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Managing the Need for Growing Reinjection Capacity at Hellisheiði Power Plant, Iceland

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ABSTRACT

Since the commissioning of Hellisheiði power plant, SW Iceland, in 2006 and subsequent increments in production until 2011, constant addition to the reinjection capacities of the power plant has been necessary. The reasons for the constant higher capacity need are a decrease in injection rates of injection wells, decline in flowrate from medium to high enthalpy wells and in some cases lowering of discharge enthalpy of medium to high enthalpy wells. The lowering of flowrate from medium to high enthalpy wells has been compensated by increasing the flowrate from liquid enthalpy wells to try to maintain constant steam to the power plant. As a result, the weighted average discharge enthalpy extracted from production field has been decreasing.

Initially this decline in injection rates and the increase in geothermal brine for reinjection was met with converting wells, that initially were drilled for power production but as such were not successful, into injection wells. These wells are often close to the production area and their use for reinjection had both positive and negative effects on nearby production wells. Injection into wells drilled into low-temperature formation were not successful as the decline in injection rate into these wells was rapid.

These challenges called for a systematic approach identifying possible new reinjection area for the power plant. Analytical hierarchy process was used for evaluating possible new injection sites where each possible site was rated based on seven factors related to the feasibility of the site for reinjection. The result from this process acted as a guide for a reinjection site selection and steps are being taken to move part of the reinjection of Hellisheiði power plant further away from the production field based on this approach.

1. INTRODUCTION

When planning and building a high temperature geothermal power plant more emphasis is usually put on drilling for steam than on where and how to dispose of the spent geothermal water. The cost of designing and building an injection system from a power plant is considerable compared to the total capital cost of a power plant and should not be underestimated in geothermal utilization. Historically reinjection is often only considered a method for wastewater disposal for environmental reasons but more recently it has developed into an important tool for geothermal field management (Sanyal et al., 1995, Stefánsson, 1997 and Kaya et al., 2011) For successful reinjection strategies of the spent geothermal waters in high temperature power production two criteria must be met. The reinjection must be done at the right place relative to the production field and the scaling potential of the fluid in terms of mineral scaling need to be at acceptable levels. For successful long-term reinjection both factors need to be considered in the design of the injection systems of the power plant.

Geothermal utilization involves extraction of geothermal fluid from a relatively large area and reinjection of large part of the fluid into a much smaller area. This will create a pressure low in the production zone and a pressure high in the reinjection zone. Where to reinject the spent geothermal waters is always a key question in the design of reinjection system. The pressure effects from the reinjection wells can cause discharge enthalpy changes in production wells and the spent water is colder than the fluid in the production field and if reinjected too close to the production field they could potentially cause cooling in the system as the reinjected waters flow back into the system. If, however the injection is to far away from the system there might be insufficient pressure support from the reinjection and the drawdown in the system is too high for sustainable long-term production.

In this contribution we describe reinjection at Hellisheiði power plant SW Iceland. Hellisheiði power plant is one of the largest power plant in the world and operational permits from legislators state that all geothermal brine must to be reinjected in a geothermal system together with part of the condensate. The reason for these demands is to decrease pressure drawdown in the system during production and the fact that the power plant is close to freshwater resources making surface disposal or shallow injection potentially harmful for groundwater resources. This has put considerable strain on the operation of the power plant as the amount of brine has been increasing since its commission and subsequent capacity increase. The challenges in reinjection called short term fixes and for a different approach than previously used in Hellisheiði power plant in planning and designing reinjection system.

2. HELLISHEIÐI POWER PLANT

Hellisheiði power plant is a combined heat and power plants located to the south of the Hengill central volcano which is located in the western volcanic zone SW-Iceland, approximately 20-25 km southeast of Reykjavík (Fig. 1). The Hengill volcanic system produces primarily basaltic rocks and is cut by an active NE-SW fissure swarm (Franzson et. al., 2010). The Hellisheiði geothermal field are liquid dominated fields characterized by low salinity and high H_2S and H_2 concentrations (Scott, et. al., 2011, Stefansson et. al., 2011). The temperature in the geothermal system varies considerably but in the main production field it is between 260°-320°C.

