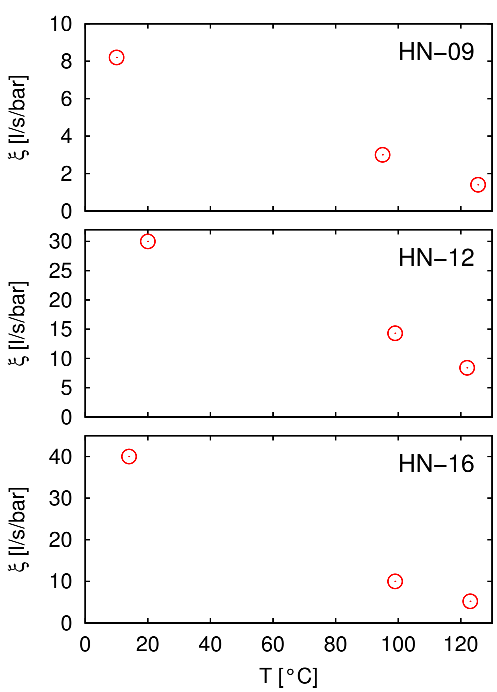

Figure 4. Injectivity (ξ) measured for different temperatures of injected water (T) in three wells in the Húsmúli Area. The injectivity for the lowest temperature value in wells HN-12 and HN-16 are not well defined.

3. Operating the Húsmúli Reinjection Zone

In Fig. 5 a simplified diagram of the Hellisheiði Power Plant is shown. The geothermal fluid is separated at 9 bar-a. The geothermal brine is then flashed down to 2 bar-a and the resulting brine is then used for heating up cold ground water for space heating. According to regulations and operation permits the geothermal brine must be reinjected into the geothermal reservoir. The condensate water from the turbines can, however, be disposed of in shallow groundwater wells. The water coming from the low pressure boilers is oversaturated with silica, which can cause scaling problems. Cooling in the heat exchanger of the district heating utility slows down the scaling, but is not enough for preventing it. One way of preventing scaling in the pipelines and reinjection well is to dilute the geothermal brine using condensate water (Sigfússon and Gunnarsson, 2011). Diluting the brine after the heat exchangers in the ratio 7:3 (brine:condensate water) results in temperature of 70 – 75°C. The injectivity of the injection wells in the temperature range from 70 – 120°C is so sensitive to temperature changes that a net gain in injected brine can be achieved by diluting it with 40°C condensate water – even though the quantity of injected fluid increases by ~40%.

The water is pumped into the wells under pressure of 8 bar (on well head). The water level in the geothermal system in the Húsmúli Area is ~200 m below surface. Thus, the total pressure increase in the wells during operation is ~28 bar. The total flow into the Húsmúli reinjection zone is 400 l/s at the time of writing. 280 – 300 l/s of that is geothermal brine but the total brine, that has to be disposed of is ~500 l/s. The remaining ~220 l/s have to be

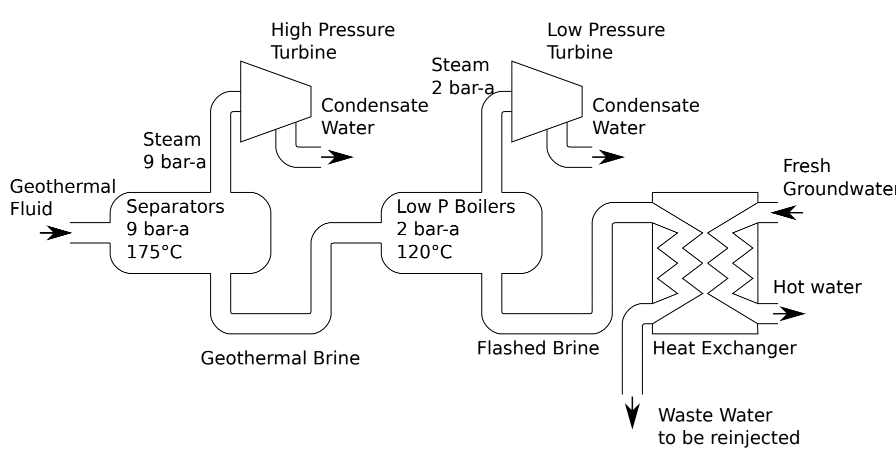

Figure 5. A simplified diagram of the Hellisheiði Power-Plant. Electricity is produced in a double flash system and the geothermal brine is used to heat up water for space heating.

