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Preliminary Modelling Activities for an Adaptive Traffic Light System for the Hengill Geothermal Field

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ABSTRACT

Monitoring micro-seismicity during operations of a geothermal field is crucial for the understanding of seismic hazard and the reservoir evolution. Induced earthquakes in the context of geothermal projects are on the one hand an important tool to enhance the permeability and thus productivity of reservoirs and to image structure and processes. On the other hand, felt and in particular damaging induced earthquakes are a major threat to societal acceptance and regulatory license to operate. With the adaptive data-driven ATLS (Adaptive Traffic Light System), we aim at managing and mitigating the risk posed by induced earthquakes during stimulation and operations, while at the same time ensuring and optimising the productivity. RISC is developed as part of the EC Geothermica project COSEISMIQ (www.geothermica.eu/projects/coseismiq/) and will demonstrate the full potential of adaptive tools for risk mitigation and reservoir optimisation on the Hengill volcanic region. There, two power plants (Hellisheiði and Nesjavellir) have a total production capacity of 423 MWe and 433MWth, but to maintain this energy output, new production wells and reservoir stimulations are needed, often associated with induced seismicity. RISC integrates the entire processing chain, from automated picking of waveforms and data processing to seismic hazard and risk forecasting, including a strong seismicity modelling component. The seismicity forecasting module routinely computes and weights different models, ranging from purely statistical to fully coupled, 3D hybrid models. To implement such complex data-driven risk mitigation tool in Hengill, we performed a preliminary analysis of the past seismicity at two re-injection sites and provide preliminary numerical modelling for one of the sequences using the hybrid simulator TOUGH2-Seed. Future analysis will aim, on the one hand, at understanding the physical processes happening at the different sites, and on the other hand, at evaluating the performance of such code for future real-time application.

1. INTRODUCTION

Recent examples of geothermal stimulations have highlighted the need for a well-designed, data-driven traffic light system to avoid induced seismicity (Grigoli et al., 2017). Some cases have shown that a purely threshold-based system is clearly not enough to prevent largely felt induced events (e.g. Pohang – Grigoli et al., 2018; Hofmann et al., 2019; Lee et al., 2019), while more complex tools have been proved successful (Kwiatek et al., 2019). An adaptive traffic light system is largely based on modelling activities, which needs to be strongly driven by data.

Within the project COSEISMIQ, we aim at improving the efficiency of the real-time monitoring tools, and at developing advanced models and their weighting by exploiting data from Hengill geothermal area in Iceland. The COSEISMIQ project aims at integrating seismic monitoring and imaging techniques, geomechanical models and risk analysis methods. In this paper, however, we focus on a preliminary analysis of Icelandic data and the use of a candidate modelling tool for future application in an advanced traffic light system. The data analysis and modelling conducted here aim at understanding the physical processes at play in the induced seismicity observed at different reinjection areas of the Hellisheiði geothermal field. The final goal is to develop tools that can explain observed trends, and consequently are capable to forecast future, unwanted seismicity.

Iceland's abundance of volcanic areas and geothermal natural resource associated has fostered the use of geothermal energy. The country has used geothermal heating for the past century with increasing demand. Geothermal power plants are nowadays constantly being developed also for electricity production (25% of the electric supply in 2008 – Halldorsson et al., 2012). The Hengill area, located in the South-West of Iceland, is largely exploited, with Hellisheiði being one of the recently developed power plants starting operations in 2006. Such a power plant produces both electricity and district heating with respective installed capacities of 303 MW_e and 133 MW_{th}. Since the onset of operations at Hellisheiði, reinjection of spent geothermal fluids has been dedicated in designated areas.

In the past decade, the reinjection of geothermal fluids has become common practice in geothermal power plants. Reinjection was first designed to dispose of used fluids but has since then been found to be beneficial to the geothermal system. Indeed, reinjection acts as additional recharge into the system, minimizes the pressure drop in a reservoir subjected to continued utilization and prevents land subsidence. It also enhances the operational efficiency by circulating fluid through the reservoir rocks (Kristjánsson et al. 2016). Moreover, reinjection into deep layers ensures that the chemically contaminated injected water does not percolate into freshwater aquifers used to supply drinking water. Despite its advantages, reinjection can also induce earthquakes that can be felt locally and can cause nuisance in the affected population.

Here we focus on analysing two re-injection sites of the Hellisheiði power plant. Despite only 5 km distance, the two injection areas of Húsmúli and Gráuhnúkar show clear differences in the frequency and magnitudes of induced seismicity. These differences and their controlling factors are not yet fully understood. This work focuses on the study of the geological and geomechanical parameters that could play a role in setting these differences in seismic response and implementing the findings in numerical modelling of fluid flow and seismicity. A preliminary model of the reinjection zones in the Hellisheiði Geothermal Power Plant in SW-Iceland is tested using a coarse computational domain for the entire Hengill geothermal system (Bjornsson et al., 2003; Gunnarsson & Aradóttir, 2015). A time series of injection in Húsmúli is reproduced and the simulated seismicity catalogues are analysed.

2. SITE DESCRIPTION

2.1 Hengill Volcanic Area and the Hellisheiði geothermal power plant

The Hengill volcanic system covers an area of 60 by 10 km at the junction of three main tectonic features of the Icelandic: the West Volcanic Zone (WVZ), the Reykjanes Volcanic Belt (RVB), and the South Iceland Seismic Zone (SISZ). The area is at a transition zone between the normal NE-SW faults of the rift (Reykjanes Peninsula), and N-S oriented strike-slip faults of the SISZ (Ágústsson et al., 2015). The Hengill area is composed of a central volcano and several fissures with a graben structure extending to the North-East and South-West (Tómasdóttir, 2018, Figure 1).