The power plant was commissioned in 2006 with the installment of two 45 MW_e turbines. In 2007 a 33 MW_e low pressure turbine was installed that uses steam from a second stage flashing of the separated geothermal water and two additional 45MW_e turbines were started in 2008 and another two 45 MW_e units in 2011. Heat exchangers to produce hot water for space heating in the capital area were commissioned in 2010 producing 133 MW_{th}. Total installed capacity in Hellisheiði power plant is 303 MW_e and 133MW_{th}. Further 67 MW_{th} expansion thermal capacity is planned late 2019. At full capacity Hellisheiði power plant will produce 303 MW_e and 400 MW_{th}.

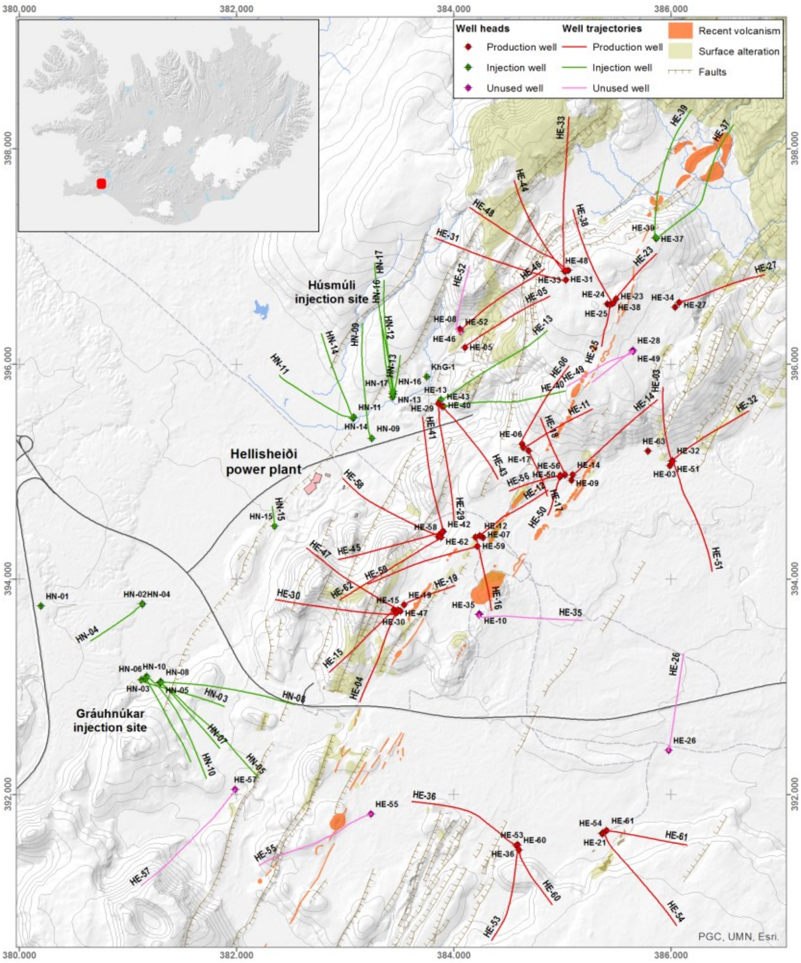

Figure 1: Overview of production and injection wells at Hellisheiði geothermal field. Injection wells (green wellheads and trajectories) with the HN prefixes are drilled as injection wells but wells with HE prefixes are drilled as production wells but have since been converted to injection wells.

3. REINJECTION AT HELLISHEIÐI POWER PLANT

Production density is very high in Hellisheiði geothermal field. The production field is relatively small compared to the size of the power plant leading to production density as high as 250 kg/s/km² within the most productive parts of the field (Gunnarsson and Mortensen, 2016). This high production density has caused significant pressure drawdown and decreased performance of wells (Sigurðsson et al., 2020, Gunnarsson et al., 2020). Under these circumstances reinjection of the spend geothermal waters is very important for pressure maintenance in the system and as a tool for reservoir management.