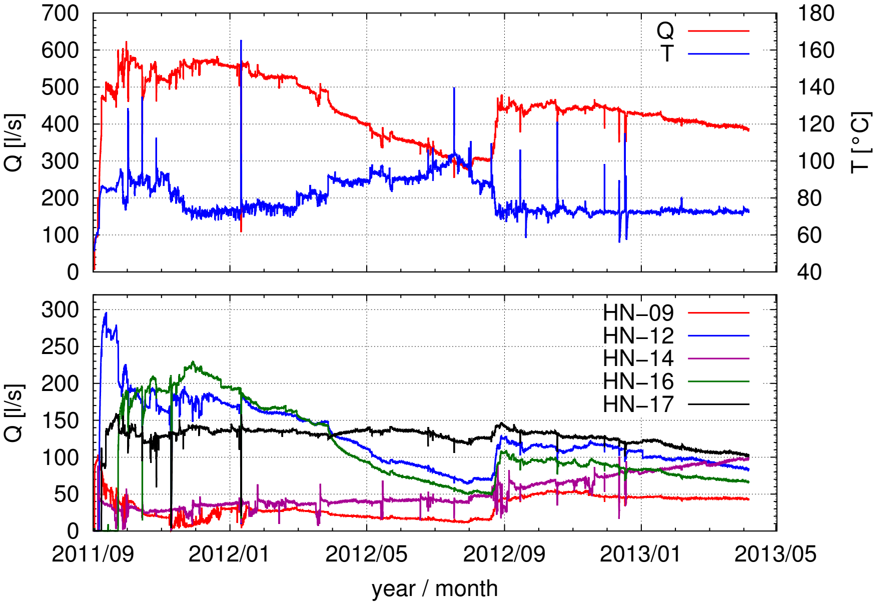

Figure 6. Upper graph: Total flow (*Q*) in to the Húsmúli reinjection zone and the temperature (*T*) of the injected water from the commission of the zone in September 2011 till middle of April 2012. Lower graph: Flows (*Q*) into individual wells. Time scale is the same for both graphs.

reinjected into the Gráuhnúkar Reinjection Zone. As said above, the original plan was to shut of the reinjection in the Gráuhnúkar Area and convert it into a production field. This has not been possible because the wells in the Húsmúli Area have declined during operation. In Fig. 6 it is shown how the injection into the zone has developed with time. The upper part of the graph shows the total injection and the temperature of the injected water vs. time in the period from September 2011 till middle of April 2013. Shortly after reinjection started the total performance of the area was over 600 l/s of ~75°C hot water. Since then, the efficiency of the area has declined. It is, however, interesting to see the effects of temperature on the performance of the wells. The performance drops significantly in the spring and summer of 2012, when the district heating utility of the Power Plan was slowed down and eventually shut down and the temperature of the reinjected water heated up to 90 – 95°C. By the end of summer 2012, the performance of the Húsmúli reinjection zone was down to 300 l/s.

In the autumn of 2012, the district heating utility was turned back on causing the temperature of the injected water to drop from 90°C to 75°C. The performance of the Húsmúli Reinjection zone increased subsequently from ~300 l/s to ~450 l/s. This change in temperature increased significantly the flow into all wells except for HN-14, where a sudden increase is not so clear (see Fig. 6). However, after the district heating utility was turned on, the performance of well HN-14 has gradually increased and now it is the second most efficient well in the area swallowing ~100 l/s of 75°C hot water. All other wells have been gradually declining in performance. It is not clear why the wells do decline in general. It could be due to pressure build up in the Húsmúli Formation and it could also be due to scaling in the wells. Increasing efficiency of well HN-14 contradicts the hypothesis of lower performance due to scaling. The behavior of HN-14 could be connected to movements of fractures in the area due to pressure build up. Surface movements have been observed since the reinjection started and such movements might have influenced permeable fractures that well HN-14 is connected to (Bessason et al., 2012).

