PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 31 - February 2, 2011
SGP-TR-191

MASTERING REINJECTION IN THE HELLISHEIDI FIELD, SW-ICELAND: A STORY OF SUCCESSES AND FAILURES

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ABSTRACT

Reinjection has posed a major problem in the operation of the Hellisheidi Power Plant, SW-Iceland. The formation temperature at the originally planned reinjection zone proved to be very hot (>300°C) when injection wells were drilled there.

In order to be able to use that zone for production a new reinjection zone was planned. The new zone has been promising despite problems in operating the new injection wells. The wells are drilled into a fault that is active and injection tests have resulted in swarms of small earthquakes.

The injectivity of the wells in the new reinjection zone is highly dependent on temperature of the reinjected water. This dependence can be explained by thermo-mechanical effects on fractures in the fracture governed reservoir.

INTODUCTION

The Hellisheiði Geothermal Field is located in the southern part of the Hengill Area, SW-Iceland. The Hengill Area is an active volcanic systems consisting of Mt. Hengill and fracture zone to the NW and to the SW (Sæmundsson, 1967, Franzson et al., 2005). Two power plants have been built in the area; one in Nesjavellir in the northern part of the area and one in Hellisheiði in the southern part. At least two other geothermal fields in the area are believed to be feasible for electrical power production; the Bitra and the Hverahlíð Fields.

The Hellisheiði Power Plant was commissioned in year 2006. It utilizes the geothermal activity in the southern part of the SW-NE fracture zone which goes through the Hengill Area. A map of the Area can be seen in Fig. 1. The power plant produces electricity and hot water for space heating using water-steam mixture from 34 wells in the area. The geothermal fluid is separated at a pressure of 9 bar-a and the steam is used to drive four 45 MWe pressure turbines. The separated water is flashed from 9 bar-a to 2bar-a in a low pressure boiler to obtain steam for one 33 MWe low pressure turbine. Thus the total production capacity of the Hellisheiði Power plant is 313 MWe.

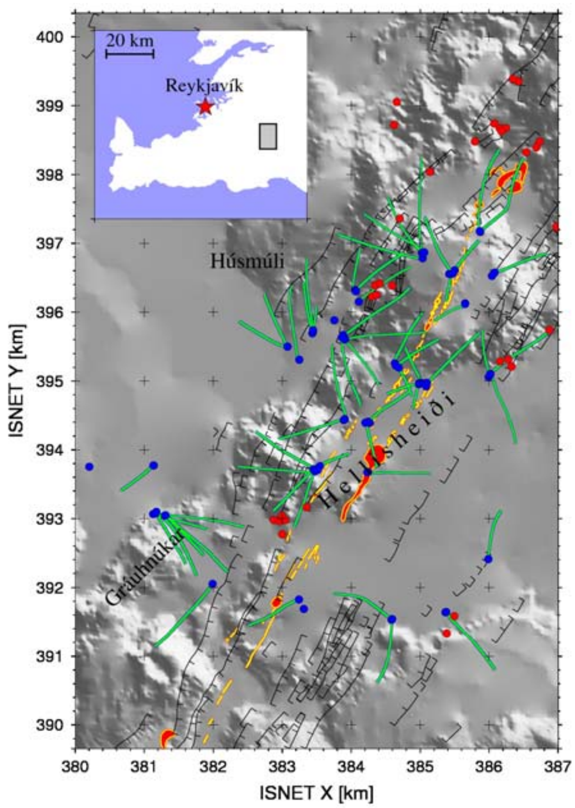

Figure 1: Map of the Hellisheiði Geothermal Field. The inset shows the location of the field in SW-Iceland. Well heads are depicted with blue dots, tracks of directionally drilled wells with green lines, hot springs and fumaroles with read dots, faults with combed lines, and volcanic fissures and craters with yellow/red areas.

