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# Heat Transfer and Flow Paths in the Deep Part of the IDDP-2 Well in Reykjanes, SW Iceland

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## ABSTRACT

Generally, it is assumed that the main mechanism that transfers heat from heat sources of volcanic geothermal systems is driven by a Convective Downward Migration (CDM) process: a cooling front, driven by convecting water, migrates into hot rock through fractures that open up due to thermo-elastic contraction by cooling of the rock. Drilling into superheated formations in Iceland has revealed extensive fluid losses at depth for reasons that are not fully understood. A possible mechanism is that, as in the CDM process but on much shorter timescale, the introduction of cold drilling fluids leads to thermo-elastic contraction of the rock that opens fractures to significantly enhance the fluid injectivity.

In the present study the focus is on the deep part of the Reykjanes geothermal system, on seismic events induced during drilling and stimulation of the IDDP-2 well and other data that can reveal the permeability structure and flow paths below the present production field. Double-difference earthquake relocations during drilling and stimulation of the well, i.e. from August 2016 to end of September 2017 map possible flow paths stimulated by injection of fluids. The mapped flow pathways can be used to restrain thermo-hydro-mechanical models of the proposed conditions that enhance permeability by opening of fractures. The results will be used in an ongoing study of the CDM process and possible effect on heat transfer close to the IDDP-2 well.

## 1. INTRODUCTION

The second well of the Iceland Deep Drilling Project (IDDP) was drilled in the Reykjanes geothermal area in 2016 and 2017 by HS Orka Ltd. with the support of IDDP project consortium and H2020 funded project DEEPEGS. In January 2017 measurements confirmed the well reached critical conditions at the slant depth of 4659 m (the vertical dept of approximately 4.5 km) (Fridleifsson et al., 2017). After completion of the well in February 2017 it was submitted to cold water injection until August 2018, when it was allowed to heat-up partly with injection of geothermal water from the injection system of the Reykjanes power plant and then finally allowed to heat-up from October 2018. The present plan is to production test the well in October 2019 (Fridleifsson et al., 2019). The drilling and stimulation of the well has already provided valuable data about the temperature and permeability at depth in the Reykjanes geothermal field.

The exploitation of Reykjanes geothermal field goes back to 1968 with separation of mineral salts from the geothermal brine. In the 1990's, Hitaveita Suðurnesja (Reykjanes District Heating), now HS Orka, acquired the development of the geothermal field and drilled its first well for electrical generation in 1998. It was not until 2006 HS Orka commissioned the Reykjanes power plant with a generation capacity of 100 $MW_e$. Since 1956, a total of 34 wells have been drilled in Reykjanes for exploration, production, or geothermal re-injection. The conceptual model of the geothermal system is described by Thorbjornsson et al., (2014) and Khodayar et al. (2016; 2018). Before the drilling of the IDDP-2 well, the deepest production wells in Reykjanes reached down to about 2.5 km.

Deep drilling in high-temperature geothermal systems by the Iceland Deep Drilling (IDDP) project (Fridleifsson et al., 2014) is aimed at increasing the power output of high-temperature geothermal fields by an order of magnitude without increasing their environmental footprints. The drilling of two wells within the project has opened a window to look into the deeper parts of the geothermal systems and study the nature of their roots; that is, their heat sources. The first, drilled in Krafla, unexpectedly encountered magma at only 2.1 km depth and became the world's hottest production well at the time, yielding more than 450°C **superheated** steam (Elders et al., 2014).The second, drilled in the Reykjanes geothermal field in Iceland, reached a total depth of 4.5 km in January 2017, achieving the main objective of the IDDP project by reaching **supercritical** conditions (Fridleifsson et al., 2017).

In an ongoing research project at the University of Bergen, SiGS (**S**upercr**i**tical and Superheated **G**eothermal **S**ystems - coupled subsurface deformation and convective heat transfer), data from both the IDDP sites is being used to study mechanisms that affect heat transfer in vicinity of the geothermal heat sources. Drilling of the IDDP-2 well resulted in total loss of circulation below 3.2 km depth (Fridleifsson et al., 2017) and one of the SiGS's research questions is if the introduction of cold drilling fluids leads to thermo-elastic contraction of the rock that opens fractures to significantly enhance the fluid injectivity. This is further supported by the induced seismicity below 3.5 km depth during the drilling of the well (Gudnason et al., 2020).