It is interesting to compare the reinjection zones in the Húsmúli Area and in the Gráuhnúkar Area. The water, which is reinjected into the Gráuhnúkar Reinjection Zone is not diluted with condensate water and is, thus hotter or 95°C, when the district heating utility is running (120°C when it's not). Scaling is prevented by allowing the silica sufficient time to polymerize. A 3 km long 1000 mm wide pipeline connecting the reinjection zone to the power plant serves as a retention tank (Sigfússon and Gunnarsson, 2011, Gunnarsson et al., 2010). The natural conditions in the Gráuhnúkar Zone are also different from those in the Húsmúli Area. The formation temperature is significantly higher in Gráuhnúkar Area or ~300°C whereas it is 220 – 250°C in the Húsmúli Area. The injection in the Húsmúli Area did also caused considerable induced seismicity, but very little seismic activity has been observed in the Gráuhnúkar Area. It is not clear, if it is due to natural conditions or because of technical setup, that the Gráuhnúkar Reinjection Zone has not declined as the Húsmúli Zone has done. The wells in Gráuhnúkar show the same temperature behavior, i.e. the performance increases when the water is cooled. It could be that the higher formation temperature is what makes the Gráuhnúkar Area a efficient reinjection zone, which is the same reason for it being considered to be a feasible production field.

4. Induced Seismicity

4.1 Seismicity During Drilling and Well Testing

First signs of induced seismicity in the Húsmúli formation were small earthquakes that occurred during drilling and testing of a well ~500 m north-east of the well head of well HN-12, HN-13, HN-16, and HN-17. The well (HE-08), which is one of the first production wells drilled in the Hellisheiði field, was drilled to the depth of 2808 m in June and July 2002. During drilling and stimulation of the well few earthquakes were observed by the SIL seismometer network of the Icelandic Meteorological Office (Björnsson (2004)). This events were small, the biggest one was of magnitude M_L 2.3.

No induced earthquakes were detected by the SIL network during drilling and testing of the first reinjection well in the Húsmúli Zone; well HN-09. Some minor events were detected during the drilling of well HN-11 was drilled and also few months later when a week long pumping tests with cold water was done in well HN-09. Most of the activity before the Húsmuli Reinjection Zone was commissioned, was observed during drilling and testing of wells HN-12, HN-16 and HN-17. In well HN-12 and HN-16 pumping tests were done with different temperatures of water (15°C, 80°C and 120°C). As discussed above, the injectivity of the wells for the colder water was much higher than for the hotter water (see Fig. 4). The induced seismicity was also apparently more for injection of colder water than for injection of hotter water. The pressure difference in the wells at the depth of the feed zones was however higher in flow tests with hotter water than in test with colder water.

The most intensive events, which occurred during the testing period of the Húsmúli Reinjection Zone, happened when drilling well HN-17. In Fig. 7 the magnitude of the events and their accumulated number are plotted vs. time. Swarms of earthquakes occurred when permeable formations were intersected. The biggest earthquakes, when the circulation fluid was lost on the 11th of February and when the bottom feed zones were intersected, were felt in the nearby village of Hveragerði ~10 km from the Húsmúli Area. During the drilling of HN-17 a network of local portable seismometers was used for registering the events. The data from these seismometers has not been processed. The data shown in Fig. 7 is from the SIL network of the Icelandic Meteorological Office. It is assumed that the accuracy in location – especially in depth – will improve when the data from the local network will be processed.