The 120°C hot brine from the low pressure boiler is used for space heating in the Reykjavík Area. The brine cannot be used directly for space heating, due to its chemistry. It is therefore used to heat up cold fresh groundwater in heat exchangers in the district heating utility of the power plant. The district heating utility was commissioned in the autumn 2010. The heated groundwater is pumped through a 20 km pipeline to consumers in the Reykjavík Area. The brine which is 80°C when the district heating system is in operation is to be reinjected into the Geothermal Reservoir.

It has not been as straight forward task to reinject the water into the reservoir as presumed. It was discovered that the originally planned reinjection zone in the southern edge of field was hot. Temperatures higher than 300°C were measured in wells there, which indicates that the area could be ideal for production. In order to be able to use that zone another reinjection zone has been planned and a few wells have been drilled there. Operating the reinjection system has been difficult. It was not possible to reinject all the waste water that was coming from the power plant making it necessary to dump a part of it into upper groundwater reservoir. It seems like the wells close when 120°C water is pumped into them. Scaling has also been a problem in pipelines and most probably in wells too. It is possible that scaling is partly responsible for diminishing injectivity of wells as time passes by.

A lot of effort has been put into solving the reinjection problems of the Hellisheiði Power Plant. The chemistry of the brine has been thoroughly studied in order to prevent scaling in pipelines and wells (Sigfússon 2010). The hydrogeology of the reinjection wells was studied and methods developed for increasing the amount of brine that can be reinjected into the system. Currently all the brine from the power plant can be reinjected into the system and it looks like all the brine from present operation can be reinjected into the new reinjection zone.

Two new 45 MWe tubines will be commissioned by the end of this year. That will increase the amount of brine significantly and for the time being it is not possible to reinject all that brine into the new reinjection zone. Thus, further studies are needed if the old reinjection zone is to be converted into a production zone.

THE REINJECTION ZONES

The Gráuhnúkar Area

Originally the Gráuhnúkar Area was planned as the reinjection zone of the power plant. No geothermal surface activity manifests itself there and the area was believed to be in the edge of the temperature anomaly in Hellisheiði. Resistivity measurements (TEM and MT) gave no indications that this area could be hot (Árnason et al., 2010). Resistivity anomalies that are known as fingerprints of high geothermal activity are 1.5-2 km east of Gráuhnúkar. Thus, it came as a surprise that temperature higher than 300°C was measured in injection wells that were drilled in the Area. The high formation temperature in the Gráuhnúkar Area is connected to the hottest parts of the Hellsheiði field. The formation temperature is shown in Fig. 3.

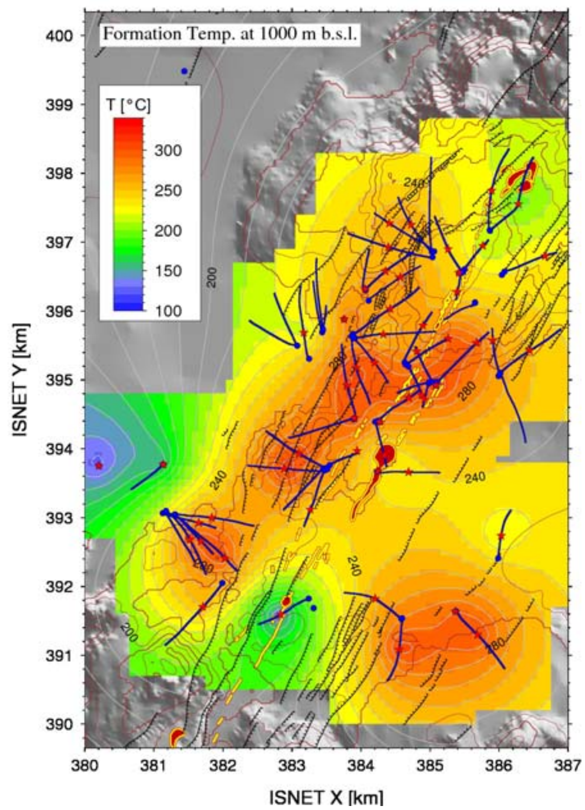

Figure 2: Formation temperature at the depth of 1000 m below sea level in the Hellisheiði Field. Well heads are depicted as blue points, directionally drilled wells as blue lines, the data points (the intersection of the wells to 1000 m b.s.l.) are depicted as red stars. Formation temperature between data points is calculated using the surface interpolation scheme of the GMT software package (Wessel & Smith, 2010).