Two geothermal power pants lie on either side of the Hengill volcanic area: the Hellisheiði in the South (Figure 1) and Nesjavellir in the North, both operated by Reykjavik Energy (OR). The Hellisheiði field comprises 30 extraction wells, producing at a rate of 500 kg/s of 180 °C steam for electricity generation, for a total installed capacity of 303 MW_e and 133 MW_{th}. Reinjection occurs at four sites: Húsmúli, Skarðsmýrarfjall, Sleggja and Gráuhnúkar, with a combined average injection rate of 1000 L/s (Hjörleifsdóttir, 2019).

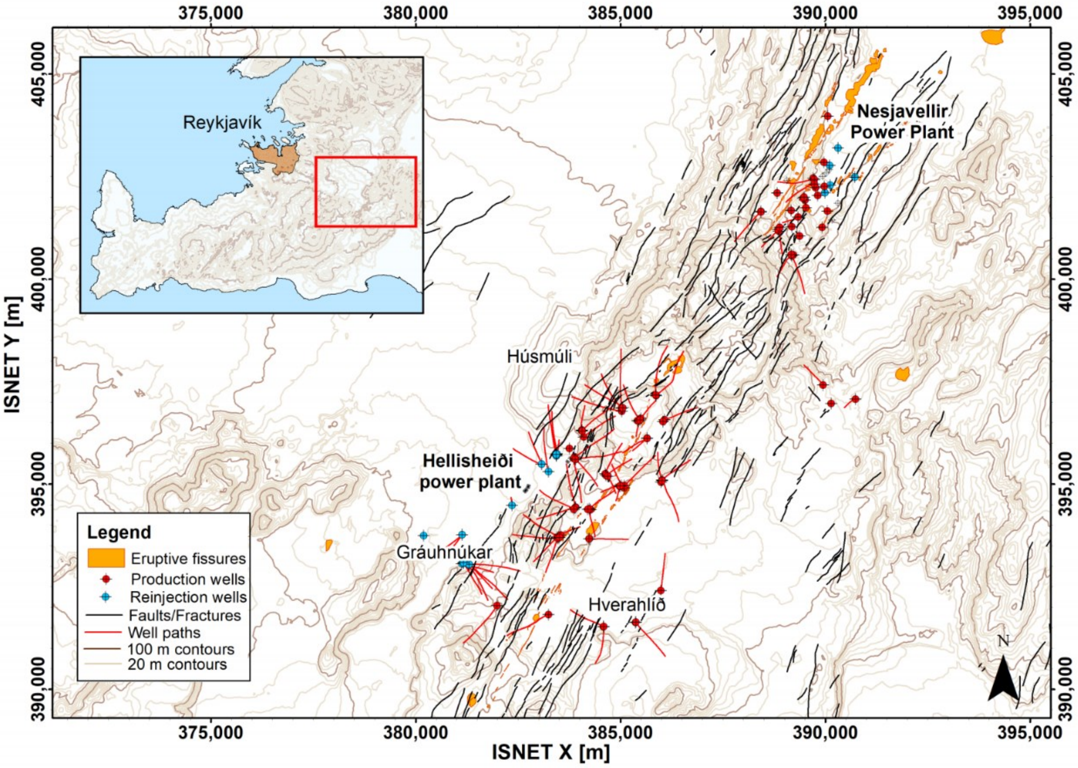


Figure 1: Map of the Hengill area showing the Húsmúli and Gráuhnúkar injection areas (Tómasdóttir, 2018).

2.2 Reinjection Regions: Húsmúli and Gráuhnúkar

2.2.1 Natural Seismicity prior to the reinjection operations

Natural seismicity occurred at the Húsmúli area before 2000. During a volcanic uplift episode, tens of thousands of events were recorded in the Hengill region from 1995 to 1998, of which more than 1000 were located in the Húsmúli zone with a maximum magnitude of M_L 3.5. Hypocentre locations from this period highlight a structure oriented NNE (i.e. same orientation as the SISZ) in the Húsmúli area (**Error! Reference source not found.**). On the contrary, natural seismicity in Gráuhnúkar in the years before drilling and injection (1995-2006) was much scarcer. Only around 200 events occurred during the 1990s uplift episode, with a maximum magnitude of M_L 2.7.

2.2.2 Induced Seismicity

The two reinjection areas, Gráuhnúkar and Húsmúli, count 9 and 8 wells, respectively (Figure 1 and 2). Gráuhnúkar has been in operation since 2006 with 6 active wells and Húsmúli since 2011 with 5 active injection wells. While the two injection regions are only 5 km apart, their seismic response to operations like drilling and injection are very different.