The induced seismicity observed during the drilling and testing of the wells in the Húsmúli Area should have been taken more seriously. Induced seismicity of high intensity was unknown in Iceland and the seismic activity was not considered to be a risk. It was even viewed as a positive sign of that the injection was opening up fractures and creating better permeability. The induced seismicity was viewed as a temporary phenomenon, which would not cause any problems during operation of the reinjection system.

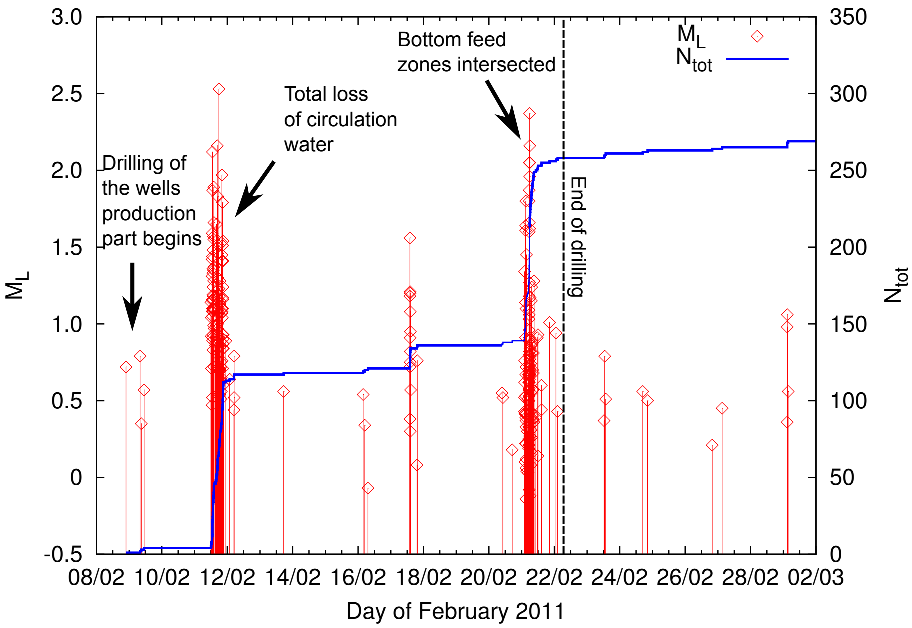

Figure 7. Triggered earthquakes registered by the SIL network of the Icelandic Meteorological Office when well HN-17 was drilled in February 2011. Magnitude (M_L) and accumulated number of events (N_{tot}) are plotted vs. Time.