The high formation temperature makes the Gráuhnúkar Area promising for production. Wells in the area NW of Gráuhnúkar yield high enthalpy fluid (> 2000 kJ/kg) in high quantities. Due to time constrains in the construction and operation plans of the Hellisheiði Power Plant the area had to be used as a injection zone. No time was available to change those plans and no other injection zone available for reinjecting the brine from the power plant. Since the commission of the plant in 2006 the area has been in use. It is not clear what long term effect the injection has on the possibility of using the area for production.

The Húsmúli Area

The new Húsmúli Area is located west of the main production wells in the Hellisheiði field. It is located in the edge of the temperature anomaly. Six reinjection wells have been drilled in the area. Their main target is a NW-SE fault. The first well HN-09 was drilled in February 2008. Its injectivity was estimated 4.5 l/s/bar in pumping tests in the end of the drilling operations. In May 2008 well HN-09 was connected and reinjection in the Húsmúli Zone started. It the beginning it was possible to pump 90 l/s into the well at well head pressure of 2 bar-g. The temperature of the water at that time was 120°C. The district heating system was not yet operational and the brine water was coming directly from the low pressure boilers.

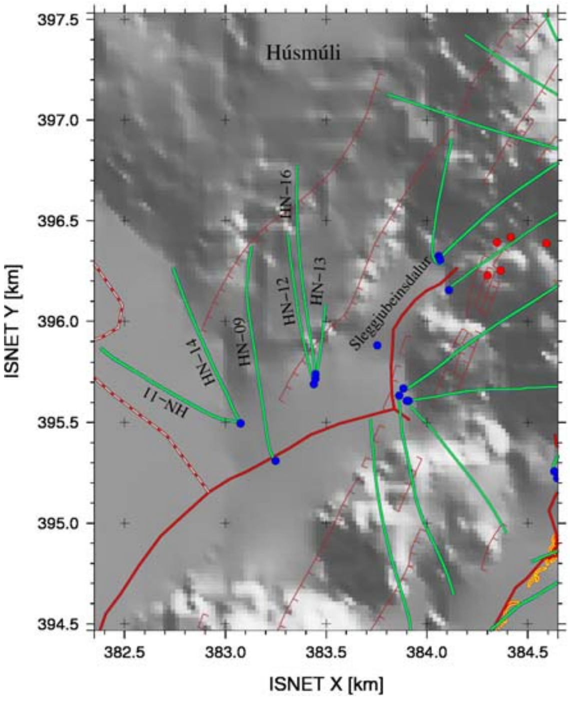

Figure 3: The injection wells in the Húsmúli Area. The faults that the wells intersect seem to close south of well HN-09. The most permeable wells are the northernmost ones, HN-12 and HN-16.

These results were encouraging and more injection wells were planned in the Húsmúli Area. In December 2008 the quantity of water that well HN-09 received had dropped down to 36 l/s for well head pressure of 2 bar-g. Well HN-11 was then being drilled but that one turned out to be rather tight and have water level approximately 30 m below surface, which is the cold groundwater level in the area. The groundwater level in the geothermal reservoir is 200 m below the surface. During pumping tests in HN-11, HN-09 was also monitored for possible interference between these two wells. No interference was found but the water level in HN-09 was measured at ~30 m below surface, i.e. at similar depth as the water level of HN-11. It was concluded that the seven months of injecting into well HN-09 had filled the aquifer in the Húsmúli Area and that the aquifer was poorly connected or not connected at all to geothermal reservoir. It looked like the new reinjection zone was a total failure.

These results were a disappointment. It was, however, decided to do pumping tests in HN-09 to confirm that the water level was at a depth of only 30 m and to check if the injectivity of the well had changed. It is known that after being flashed from 9 bar-a to 2 bar-a the brine is oversaturated in silica. Scaling in the injection wells and neighboring formation could have affected its injectivity (Gunnarsson, I. et al., 2010).