Three of the first four injection wells drilled in Hellisheiði, HN-1, 2 and 4 (Figure 1) in an area with limited permability. These wells are 1300 to 2000 m deep but only had permeable aquifers at shallow 400-600 m depth and at temperature 30-50°C. Plans for reinjection into these wells were terminated before the powerplant was commissioned. HN-3 was drilled in the Gráuhnúkar area south of the power plant (Figure 1) in 2006 and based on the results of that well five more wells (HN-5, 6, 7, 8 and 10) were drilled in 2006 and 2007.

Reinjection started at in Gráuhnúkar power plant in 2007, a year after power production started. The Gráuhnúkar reinjection zone was expected to be enough for all the brine from the power plant. Temperature measurements in the injection wells made after drilling showed that the field was hotter than excepted and could potentially be a feasible production field (Gunnarsson et al. 2015). As a result, preparation started to relocate the injection site for the power plant and subsequently drilling started in Húsmúli field north of the power plant. Seven injection wells, HN-9, 11, 12, 13, 14, 16 and 17 (Figure 1), were drilled in 2008 to 2011 for this purpose. The new reinjection field, Húsmúli, was expected to take over as an injection site for the power plant and Gráuhnúkar was seen as a production field in the future. Reinjection started in Húsmúli late 2011. When injection started in Húsmúli a very large number of earthquakes were observed (Bessason, 2012; Gunnarsson, 2013), including two events of ML 4.4, causing significant tremors in nearby communities. Close monitoring of the seismicity in the Hellisheiði field during the last few years shows that the seismicity has been fading out, suggesting that the reinjection has released stresses that were present in the crust (Gunnarsson et. al. 2015).

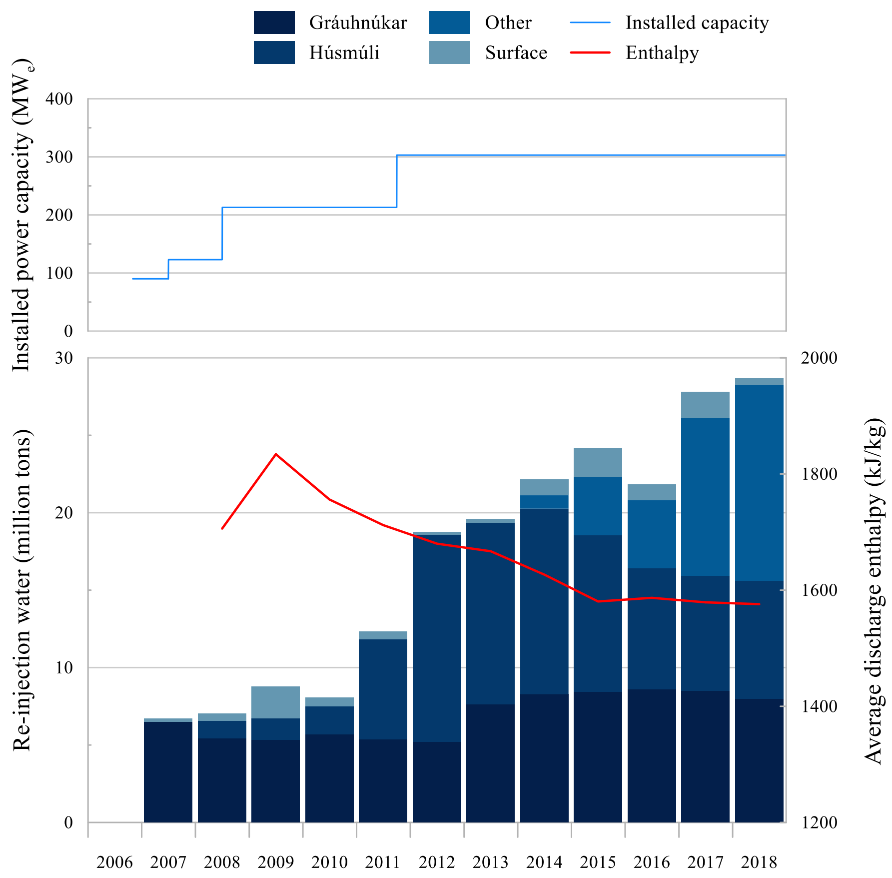

Figure 2: Amount of geothermal water injected, installed power capacity and weighted average discharge enthalpy for production wells in Hellisheiði power plant.