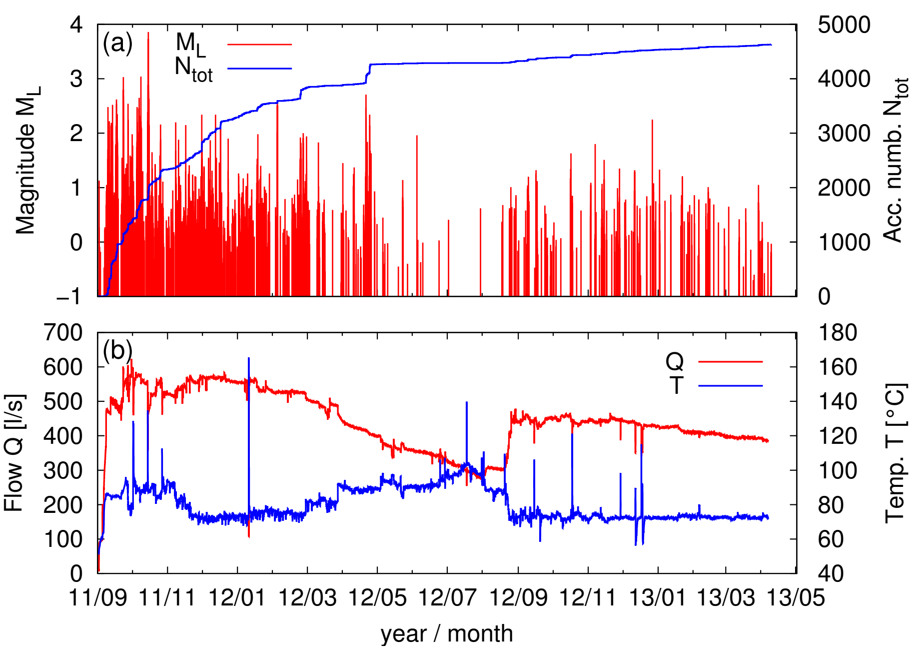

Figure 8. (a) Seismicity in the Húsmúli Area from the commission of the reinjection system there in September 2011 till beginning of April 2013. The magnitude (M_L) and the accumulated number of events (N_{tot}) are plotted v.s. time. (b) Total flow of reinjected water (Q) and its temperature (T). (Same time scale in (a) and (b).

4.2 Seismicity During Operation

The Húsmúli Reinjection Zone was commissioned in September 2011. The reinjection caused intensive induced seismicity. The biggest events of magnitude M_L 4 occurred in middle of October 2011. In Fig. 8 (a) the magnitude of the induced earthquakes (M_L) and the accumulated number of events (N_{tot}) is plotted vs. time. The data is taken from the seismometer network of the Icelandic Meteorological Office, the SIL network. The magnitude estimates were done automatically, but the magnitude of the biggest earthquakes is slightly underestimated in the automatic routine. The intensity of the earthquakes and their number came as a surprise. The Húsmúli Formation is not known as a seismically active area and the applied pressure of 28 bar (8 bar of well head pressure and 200 m worth of hydrostatic pressure) is far from being enough for breaking the rock by itself. The accumulated number of events N_{tot} reveals the nature of the earthquakes. The frequency of events was highest in the beginning of the reinjection. It then faded away during the operation of the reinjection system. This indicates that the reinjection released stresses that had already build up in the crust near the Húsmúli Formation. These stresses are partly of natural causes and could also partly be caused by crustal movements due to mass extraction from the geothermal reservoir. The reinjection released these build up stresses and the system is now reaching equilibrium, as can be seen from the flattening of the accumulated number of events curve.

In Fig. 8 the total flow into the Húsmúli area (Q) and the temperature of the injected water (T) is plotted with the seismicity (M_L and N_{tot}). There are clear indications that the temperature of the injected water does influence the induced seismicity. Very few events were recorded during the summer of 2012 when the district heating utility was off-line and the temperature of the injected water was hotter (95°C instead of 75°C). By the end of summer when the district heating utility was started and the water cooled down again the seismicity started again.