Pressure and temperature probe was placed in the well and the plan was to do pumping tests using 15°C water. The flow was supposed to be increased to 70 l/s in two approximately equal steps of 2 hours of length each. The well head pressure started to behave strangely as soon as the 15°C water started to flow into the well. Under pressure was measured on well head during the whole test and even when the all available amount of water was injected.

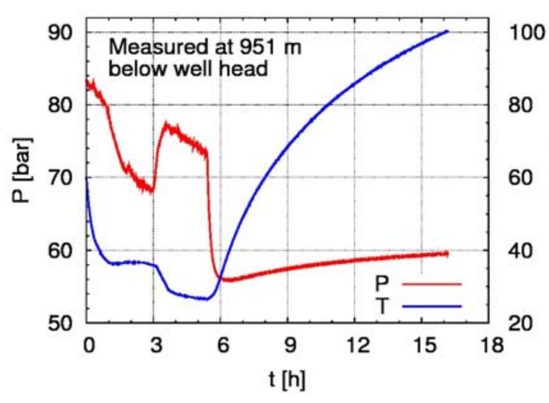

Figure 4: Pressure (P) and temperature (T) measured in well HN-09 during pumping tests. The probe was located at 951 m below the well head (1000 m of well length).

In Fig.4 the pressure and temperature measured at the depth of 951 m is plotted vs. time. The well is changing the whole time during injection of the water. The pressure does not reach equilibrium in the steps and is dropping drastically during them. Only a fraction of this pressure difference can be explained by the weight change of the water column above the pressure sensor due to temperature changes.

Approximately 5 ½ hours into the experiment the injection was turned off. The sensor was kept in the well for the next 14 hours while the well was reaching equilibrium after the test. The temperature reaches 100°C in this period and the pressure increases 4 bar. The main feed zones of this well are at 2250 m below surface and due to thermal expansion the water level rises when the well heats up again. This rise in water level explains the slowly increasing pressure after the pumping test. The water level when the injection was turned off was estimated to be at depth of 300 m below surface using the measured pressure.

It was not possible to estimate the injectivity from the results of this experiment as planned. It could however be seen that the aquifer in the Húsmúli Area had not been filled up, which was very good news indeed. It was decided to proceed with drilling new injection wells in the area. To date five injection wells have been drilled in the area (HN-09, HN-11, HN-12, HN-14, and HN-16) and one shallow well (HN-13), which was intended for dumping water in the groundwater system above the cap rock of the geothermal system in case of emergency. Wells HN-11 and HN-14 have low permeability, especially HN-11 which is practically useless for reinjection. Well HN-09 is fairly permeable and HN-12 and HN-16 are very permeable. In Table 1 is a list of all the wells in the Húsmúli area showing their length, the depht of their main feed zones and their natural water level.

Table 1: List of wells in the Húsmúli Reinjection Zone showing their total length (l_{tot}) the depth of their main feed zone (l_{fs}) and their natural water level (d_{wl}).

Well	l_{tot} [m]	d_{fz} [m]	d_{wl} [m]
HN-09	3023	2250	250
HN-11	2703	760	30
HN-12	1945	1755	280
HN-13	1001	775	70
HN-14	2039	2000	230
HN-16	2204	1902	270

The wells are all directionally drilled and their targets are active faults with oriented SW-NE. The more permeable wells (HN-9, HN-12, and HN-16) intersect the faults at depths below 1750 m. Wells HN-12 and HN-16 have their main feed zones near the bottom. It seems like these faults are closed south of HN-09. Well HN-14 has, as mentioned above, very low permeability and HN-11 is very tight.

What is also interesting about the Húsmúli area is that no coupling has been measured between the wells there and the production and inspection wells west of the area. There seems to be a very tight barrier between the faults in Húsmúli and the faults that production wells to the west intersect. This is encouraging since the risk of shortcut between reinjection wells and production wells should be low.