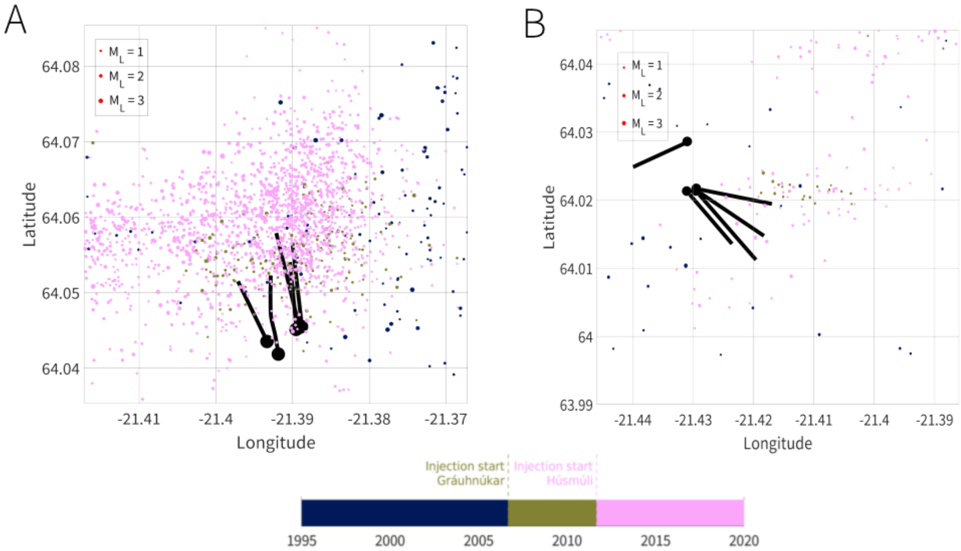


Figure 2: Map of the seismicity before 1999 (blue dots) and after 1999 (red dots). Size of dots corresponds to magnitude level. Black lines are the active reinjection wells. A) Húsmúli reinjection zone B) Gráuhnúkar reinjection zone.

Drilling in Gráuhnúkar started in 2006 with injections following soon (Hardarson et al., 2010; Flóvenz et al., 2015). No alarming increase of seismicity was observed during either the drilling or injection operations. The magnitude of most induced earthquake was lower than M_L 1.5 with the largest event recorded at M_L 2.0. The injection rate from 2006 to mid-2011 was kept around 200 L/s and was increased suddenly to 350 L/s in June 2011 before being lowered when the Húsmúli reinjection started operating in September 2011 (Hardarson et al., 2010; Gunnarsson, 2013; Flóvenz et al., 2015). With this increase in the injection rate and since 2013, the seismicity has seen a significant increase ranging from a few to ten events per month with some events above magnitude M_L 2. Despite this increase in the past six years, the seismicity in Gráuhnúkar is considered low to moderate. The injection rate is now mitigated, and seismicity seems to be taking off when the 300 L/s mark is approached (Flóvenz et al., 2015).

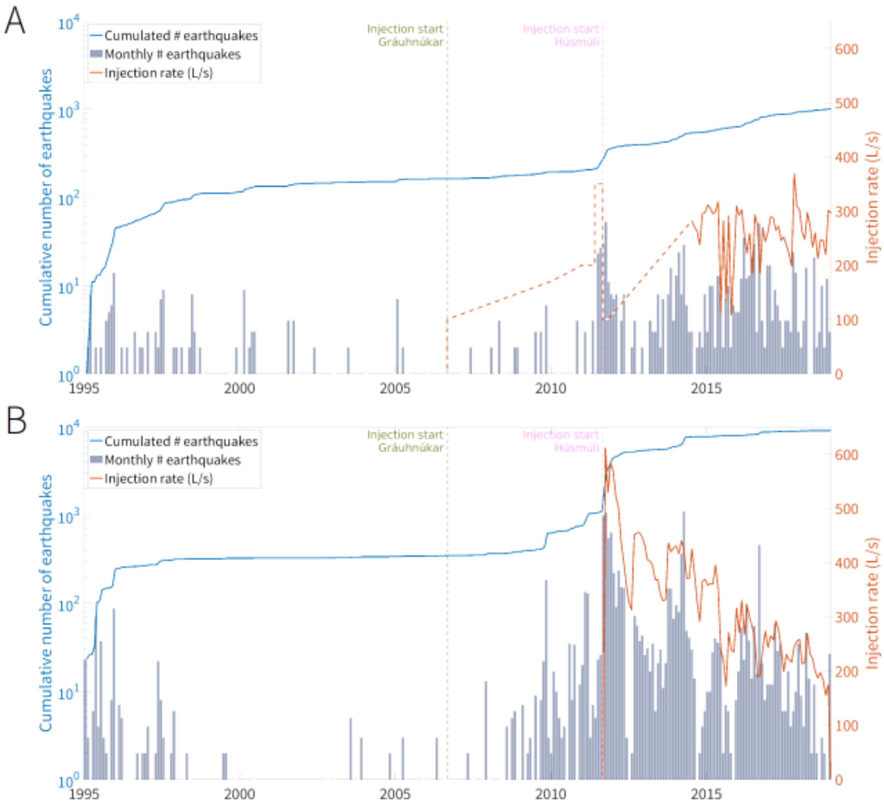


Figure 3: Injection rates, monthly and cumulative earthquakes counts since 1995 A) Gráuhnúkar reinjection zone B) Húsmúli reinjection zone.

-B presents a rough reconstructed history of the injection rates in Gráuhnúkar between 2006 and mid-2014 based on literature (Hardarson et al., 2010; Flóvenz et al., 2015). From mid-2014 on, the actual recorded injection rates are shown monthly.

In Húsmúli, drilling started in 2007 and injections in 2011. Immediately after the beginning of the drilling, an important number of seismic events were recorded by the monitoring network and felt by the population (Orkustofnun: National Energy Authority of Iceland; Hardarson et al., 2010; Gunnarsson 2013). This seismic activity has been linked to repeated circulation losses during the drilling process (Flóvenz et al., 2015). Related to injection activities, about 1900 induced earthquakes occurred between mid-September and mid-October 2011, with the largest event recorded at M_L 3.8 (Halldorsson et al., 2012). Induced seismicity in Húsmúli has been considerably reduced since 2012 thanks to the reduction of the injection flow rates (**Error! Reference source not found.**-A). Since May 2012, on average 30 events per month are recorded in Húsmúli, mostly around the wells between 1 and 4 km depth.

Differences in natural pre-drilling and induced seismicity between Húsmúli and Gráuhnúkar mirror the differences observed during drilling and injection. This could indicate structural differences (e.g. presence/absence of structures, size of structures, orientation). For instance, the presence of NNE structures in Húsmúli could drive the lateral transfer of pressure during drilling and injection and enhance the propagation of brittle failures far from the injection area.