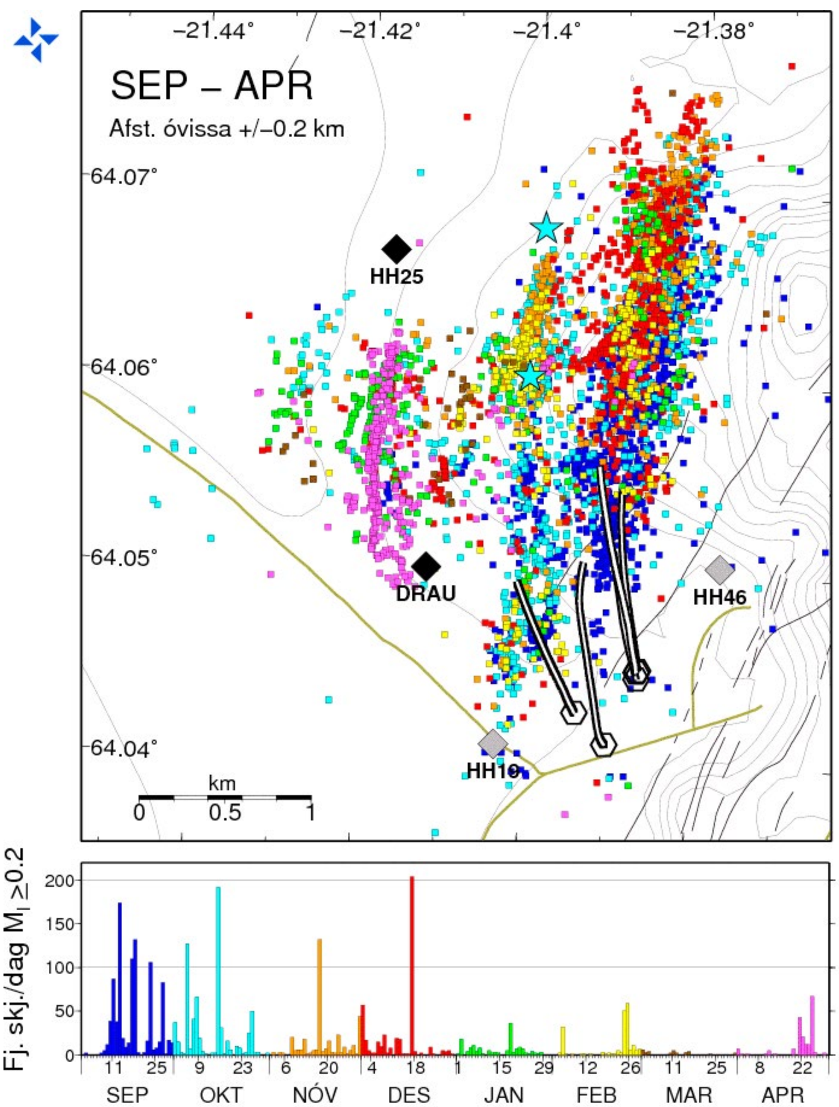

Figure 9. The epicenters of the induced from beginning of September 2011 till the end of April 2012 localized with accuracy of ±0.2 km. The coloring of the dots corresponds to the month when they occurred. The blue stars show the biggest events, which occurred in October 2011. The lower part of the figure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

In Fig. 9 is a map showing the epicenters of the triggered earthquakes where they have been localize with an accuracy of ±0.2 km. The earthquakes seem to occur on faults that are oriented more N-S, but not NE-SW which is the characteristic orientation of the faults and other landscape features of the Hengill Area. Such N-S faults are typical for the South Iceland Seismic Zone (SISZ) and the Hellisheiði is near the western edge of that zone. Last big event in the SISZ happened in May 2008 on two faults near the village of Hveragerði ~10 km from the Húsmúli (Hreinsdóttir et al., 2009). In June 2000 two big earthquakes occurred in the SISZ the first one in the easternmost part and the second one in the central part of it. According to historical records few bigger earthquakes happen in the SISZ every century. They start in the eastern part of the zone and then move towards west within few years, which is exactly what happened in the 2000/2008 events (Thoroddsen, 1905, Hreinsdóttir et al., 2009). It seems like the reinjection has triggered earthquakes on faults of the SISZ faulting system. It is interesting that the SW-NE faults that are clearly visible on surface and are a typical of the landscape in Hellisheiði and the entire Hengill Area do not seem to be activated during the reinjection. These SW-NE features have often been used when planing production and injection wells. Maybe that procedure need to be revised.

5. Summary and Conclusions

Two reinjection zones are operated for the Hellisheiði Power Plant. The older one, the Gráuhnúkar Area is located at the southern edge of the Hellisheiði Geothermal Field. The formation temperature in the Gráuhnúkar Area is high (<300°C) making it a feasible production field. Thus, a new reinjection zone was planned in the Húsmúli Area on the northern edge of the Hellisheiði Geothermal Field. Seven injection wells have been drilled there, of which five are used for reinjecting water. The formation temperature of the Húsmúli Area is less than of the Gráuhnúkar Area, 220 – 250°C and the targets of the wells, which are directionally drilled, are faults in the Húsmúli Formation. The performance of the Húsmúli Reinjection Zone has not been enough to terminate the reinjection in the Gráuhnúkar. Thus, currently both sites are use for reinjection.