The unexpected results in the testing of well HN-09 that are shown in Fig. 4 raised many questions on the behavior of wells in fractured reservoirs. Injection of cold water is a common practice for stimulating wells in fractured reservoir after drilling (Axelsson et al., 2006). Well HN-09 had already been stimulated by the end of drilling and had a relatively high injectivity index (4.5 l/s/bar).

The pumping test was repeated in the well and it was decided to do well tests with water at different temperatures. After apparently enhancing the permeability of HN-09 by injecting cold water into it, the question was how big effect temperature could have on the permeability of the well.

TEMPERATURE DEPENDENT INJECTIVITY

Measuring the temperature dependency

The injectivity was measured vs. temperature in well HN-09. Pumping test were done using three types of water; untreated brine directly from the low pressure boiler, which has temperature of 120°C, mixture of brine and condense water from the turbines, and cold groundwater. The brine and condense water was mixed in the ratio 7:3, which yields a temperature of approximately 90°C. The temperature of the cold water is 15°C.

The pumping tests for estimating the injectivity were conducted as follows. Maximum flow of water at preferred temperature was injected into the well for few days. The well head pressure was monitored in order to estimate when the well had reached equilibrium. A pressure and temperature sensor was placed in the well at the depth of its main feed zone. The flow was shut down in three steps and waited for ~3 hours after changing the flow in each step. In Fig. 5 an example of pumping test results are shown. The results are from well HN-16 when the injectivity was measured with unmixed brine (T=200°C). The flow (Q) is plotted versus measured pressure (P) in the inset. The slope of the linear fit, i.e. the injectivity (ξ) was estimated 5.2 l/s/bar for this temperature in this well.

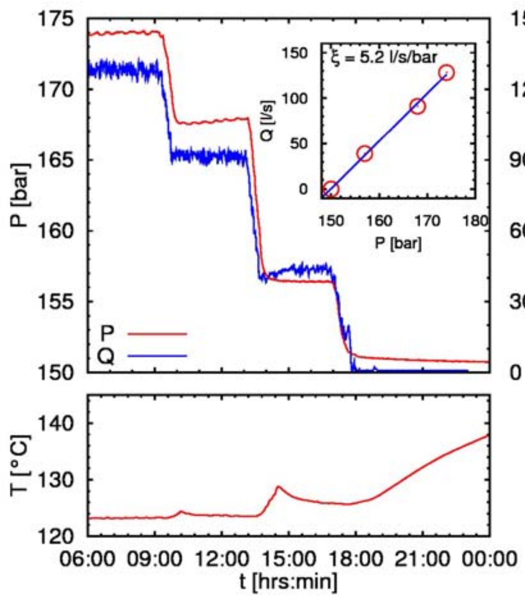

Figure 5: Injection test in well HN-16 using 120°C hot water. The pressure sensor is placed 30 m above the bottom of the well. The upper part shows the pressure (P) and flow (Q) vs. time. The inset shows the Q vs. P in the steps. The slope gives the injectivity ($\xi = \Delta Q/\Delta P$). The lower part show the temperature vs. time.

These experiments were done in the three most promising wells in the Húsmúli Reinjection Zone, i.e. HN-09, HN-12, and HN-16. The resulting ξ vs. T is plotted for all the wells in Fig. 6. It should be mentioned here that the values for cold water in wells HN-12 and HN-16 are inaccurate. The wells are so permeable that the pressure changes in the pumping tests were not very clear.

Origins of temperature dependent injectivity

The permeability in the Hengill Area is governed by fractures. The flow per unit length along a fracture (q) is given by

$$\frac{q}{P} = \frac{d^3}{12\mu l} \propto \xi, \quad (1)$$

where d is the with of the fracture, l the distance over which the fluid flows, μ is the viscosity of the fluid, P is the pressure difference over the fracture, and ξ is the injectivity. The viscosity of water is five times higher for water at 20°C than for water at 120°C. Thus, one should expect the injectivity to be five times higher for 120°C water than for 20°C water, since the flow is proportional to $1/\mu$ according to Eq. (1). The injectivity at different temperatures in three wells in the Húsmúli Area is shown in Fig. 6. As can be seen, the temperature dependence of the injectivity does not behave as one would expect if viscosity is the only temperature dependent parameter (see Eq. (1)). The flow is proportionally dependent on d^3 and changing width of fractures due to thermal expansions must explain this behavior. The change in width not only cancels out the effects of viscosity, which is, as mentioned above, five times higher for 20°C hot water than for 120°C water. It increases the injectivity more than 6 times when the temperature is lowered from 120°C to 20°C.