2.3 Impact of the Geology

Húsmúli is located near the western border of the Hengill Volcanic System and closer to the main volcanic centre to the north, while Gráuhnúkar lays in a more axial position inside the Hengill fissure system. Due to this difference, Gráuhnúkar sits in an area where the top basement is deeper (1800m) compared to the Húsmúli area (1200m). Two wells in Húsmúli are within the basement (HN-09 and HN-11) and four others (HN-12, HN-14, HN-16 and HN-17) have a terminal depth near the basement interface. None of the wells in Gráuhnúkar reaches the basement although terminal depths are very similar to the Húsmúli wells (Figure 4). Seismicity in Húsmúli is localized around the wells between 1km and 4km, occurring mainly in the basement which could suggest a link between injection into the basement faults and induced seismicity.

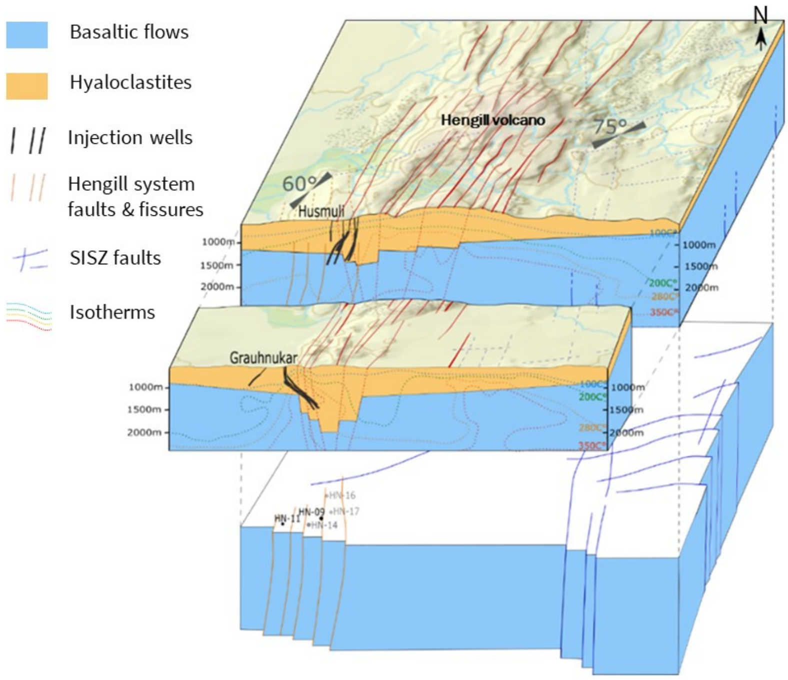


Figure 4: 3D conceptual model of the Hellisheiði area featuring the reinjection zones of Húsmúli and Gráuhnúkar.

2.4 Impact of the Stress Field

Variations of induced seismicity can be linked to a spatially heterogeneous stress field or variations of stress values with time. Unfortunately, information on the stress field in Hellisheiði is rather scarce. We rely on a published study of in-situ measurements carried out in one well in Húsmúli (HN-16) (Batir et al., 2012), published focal mechanisms around the Hellisheiði area and an extensive database of recently derived focal mechanisms for Húsmúli made available by ISOR (Iceland Geo-Survey).

In-situ well measurements show a S_{Hmax} oriented N22°±5° for borehole breakouts identified in the range 1000-2000mMD (Batir et al. 2012). The magnitudes of stresses could not be estimated within an acceptable range of uncertainties using well in-situ measurements.

The inversion of focal mechanisms for induced seismicity in Húsmúli yielded a rather uniform stress state for the period September 2011-May 2012. This period corresponds to the beginning of injection and the highest levels of induced seismicity recorded in Húsmúli. The mean principal stress σ_1 is oriented N40°28' with a mean stress ratio R=0.35. This corresponds to a strike-slip to normal stress state, which is consistent with the dual nature of the tectonic setting in Hengill at the junction between RVB and SISZ (Ágústsson et al., 2015).

3. PRELIMINARY MODELLING OF HÚSMÚLI INDUCED SEISMICITY

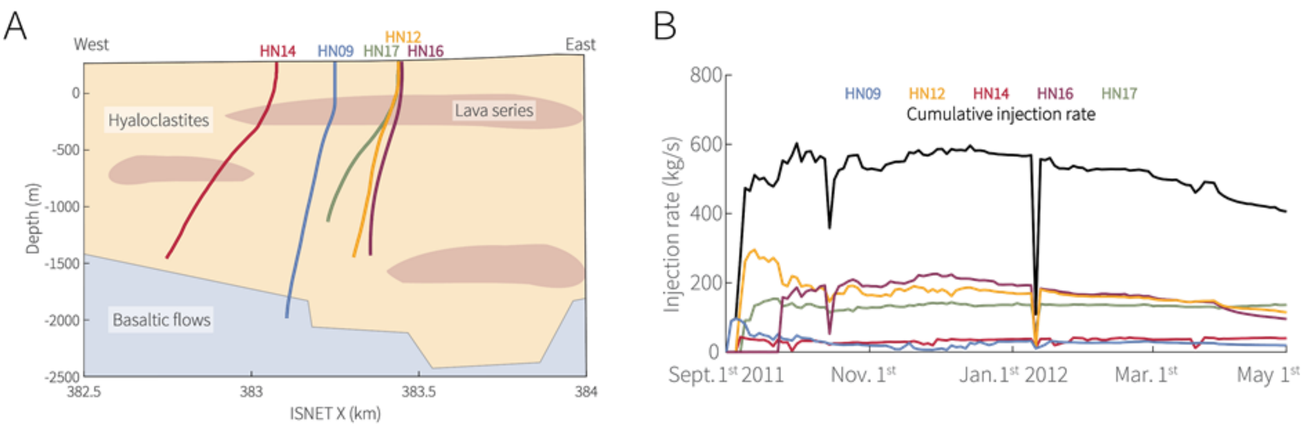
Based on some previous modelling activities for geothermal in Iceland and in particular the Hengill area, we adopted TOUGH2 as fluid flow simulator. The large scale TOUGH2 model for the Hengill geothermal field was provided by Reykjavik Energy (Bjornsson et al., 2003; Gunnarsson et al., 2011; Gunnarsson & Aradóttir, 2015; Aradóttir et al., 2015; Tómasdóttir, 2018).