Well tests in the Húsmúli Area revealed that the injectivity of the wells is temperature dependent. The wells are much more permeable for colder water than for hotter water. Even in the temperature range in which the reinjection system of the Hellisheiði Power Plant is operated, the injectivity can change by more than 50%. The permeability in the Hellisheiði Geothermal Field is fracture governed. The temperature dependence can be explained by the changing aperture of permeable fractures due to thermal expansion/contraction. It is important to take this effect into account when operating the reinjection system of the Power Plant. The injectivity can be increased significantly by cooling the injected water. In the Hellisheiði Power Plant the geothermal brine is cooled in the heat exchangers of the district heating utility. Further cooling is then achieved by diluting the geothermal brine with condensate water. Even though the quantity of the fluid to be injected in increased by that method, the increase in injectivity is such, that it results in a net gain of reinjected brine. Diluting the geothermal brine with condensate water has also the purpose of preventing scaling.

The wells in the Húsmúli Reinjection Zone are operated at well head pressure of 8 bar. The natural water level in the area is 200 m, which results in additional hydrostatic pressure of 20 bars in the well, when it is full of water. Thus, the pressure increase in the wells during operation is 28 bar. The performance of the Húsmúli Reinjection Zone has declined since it was commissioned in September 2011. In the beginning the flow did stabilize around 550 l/s. By the end of Summer 2012 the flow was down to 300 l/s. At that time the capacity of the Gráuhnúkar Reinjection Zone was also becoming fully utilized. Starting the district heating utility, which had been off-line during the summer, cooled the water from 95°C to 75°C. Subsequently the flow into the reinjection wells in the Húsmúli Area increased to 450 l/s. Since then it has slowly declined and is now ~400 l/s. Such a decline has not been observed in the Gráuhnúkar Reinjection Zone. It is not clear if that is due to natural setting – the formation temperature is considerably higher in the Gráuhnúkar Area – or different technical setup – the geothermal brine injected in the Gráuhnúkar area is not diluted with condensate water, but allowed time for polymerizing in a long wide pipe.

Induced seismicity was observed during drilling and testing of the wells in the Húsmúli Area. This activity was not considered to be a problem, it was indeed viewed as positive sign of that the wells were connected with permeable fractures that were being stimulated during the pumping tests. The intensity of the induced seismicity when the Húsmúli Reinjection Zone was commissioned came as surprise. Such an intense seismicity had not been observed before during injection into an Icelandic Geothermal Field. The applied pressure in the wells was also not high enough to cause hydrofracturing. The explanation for this intensive seismic activity is that the reinjection triggered earthquakes, which released stresses that had already built up in the area. It was expected that the seismicity would mostly fade out as the stresses where released. So it did, but the number of events and their magnitude was far more than anyone had expected.

The induced earthqakes occurred on faults that have N-S orientation. Most faults in the area and geological features have SW-NE orientation. These N-S structures that appeared in the earthqake distribution may indicate that the fractures are connected to the South Iceland Seismic Zone (SISZ). The faults of the SISZ are strike slip faults with N-S orientation. The faults in the Helliheiði region are, however, normal faults. The active faults during the commissioning of the reinjection in the Húsmúli Area might belong to the westernmost part of the SISZ system which was under stress after recent big earthquakes Hreinsdóttir et al. (2009). This is something that has to be studied further. A GPS measuring network is operated in the area to study the movement of the crust in the Hellisheiði Area. Those measurements might shine light on the origin of the stresses that were released during the commissioning of the reinjection wells in the Húsmúli Area.

The seismic activity came as a big surprise. Due to these events a considerable amount of work was invested in writing a protocol for developing reinjection zones in volcanic geothermal systems in Iceland. This work was done at the initiative of OR – Reykjavík Energy that operates the Hellisheiði Power Plant. The purpose of that work was to find ways to mitigate the risk of developing and operating reinjection in geothermal areas (Bessason et al., 2012).

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