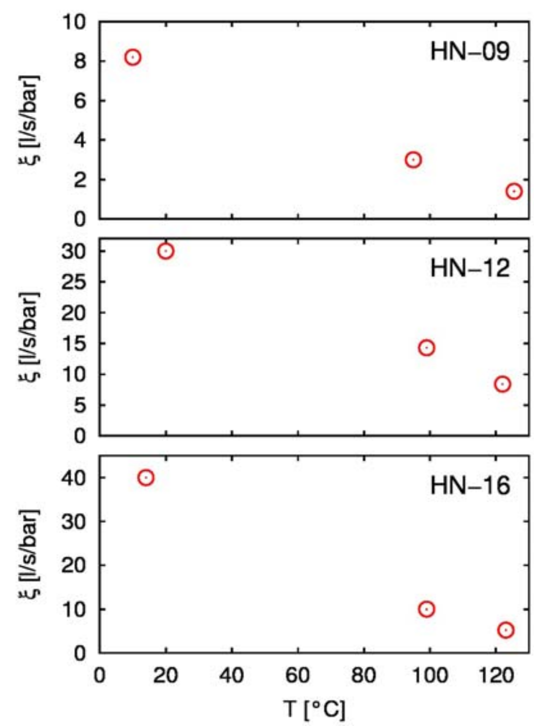

Figure 6: Injectivity (ξ) at different values of temperature (T) in three wells in the Húsmúli Reinjection Zone. The values of ξ for the lowest temperatures in wells HN-12 and HN-16 are not very accurate.

Thermo-Mechanical Effects

During injection of cold water into the Húsmúli Reinjection zone numerous earthquakes have been registered. The Icelandic Meteorological Office operates an automatic seismometer network which detected the earthquakes.

In Fig. 7 the locations of the earthquakes that were measured during the injection of cold water into HN-09 are plotted. These data are from pumping test that was done from 10th to 12th of February 2009. A pressure and temperature sensor was placed in the well during the injection of the cold water. The graph in Fig. 7 shows the pressure and temperature vs. time during the injection. The lower part of the graph shows the magnitude of the earthquakes.

Earthquakes during injection of cold water have often been registered. What is interesting about this data are the pressure signals that appear simultaneously to the earthquakes. This indicates that the changing width of fractures due to thermal expansion is responsible for the temperature dependence of the injectivity.

The faults in the Húsmúli Area are active and the thermally induced movements of the fractures there can trigger small earthquakes. This did also happen in the pumping tests in wells HN-12 and HN-16. The locations of measured earthquakes in those pumping test are shown in Fig. 8