Well	Coordinates injection (Tough model)		
	ISNET X	ISNET Y	Depth (m)
HN09	3.831E+05	3.96134E+05	1900
HN12	3.833E+05	3.96480E+05	1550
HN14	3.828E+05	3.96307E+05	1550
HN16	3.834E+05	3.96654E+05	1550
HN17	3.833E+05	3.96567E+05	1250

Table 1: Representation of wells feed-zones in the TOUGH2 model.

This preliminary study focuses on the Húsmúli reinjection zone located in the South of the Hengill geothermal field. Five wells are actively reinjecting spent-water and range in depths from 1.2 to 1.9 km, with only HN-09 reaching the consolidated basaltic flows (Table 1). The history of hydraulic injection for the modelled period is shown in Figure 5-B (data provided by Reykjavik Energy). The reinjection activities occurred with large flow rate at well HN-12 at the beginning, with HN-16 and HN-17 reaching a similar flow rate after a month (Figure 65-B). HN-14 is situated West of the other wells and receives lower injection rates. The deepest well, HN-09, penetrates the consolidated basaltic layer that has a lower permeability than the hyaloclastites, leading to its injectivity being lower (Figure 55-A and 5-B). The total cumulative flow rate in the field reaches a maximum of about 600 kg/s in the analysed period.

The study period covers 8 months from September 1st 2011 to May 1st 2012, covering the beginning of reinjection in the Húsmúli region. We chose to perform the preliminary modelling on this period since it is the one that has seen a large amount of seismicity recorded in the area (



-A) and is of particular interest because it is the effective start of a consistent activity in the 5 wells.

Figure 5: A) Conceptual geological model with localisation of the injection wells in the Húsmúli reinjection zone B) Injection rates in Húsmúli for the modelled period.

We employ the coupled hydro-geomechanical-stochastic simulator TOUGH2-SEED (Rinaldi and Nespoli, 2017). This hybrid model has demonstrated its potential for modelling fluid-induced seismicity in a geothermal setting and its capacity to reproduce real data.

3.1 Model set-up

The field-scale TOUGH2 model for Hengill covers an area of 50 km by 50 km with a depth of 3000 m. It comprises nearly 43.000 elements categorised into 43 reservoir domains. The mesh is centred around the production areas West of Húsmúli, with a refinement of the grid in the centre. 129 production and 31 injection time series cover almost 7 years of hydraulic data.

The TOUGH2 regional model is first ran until steady-state is obtained (Bjornsson et al. 2003; Gunnarsson et al., 2011; Aradóttir et al., 2012; Tómasdóttir, 2018). In Figure 6, we show the initial conditions in pressure (Figure 66-A) and temperature (Figure 6-B) for a radius of 10 km around Húsmúli. These initial conditions correspond to the state of the reservoir on September 1st 2011 before injections start in Húsmúli. The high-temperature zone visible in Figure 6-B sits under one of the main production zones of the Hellisheiði area.

The seeds (potential rupture points/hypocentres) are distributed in the vicinity of the injection zone of the 5 injection wells, within a 1 km radius of their geographical centre. The pressure solution is given by the TOUGH2 model and then passed to the geomechanical model to determine if failure occurs at each time step based on a Mohr-Coulomb criterion. This preliminary coupled modelling does not account for permeability changes at this point, nor for earthquake interactions. 300.000 potential rupture points are distributed in a cube with side 1 km centred around the geographical centre of the injection points.

To account for the stochasticity of the seismicity module, we run 300 single realisations with the same pressure solution and average the results on the set of realizations, by stochastically varying the seeds position, orientation, friction coefficient, and local stress conditions. We employ a full 3D stress state of the reservoir based on field measurements (Batir et al. 2012). The stresses are assigned on the seeds using a simple fraction of the applied vertical stress, with S_{Hmax_ratio}=1.46 and S_{hmin_ratio}=0.55 in keeping with focal mechanism observations and the stress measured in wells (Batir et al., 2012). The seeds are oriented at 40°N ± 20° to capture the orientation of the Hengill fissure swarm (30°N) and the normal faults observed specifically in Húsmúli (40-60°N).