Shortly after reinjection began in the Húsmúli site the flowrate in the wells started to decrease and a pattern of how flow in one well affected flow in a nearby wells was established. The reason for the decline in flowrate is still under investigation but is most likely caused by a pressure increase in the area. Scaling could also be a cause of the decline but heterogenic behavior of the wells where some wells are declining in flowrate when others are increasing in flowrate contradicts that as scaling would affect all the wells equally.

Since commissioning of the power plant in 2006 the amount of geothermal water for reinjection has greatly increased. The increase is due to increase in power production from 2006 to 2011 (Figure 2) and later because of decline in flow rate from high to medium enthalpy wells resulting in more power production from liquid enthalpy wells in the edges of the geothermal system. This reliance of the liquid enthalpy wells results in higher water extraction from the system to maintain steady steam flow for power production. Lowering of discharge enthalpy in parts of the system has also contributed to higher amount of geothermal water for reinjection. Since 2012, the first year of full power production capacity, the amount of injected water has increased from 18.5 million tons to more than 28.2 million tons annually in 2018 or more than 50% increase in 6 years (Figure 2). This increase has since 2014 been met with injection into wells that initially were drilled for production but failed as production wells. These injections wells are marked as other in figure 2. Most of these unproductive production wells are closer to the production field than the injection wells in Gráuhnúkar and Húsmúli and injection into them can potentially affect the production field. The wells are marked with green wellheads and well trajectories in figure 1 and number HE-13, HE-40, HE-37, HE-39 and KhG-1 which are currently used for reinjection and HE-38, HE-23 and HE-25 which were used for reinjection for a limited time in 2016 and 2017.

The constant need for more injection capacity in Hellisheiði power plant led to revision of the decision to not inject into wells HN-1, HN-2 and HN-4 which had poor permeability. Injection tests done in 2016 indicated that 100 l/s could potentially be injected into the three wells. Injection started in 2016 and shortly after injection began a sharp decline in the flowrate in the wells was observed (Figure 3). During a period of six months the flow in the wells reduced from more than 80 l/s to less than 20 l/s. Injection was stopped for approximately five months in 2017. When the injection was stopped the flow into the wells was 13-14 l/s and after five month break the flow increased by 10 l/s to 23-24 l/s but the decline in flowrate continued and seven months later the flow had declined to around 6 l/s (Figure 3). The water injected into these wells was the same as injected into Gráuhnúkar where no decline in flowrate was observed during the same period. The main difference between the injection reservoir in wells HN-1, 2 and 4 and those in Gráuhnúkar was that temperature in the reservoir in Gráuhnúkar in 250-300°C and compared to 30-50°C in wells HN-1, 2 and 4. The reason for the decline in flowrate is most likely contributed to the difference in reservoir temperature. The reservoir temperature could affect the flowrate in two ways. One way has to do with the temperature changes after the geothermal water moves away from the well in the reservoir. In Gráuhnúkar the water heats up due to higher reservoir temperature and eventually the potential for silica scaling would be eliminated as the water heats up. In the case of injection into HN-1, 2 and 4 the injected water cools down even further and the potential for silica scaling in never eliminated. The other possible explanation for the decline in flowrate is the effects described in well testing in Húsmúli by Gunnarsson et al 2015. The injectivity index in the Húsmúli injection wells is negatively correlated to the temperature of the injected water. This has to do with properties of the fracture laminated flow which dominate the permeability in the reservoirs. Temperature of the injected water changes the width of the fractures receiving waters due to thermal expansion/contraction of the basaltic rock in the reservoir. As injection water temperature is higher than reservoir temperature in HN-1, 2 and 4 the effect on fracture with would be narrowing of the fracture with resulting in decreased flowrate in the wells. The higher flowrate after the five-month long break in injection in 2017 (Figure 3) would then be attributed to widening of the fractures when the reservoir cooled down again during the break.