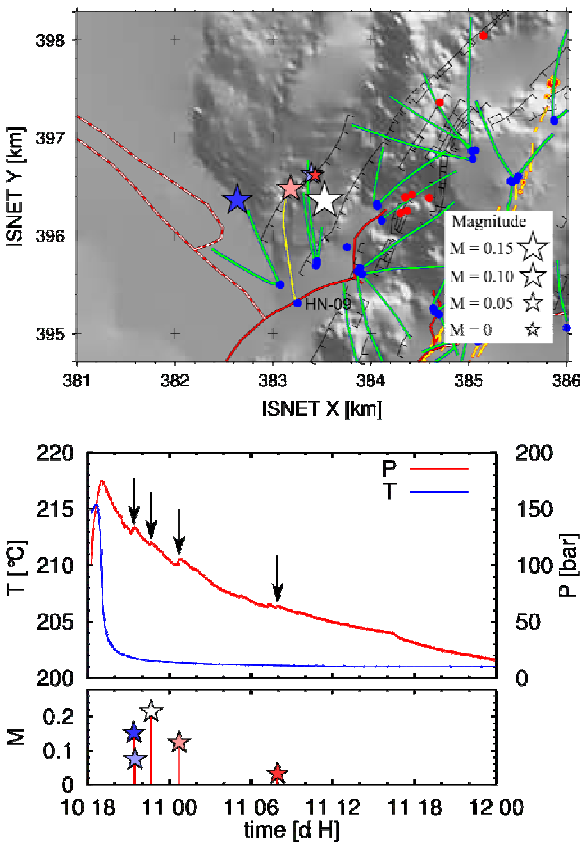

Figure 7: The map shows the location of small earthquakes during an injection of cold water into well HN-09 in February 2009. The upper part of the graph shows the pressure (P) and temperature (T) measured vs. time in the well during the injection. The time of the measured earthquakes are marked on the graph and their magnitude is shown in the lower part of the graph. The color of the stars is the same as in the map.

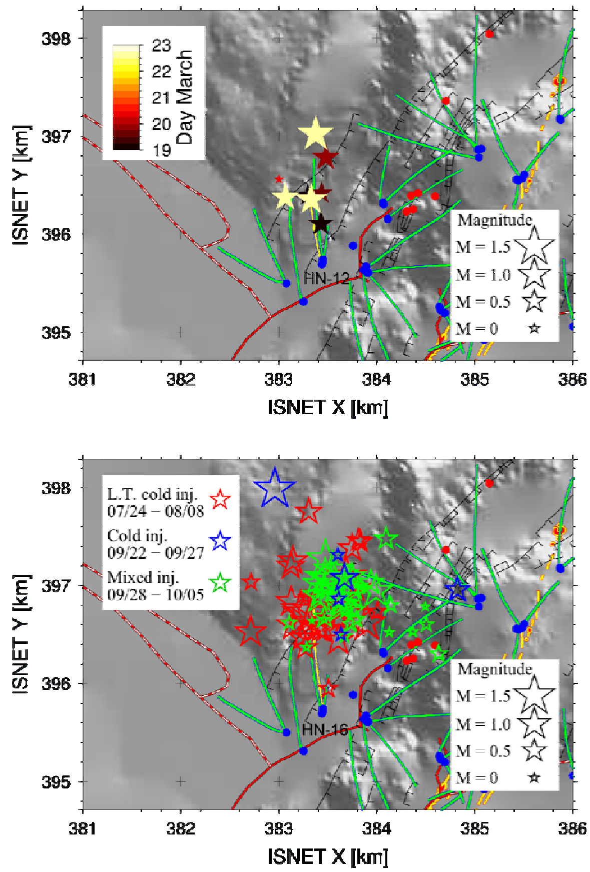

Figure 8: Upper map: Earthquakes measured during injection of cold water into well HN-12. Lower map: Earthquakes measured during injection test in well HN-12. Earthquakes were registered in a long term injection test with cold water that was undertaken in July and August 2010. Relatively few earthquakes were registered in the pumping test using cold water (20°C). More earthquakes were registered in the subsequent test using mixture of brine and condensate water (90°C).

MANAGING THE REINJECTION

As mentioned above reinjecting the brine from the low pressure boiler did not work. The permeability of the wells was simply too low for the temperature of the water coming from there (i.e. 120°C). The information on the temperature dependence of the injectivity can be used to solve the problem of reinjecting the water into the reservoir. Cooling the water increases the injectivity significantly. There are two ways of cooling the water: By thinning it with condensate water and by cooling it in the heat exchangers of the district heating utility of the power plant. Due to seasonal changes in the operation of the district heating utility in the Hellisheiði Power Plant, this method of cooling the injection water cannot be solely used. The water must be thinned using the condensate water. The amount of water to be injected increases 30% when this method is used. The increase in injectivity is much higher or ~60% resulting in a net gain in the quantity of water that can be injected at given pressure.