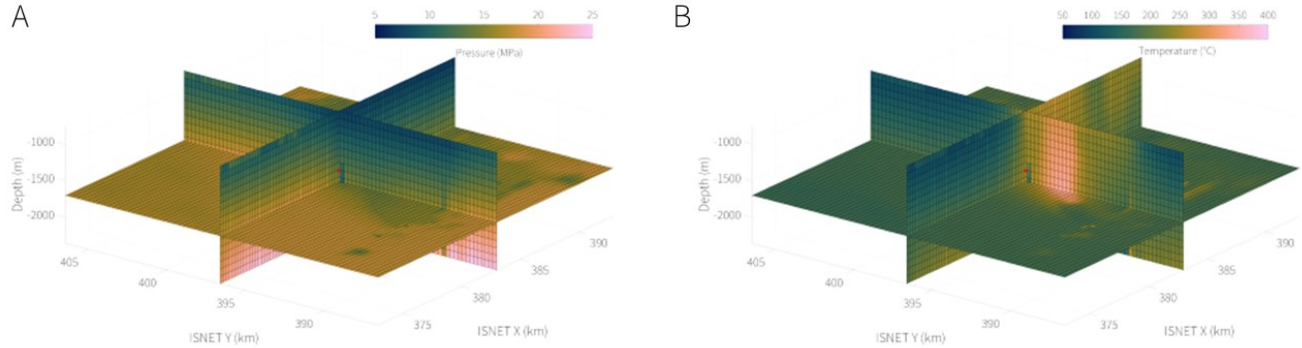


Figure 6: Initial conditions of pressure and temperature before the start of reinjection on September 1st 2011, centred around the Húsmúli reinjection zone (red dot).

3.2 Pressure and temperature evolution

Starting from the initial conditions above, we run a TOUGH2 simulation on the domain with the 5 wells actively injecting for 8 months using daily averages of the injected rate (Figure 5-B). All wells outside the Húsmúli area are turned off to focus on the direct effects of the injection. Even though we do run for the whole geometry of the regional TOUGH2 model, we focus on the immediate surroundings of Húsmúli, limiting the output to a 1.5 km radius around injections.

Physical variables (pressure, temperature, vapour saturation) are monitored during the month-long injection. After the 8 months of injection, pressure and temperature in the surroundings of Húsmúli are compared to the pre-stimulation values obtained with the steady-state (Figure 7). Temperature is decreased significantly by the injection in the vicinity of the injection points and along the well paths especially around wells HN12, HN16 and HN17 (Figure 7-B). The pressure is significantly increased at depth on a larger area (Figure 7-A).

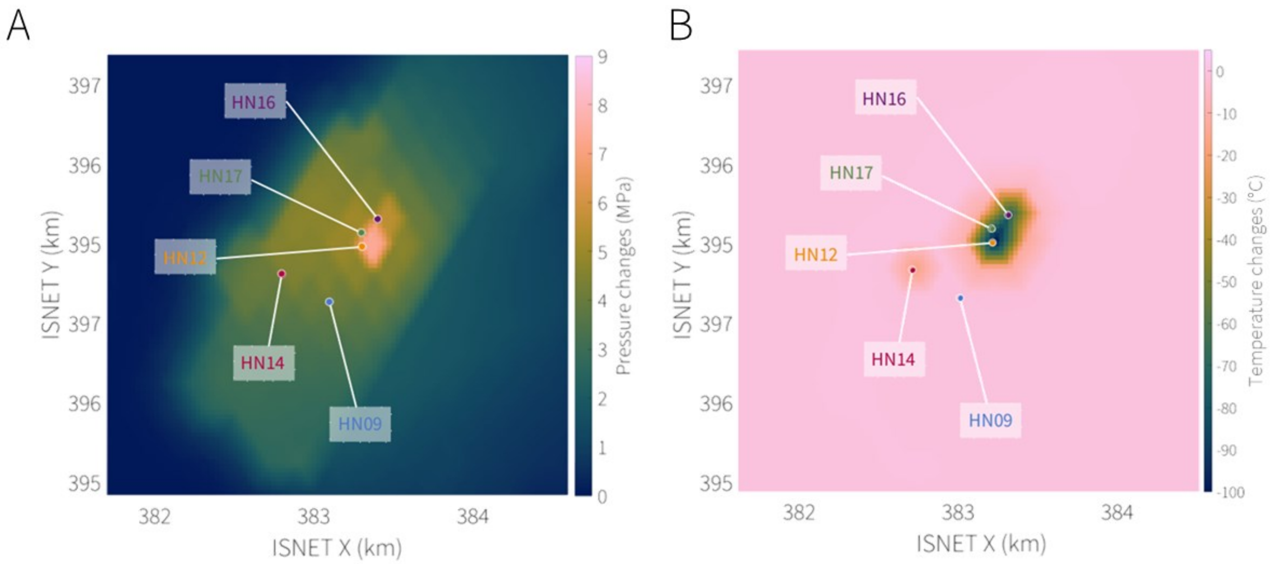


Figure 7: Changes in pressure (A) and temperature (B) in Húsmúli after 8 months of injection.

3.3 Simulated seismicity

The cumulative number of induced events and seismicity rates are shown in Figure 8**Error! Reference source not found.**. Seismicity increases with the onset of injection, marking a slight delay from the start of injection to the first simulated events, to then reach a maximum rate per day above 50 events. The rates then decrease as the injection rate stabilizes and decreases. The decrease of seismicity after the initial outburst seems to match reported decreases in the number of recorded events with the stabilisation and decrease of the injection rate in late 2011 and 2012 (Gunnarsson, 2013; Flóvenz et al., 2015).

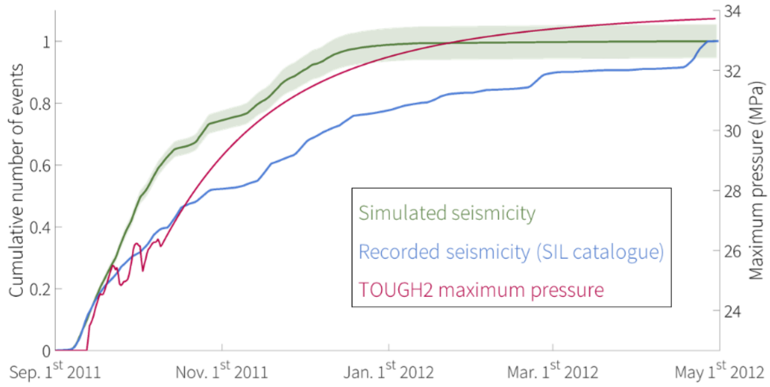


Figure 8: Comparison of modelled and observed seismicity: temporal evolution of the modelled maximum reservoir pressure and cumulative seismicity compared to the recorded cumulative seismicity.