The flowrate in the injection wells that originally were drilled for production remains high and shows no indications of decline. Some of those wells (HE-13, HE-40 and potentially KhG-1) are however too close to the production field and more injection capacity is needed to relocate the 200-300 l/s that are on average injected into these wells. Both Gráuhnúkar and Húsmúli on average receive around 250 to 300 l/s. Increasing the injection capacity for the power plant by 300 l/s is comparable to locating a new injection zone for the power plant.

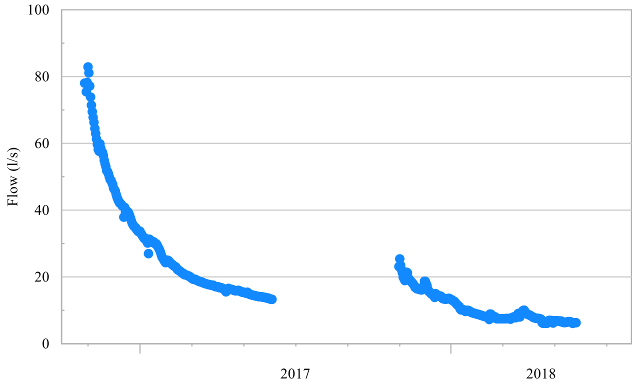

Figure 3: Combined flow into injection wells HN-1, 2 and 4 in Hellisheiði power plant.

4. SYSTEMATIC APPROACH TO FINDING A NEW INJECTION ZONE FOR HELLISHEIÐI POWER PLANT

The capital cost of drilling new injection wells and building the necessary pipes for injection is very high and required a systematic approach. The method used here was analytical hierarchy process often used for organizing and analyzing complex decisions. This approach provides a comprehensive and rational framework for structuring a decision on where to situate a new injection zone of the power plant

The selection of site for a new injection zone was partly based on work done 10 years ago when plans to move the reinjection from Gráuhnúkar were being analyzed. The list from that work was combined with new ideas and evaluated based on seven parameters. Twelve possible reinjection areas and solutions for growing injection capacity were evaluated and are shown in Figure 4. The red filled areas are possible reinjection areas and a red line indicates a solution for spent geothermal water disposal which is building a approx. 25 km pipeline to the sea and dispose geothermal water into the sea. The possible solutions are:

- **A.** On the east side of Gígahnúkur. The target here are fractures and faults on the east side of Gígahnúkur
- **B.** East of Stóri Meitill. The targets are fracture and faults on the east side of Gráuhnúkar, between Hverahlíð and Gráuhnúkar.
- **C.** Litla Skarðsmýrarfjall is a small hyaloclastic ridge to the east of current production field with visible alteration on surface and a potential geothermal system.
- **D.** Engidalur. This area is northeast the Húsmúli injection zone. The target are visible NE-SW faults on surface.
- **E.** West of Engidalskvísl. This area is northease of the Húsmúli injection zone and the injection wells would target faults in Húsmúli west of current faults used for injection in Húsmúli
- **F.** Ölkelduháls. Three wells have been drilled into Ölkelduháls Geothermal system with good permeability.
- **G.** South of Gráuhnúkar 1. This option involves enlarging the reinjection area in Gráuhnúkar. This option was split into two because of planning

H. South of Gráuhnúkar 2. This option involves enlarging the reinjection area in Gráuhnúkar. This option was split into two because of planning

J. Connect unused production wells HE-37, HE-38 and HE-39 to injection system.

K. East of Litli Meitill. The targets are normal faults in the Hengill grabbed on the east side of Litli Meitill

L. Deep reinjection. This option involves drilling a deep reinjection well (4-5 km) and reinject into the roots of the geothermal system at greater depth than current production

Q. Pipe to the ocean

Each option for more injection capacity was evaluated based on seven parameters. Each parameter was rated between 1, 3, 5, 7 or 9 where 1 is the lowest rating and 9 is the highest rating. The parameters were selected base on what was most important for successful reinjection strategies. The parameters are:

1. Amount of geothermal water that could be injected
2. Effect on the production field
3. Effect on groundwater.
4. Status of planning
5. Effect on power plant operation
6. Capital cost
7. Future expansion possibilities

The result of this evaluation was not such that the solution with the highest rating on average was selected as the solution to the injection difficulties of the power plant. Some parameters in the rating can act as a hampering factor for it to be a possible solution for injection. For example, the status of planning in the area and possible effects of groundwater can be such that the option is not feasibly although rating for other parameters was favorable. Uncertainty for some of the parameters is very high for example effect on groundwater and effect on the production field and these factors are difficult to rate with any certainty. Putting different weight on each parameter can be used to lower the average rating for those solution but that was not done here as it would not eliminate the effect of a factor that was in fact hinder the solution in becoming feasible.

Although this systematic approach using the analytical hierarchy process did not result in a selection of injection area simply based on the average rating alone it resulted in detailed analysis of pros and cons and a cost estimate for each option. That alone was very important for deciding on where to relocate the injection for the power plant.

Based on the result of this work and combined with a list of other possibilities considered more short term options work has started on preparing and building new injection zone for the power plant. The solution selected was a combination of option A and B in figure 4 combined with reinjection into a unused production well HE-55 (Figure 1). Plans have been made to drill a new injection well from the same platform as HE-55 and then if necessary, drill new wells south of HE-55. Preliminary pipe will be installed to HE-10 and HE-35 and for preliminary injection of limited amount of water. Effect of that injection on the production field will act as a guide for future injection on those wells.

4. DISCUSSION AND CONCLUSIONS

During construction phase of a high temperature power plant more emphasis is usually put on to drill for steam than to where how to dispose of the spent geothermal water. The cost of designing and building an injection system is considerable and should not be underestimated in geothermal utilization. In Hellisheiði power plant reinjection systems were twice build that were supposed to receive all the spent geothermal water for injection but in both times those plans did not go according to plan. The primary reason for the failure is that the injection zones were to small for the amount of water needed for injection and injection wells were drilled too close together resulting in pressure buildup around the wells where flow in one well decreased the flow into adjacent wells. This is the case in both Gráuhnúkar and Húsmúli reinjection zones in Hellisheiði. Injection tests after drilling and in preparation phase for the injection did not indicate this cross-well effect would not be significant. The injection tests done with cold water and their duration was not long enough for theses effect to revile themselves.

The approach used for future installments for injection capacity will be a slower process that in the case of Gráuhnúkar and Húsmúli. Building will be in steps where wells will be drilled and preliminary pipes will be used for a preliminary injection period before deciding on new injection wells in the area and building a permanent injection pipe. Emphasis will be put on distributing the injection better than in the case of Gráuhnúkar and Húsmúli as in those cases to many wells are drilled in a small area.

Flow into infield injection wells has been stable for a long time and those wells show no sign in flow decline. Those wells differ from other injection wells in that there is no pressure buildup in the area as injection and production in close together. Those wells receive the same water as the wells in Húsmúli indicating that scaling is not the cause of flow decline in the wells as scaling would affect all wells the same.