The colder water column is heavier. The density of 90°C hot water is 943 kg/m^3 and 965 kg/m^3 for 120°C hot water. Cooling the water from 120°C to 90°C increases the pressure of ~ 2 bars at a bottom of a 1000 m high water column. The pressure gain is ~2.5 bar for 1000 m water column if the water is cooled down to 80°C. The main feed zones in the best injection wells in the Húsmúli Area zone are at depth of ~2000 m, thus the pressure gained by cooling the water is ~4 bar when cooling from 120°C to 90°C and ~5 bar when cooling to 80°C. For a well having injectivity of 5 l/s/bar and the main feed zone at 2000 m depth this yields an increased flow of 25 l/s.

Thinning the brine using condensate water has not only the benefits of increasing the injectivity of the wells and increasing the pressure at the feed zone. It also helps in preventing scaling due to oversaturated silica (Sigfússon & Gunnarsson, 2011). Scaling has been a problem in the low pressure boiler, the reinjection wells and the pipelines in between. (See Sigfússon & Gunnarsson, 2011 for details on scaling issues.)

It is not fully known how the reinjection affects the production from the field. In model simulations of the Geothermal fields in the Hengill Area reinjection has been taken into account (Gunnarsson, G. et al. 2010). The effect of reinjection is double edged. It will keep up the pressure but the higher pressure drop without reinjection will enhance the enthalpy of produced fluid (Björnsson & Hjartarson, 2003). The formation temperature in the hottest part of the Hellisheiði reservoir is close to boiling curve and pressure drop will cause boiling in the system (Gunnarsson G. et al, 2010). More work needs to be done on simulating the effects of different reinjection scenarios on the properties of the geothermal reservoir. Thinning the geothermal brine with condensate water and cooling it with heat exchangers makes it possible to inject it all into the reservoir and solve the environmental problem of brine disposal. The long term effects of this solution on the geothermal reservoir are not known and have to be studied further by monitoring the system's response and by simulations.

CONCLUSION AND SUMMARY

Managing the reinjection of geothermal brine in the Hellisheiði Geothermal Field has been a great challenge. The formation temperature in the originally planned reinjection zone in the Gráuhnúkar area turned out to be higher than 300°C. Reservoirs with such temperatures are promising for production. Due to tough time schedule in the building and commissioning of the power plant no time was available to find a new reinjection zone and drill there before operation started in Hellisheiði in autumn 2006. It was therefore necessary to use the area for reinjection when the power plant was commissioned. Work is well underway in developing a new reinjection zone in the Húsmúli Area. It has still to be determined if all the brine from the Hellisheiði Power Plant can be injected into the Húsmúli Area. Thus, reinjection into the Gráuhnúkar area continues for the time being.

The problems that tight time schedule has caused in managing the reinjection in Hellisheiði raises questions on how quickly one can develop power production in a new geothermal field and how such operation should be organized.

The permeability (injectivity) of the reinjection wells is highly dependent on temperature. The colder the fluid is the higher the injectivity. By cooling the brine in heat exchangers (in the district heating utility of the power plant) and by thinning it with condensate water, this effect can be applied and all the brine can be reinjected. This effect originates in thermal expansion and contractions in the fractured reservoir.

The faults in the Húsmúli Area are active and the thermal effects of the reinjection can trigger earthquakes. Numerous earthquakes have been detected during injection into the Húsmúli Area. In one pumping experiment there seems to have been some coupling between these events to the pressure measured in the injection well. This phenomenon has to be studied further.

The effects of different reinjection schemes on the properties of the reservoir also have to be studied further. Mixing the brine with condensate water and cooling it with the district heating utility solves the reinjection problem of the Hellisheiði Power Plant. The question is if a new problem has been created by solving the reinjection problem. This question has to be addressed and therefore is necessary to monitor the properties of the reservoir and work further on simulating the effects of reinjection on its properties.

ACKNOWLEDGEMENTS

I would like to thank my colleagues at OR; Jón Búi Guðlaugsson, Einar Jón Ásbjörnsson, Bjarni Reyr Kristjánsson, Edda S.P. Aradóttir, Bergur Sigfússon and Ingvi Gunnarsson, and our consultants from ISOR (Iceland Geosurvey) for all their hard work in running experiments and gathering data, and for fruitful discussions.

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