Figure 9 presents a comparison of the recorded and modelled the spatial spread of seismicity. The anisotropy of the area is highlighted with the diagonal alignment of the seismicity cloud in the modelled seismicity (Figure 9-B ; for an isotropic model with no permeability changes such as the one we are using, a homogeneous distribution of events around injection would be expected). This anisotropy was already observed in the pressure changes resulting from the injection (Figure 7-A). The region recording the highest density of seismicity (North of the Húsmúli wells in Figure 9-A) highlights the underlying geological structures of Húsmúli. Normal faults striking 40 to 60° North compete with the Hengill fissure swarm striking 30° North and act a pressure paths leading to seismicity occurring far from the injection wells. Our model (Figure 9-B) is not taking into account the major structures at this point and only simulates seismicity within a kilometre of the injection wells leading to the localised seismicity cloud around the injection wells presented in the modelled catalogue. Furthermore, our model only accounts for pressure-related seismicity and does not include permeability changes or static stress transfer which have been shown to be driving seismicity along faults. Further modelling work will expand the seismogenic zone and include physical faults to better reproduce the observed seismicity patterns.

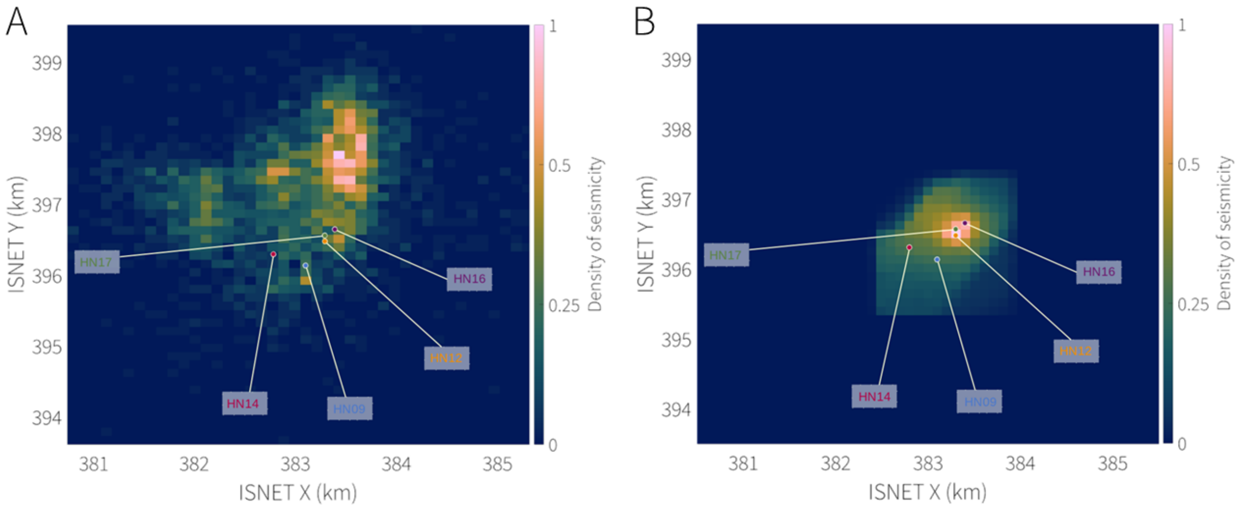


Figure 9: Comparison of modelled and observed seismicity: observed (A) and modelled (B) density of seismicity.

4. CONCLUSION AND PERSPECTIVES

Differences in the geological setting of reinjection areas Húsmúli and Gráuhnúkar provide the first clue as to why these two areas have distinct operation-induced seismicity sequences. The preliminary numerical modelling of an 8 months long injection sequence in Húsmúli opens the way for comparison of the physical processes at play. A comparison of modelled induced sequences to the recorded seismicity will be conducted to tune the TOUGH2-Seed model to fit past data. Similar simulations will be performed for both reinjection regions of Húsmúli and Gráuhnúkar in the hope of understanding better the physical phenomena at play in the different induced seismicity responses to injection and drilling operations. Future modelling will include physical hydraulic faults to match geological faults mapped in the different regions.

In time, the acquired knowledge on reinjection regions' seismic behaviour to drilling and injection will prove vital in the implementation of an adaptive data-driven tool to manage and mitigate the risk posed by induced earthquakes. This ATLS tool (Adaptive Traffic Light System) integrates the entire processing chain, from automated picking of waveforms and data processing to seismic hazard and risk forecasting, and evaluation of possible injection scenarios for their seismic potential and stimulation efficiency. The COSEISMIQ project aims at demonstrating the benefits of RISC to help guide the decision process of geothermal power plant operators.

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REFERENCES

Ágústsson, K., Kristjánsdóttir, S., Flóvenz, Ó. G., & Gudmundsson, O. (2015). Induced Seismic Activity during Drilling of Injection Wells at the Hellisheiði Power Plant, SW Iceland. In Proceedings World Geothermal Congress.

Aradóttir, E. S. P., Sonnenthal, E. L., Björnsson, G., & Jónsson, H. (2012). Multidimensional reactive transport modeling of CO2 mineral sequestration in basalts at the Hellisheidi geothermal field, Iceland. International Journal of Greenhouse Gas Control, 9, 24-40.

Batir, J., Davatzes, N. C., & Asmundsson, R. (2012). Preliminary model of fracture and stress state in the Hellisheidi Geothermal Field, Hengill Volcanic System, Iceland. In Proceedings of the Thirty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford.