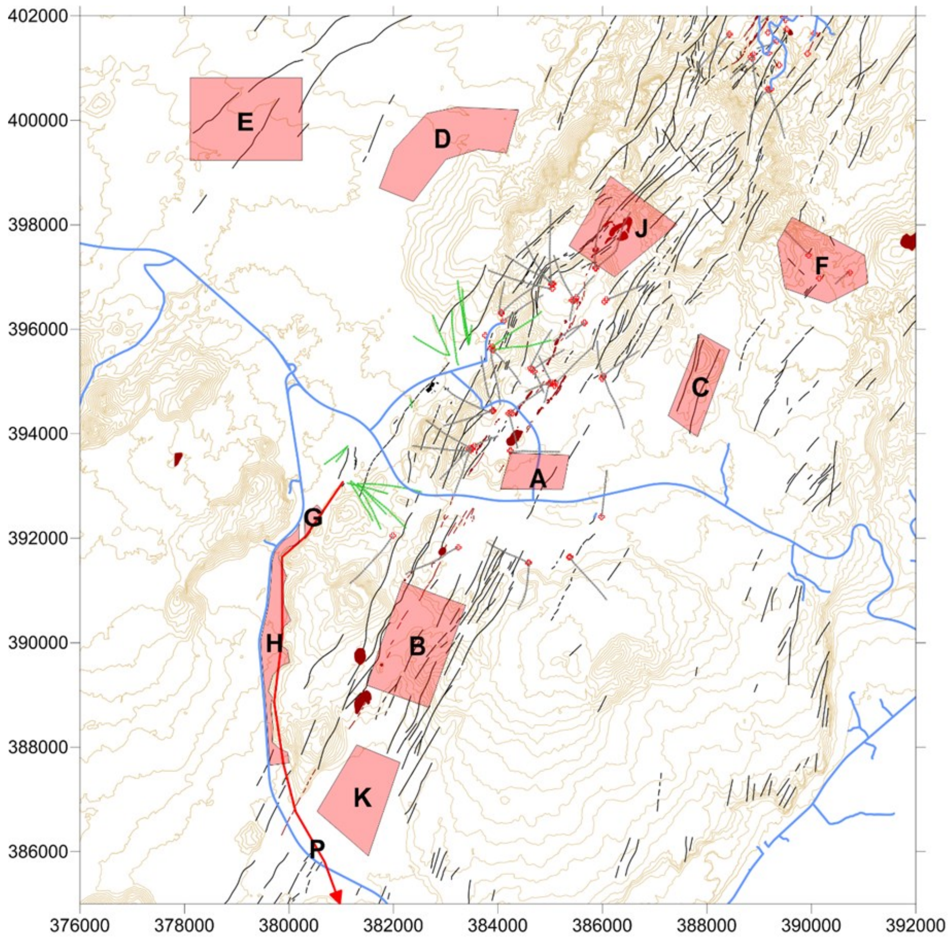

Figure 4. The red filled areas are possible injection zone analyzed as a solution for growing need for injection capacity for Hellisheiði power plant. The red line marked P indicate a 25 km pipe to the ocean.

Tracer testing of injection wells in Húsmúli (Kristjánsson et al., 2017) show good hydrological connection between Húsmúli and nearby production wells and based on the recovery of tracer thermal breakthrough was expected to be fast. Thermal breakthrough has however not been observed yet indicating a longer flow path between the injection zone and production zone than using in the model predictions (Ratouis et al., 2020). Tracer testing in the infield wells, HE-13 and HE-40 (unpublished data), show very fast first breakthrough of tracer and modeling predictions show fast cooling of nearby production wells that have not materialized. Thermal fronts travel slower that modeling suggest indicating more knowledge is need on the flow paths of the injected waters. The short-term effects of infield injection are more because of pressure increase. The pressure increase in short term can increase the flow from liquid enthalpy wells where no enthalpy changes would be observed until the thermal breakthrough reaches the well whereas the higher pressure would decrease discharge enthalpy from medium to high enthalpy wells. These effects are both observed in injection in HE-13 and HE-40 in Hellisheiði (Figure 1) where HE-5, a liquid enthalpy well, increased in flow but a medium enthalpy well, HE-43, decreased in discharge enthalpy and eventually became unproductive. Temperature measurement to the bottom of the well and chemistry indicated no cooling. The deterioration of well HE-43 was caused by pressure increase around the injection wells.

Very valuable experience of operating an injection system for Hellisheiði Power plant for eight years. Too small injection area, injection wells too close together, lack of stepwise increments, pros and cons of infield injection, decline in flowrate, scaling, temperature dependent injectivity, induced seismicity, tracer testing, cold stimulation, fast decline when injecting in cold reservoir, local pressure effects and distributed injection are all lessons learned from injection in Hellisheiði power plant. This experience together with slower and more systematic approach than before will hopefully lead to better injection arrangement that supports sustainable long term production from geothermal systems supplying the power plant with water and steam.

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