Bjornsson, G., Hjartarson, A., Bodvarsson, G. S., & Steingrimsson, B. (2003, May). Development of a 3-D geothermal reservoir model for the greater Hengill volcano in SW-Iceland. In Proceedings: TOUGH Symposium (pp. 1-11).

Dinske, C., & Shapiro, S. A. (2013). Seismotectonic state of reservoirs inferred from magnitude distributions of fluid-induced seismicity. Journal of seismology, 17(1), 13-25.

Flóvenz, O. G., Ágústsson, K., Guðnason, E. Á., & Kristjánsdóttir, S. (2015, April). Reinjection and induced seismicity in geothermal fields in Iceland. In Proceedings of world geothermal congress.

Franzson, H., Kristjánsson, B. R., Gunnarsson, G., Björnsson, G., Hjartarson, A., Steingrímsson, B., ... & Gíslason, G. (2005, April). The Hengill-Hellisheiði geothermal field. Development of a conceptual geothermal model. In Proceedings world geothermal congress (pp. 1-7). Antalya.

Gischig, V. S., and Wiemer, S. (2013). A stochastic model for induced seismicity based on non-linear pressure diffusion and irreversible permeability enhancement. Geophys. J. Int., 194(2), 1229–1249.

Grigoli, F., Cesca, S., Priolo, E., Rinaldi, A. P., Clinton, J. F., Stabile, T. A., ... & Dahm, T. (2017). Current challenges in monitoring, discrimination, and management of induced seismicity related to underground industrial activities: A European perspective. Reviews of Geophysics, 55(2), 310-340.

Grigoli, F., Cesca, S., Rinaldi, A. P., Manconi, A., López-Comino, J. A., Clinton, J. F., ... & Wiemer, S. (2018). The November 2017 Mw 5.5 Pohang earthquake: A possible case of induced seismicity in South Korea. Science, 360(6392), 1003-1006.

Gunnarsson, G., Arnaldsson, A., & Oddsdóttir, A. L. (2011). Model simulations of the Hengill area, Southwestern Iceland. Transport in porous media, 90(1), 3-22.

Gunnarsson, G. (2013). Temperature Dependent Injectivity and Induced Seismicity–Managing Reinjection in the Hellisheiði Field, SW-Iceland. GRC Transactions, 37, 1020-1025.

Gunnarsson, G., & Aradóttir, E. S. (2015). The deep roots of geothermal systems in volcanic areas: boundary conditions and heat sources in reservoir modeling. Transport in Porous Media, 108(1), 43-59.

Gunnarsson, G., Kristjánsson, B. R., Gunnarsson, I., & Júlíusson, B. M. (2015). Reinjection into a fractured reservoir—induced seismicity and other challenges in operating reinjection wells in the Hellisheiði Field, SW-Iceland. In Proceedings world geothermal congress.

Halldorsson, B., Olafsson, S., Snaebjörnsson, J. T., Sigurosson, S. U., Rupakhety, R., & Sigbjörnsson, R. (2012). On the effects of induced earthquakes due to fluid injection at hellisheidi geothermal power plant, Iceland. Proc. 15th WCEE, Lissabon, Portugal.

Hardarson, B. S., Einarsson, G. M., Kritsjánsson, B. R., Gunnarsson, G., Helgadóttir, H. M., Franzson, H., ... & Gunnlaugsson, E. (2010, April). Geothermal reinjection at the hengill triple junction, SW Iceland. In Proceedings World Geothermal Congress, Bali, Indonesia (pp. 25-29).

Hjörleifsdóttir et al., 2019. Induced earthquakes in the Hellisheiði geothermal field, Iceland. 3rd Schatzalp Workshop on Induced Seismicity.

Hofmann, H., Zimmermann, G., Farkas, M., Huenges, E., Zang, A., Leonhardt, M., ... & Fokker, P. (2019). First field application of cyclic soft stimulation at the Pohang Enhanced Geothermal System site in Korea. Geophysical Journal International, 217(2), 926-949.

Kristjánsson, B. R., Axelsson, G., Gunnarsson, G., Gunnarsson, I., & Óskarsson, F. (2016). Comprehensive tracer testing in the Hellisheidi Geothermal Field in SW-Iceland. In Proceedings, 41st Workshop on Geothermal Reservoir Engineering (Vol. 730).

Kwiatek, G., Saarno, T., Ader, T., Bluemle, F., Bohnhoff, M., Chendorain, M., ... & Leonhardt, M. (2019). Controlling fluid-induced seismicity during a 6.1-km-deep geothermal stimulation in Finland. Science advances, 5(5), eaav7224.

Lee, K. K., Ellsworth, W. L., Giardini, D., Townend, J., Ge, S., Shimamoto, T., ... & Chang, C. (2019). Managing injection-induced seismic risks. Science, 364(6442), 730-732.

Rinaldi, Antonio Pio & Nespoli, Massimo. (2016). TOUGH2-Seed: a coupled fluid flow and mechanical-Stochastic approach to model injection-induced seismicity. Computers & Geosciences. 108. 10.1016/j.cageo.2016.12.003.

Shapiro, S. A., & Dinske, C. (2009). Fluid-induced seismicity: Pressure diffusion and hydraulic fracturing. Geophysical Prospecting, 57(2), 301-310.

Tómasdóttir, S. (2018). Flow Paths in the Húsmúli Reinjection Zone, Iceland.

Vilarrasa, V., Rinaldi, A. P., & Rutqvist, J. (2017). Long-term thermal effects on injectivity evolution during CO2 storage. International Journal of Greenhouse Gas Control, 64, 314-322.