## 2. HEAT TRANSFER IN HIGH TEMPERATURE GEOTHERMAL SYSTEMS

High temperature geothermal systems exist in volcanically active areas and their heat sources are believed to be cooling magma chambers or intrusions deep in the systems (Figure 1). To explain the high energy output from the systems, both transient heat sources like intrusions and direct contact between the geothermal fluids and the hot boundary rock of the magma have been proposed, see for example Bodvarsson (1948) and Bjornsson and Stefansson (1987). Furthermore, this contact will need to be maintained over the lifetime of the activity to fully explain the high energy outputs of the systems over long time scales (Bodvarsson, 1982; Bjornsson et al., 1982). The main reason is that during solidifying of magma intrusions, poorly permeable, solidified rock will insulate the magma from the hydrothermal system above. This layer of solidified rock will thicken with time, lowering heat output from the intrusion with time as well (Bjornsson and Stefansson, 1987). Therefore, either intrusive intensity needs to be quite high or water needs to penetrate into the rock boundary (solidified rock) by some mechanism. Bodvarsson (1982) demonstrated the first to be a rather unlikely mechanism for hydrothermal systems in Iceland.

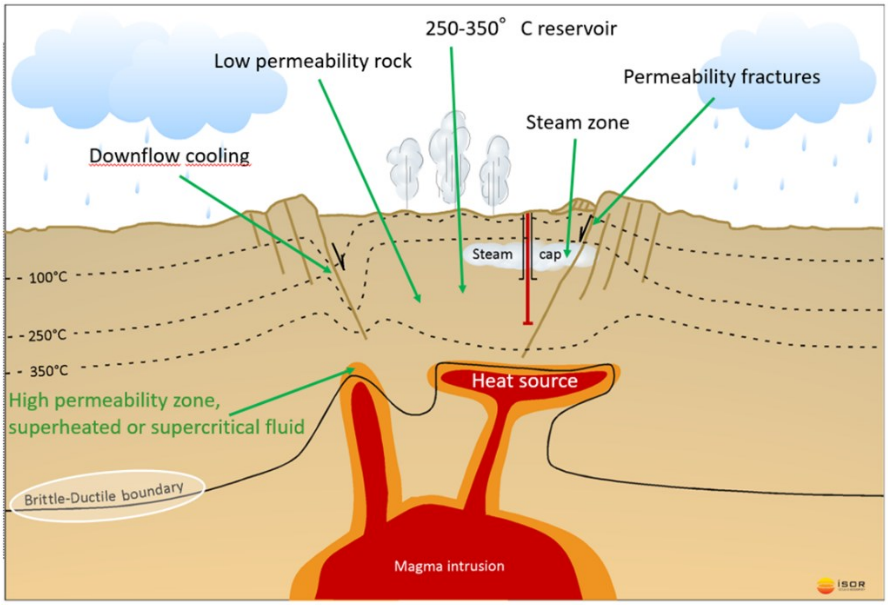


**Figure 1: Sketch of a typical high temperature geothermal system showing speculated high permeable zone close to the heat sources.**

### 2.1 Convective Downward Migration

Generally, it is assumed that the main mechanism that transfers heat from heat sources of volcanic geothermal systems is driven by a Convective Downward Migration (CDM) process. In this process a cooling front, driven by convecting water in the hydrothermal system, migrates into hot boundary rock of magma, through fractures that open up due to thermoelastic contraction and thermomechanical fracturing induced by cooling of the rock (Lister, 1974; Bodvarsson, 1982). This process transports thermal energy, derived from the cooling magma, by convection in the fractures that connects with the hydrothermal systems. Figure 2 shows Lister's 1-D cracking front model. The cooling front moves downward into the hot rock and heat is swept out with the circulation of geothermal fluid in the fractures that open up due to thermal contraction of the surrounding rock. The process is driven by the temperature difference between the fluid and the hot boundary rock, causing a volume of the rock to cool down and contract because of the thermal stress induced.

The CDM process can either be described as fully thermomechanical or purely thermoelastic, with the first case describing thermomechanical cracking of the rock and second case describing thermal contraction around an already existing fracture in the rock (Figure 4). A solution to the thermoelastic problem in 2-D has been described by Axelsson et al. (1985). A possible solution to the thermomechanical problem, including fracture, has been described by Lister (1974) but remains to be tested further as he himself describes his work as an attempt to make a first-order examination of the most likely physical processes.

The CDM process has been incorporated approximately in numerical models of volcanic geothermal systems by increasing the permeability near the heat sources, conceptually depicted in Figure 1 and Figure 2. This has been achieved by either setting it as function of temperature, and increasing it at temperatures slightly over the solidus temperature of magma (Thorgilsson et al., 2018; Scott et al., 2018), Figure 3a), or by inserting a horizontal layer of high permeability overlaying a low permeable hot boundary layer representing the heat source, Figure 3b) (Thorgilsson et al., 2018; Kissling and Weir, 2005). Case studies within the Deep Roots of Geothermal System (DRG) project (Ingólfsson et al., 2016) used data sets obtained during drilling and testing of the first IDDP well in Krafla geothermal system to test both methods. In the models, both approaches to altering the permeability deep in the system enable water to circulate through layers representing hot boundary rock, resulting in more heat uptake by the convective fluids in the model, obtaining conditions in shallow layers that are fully comparable to known conditions in the shallow geothermal reservoirs in Krafla located close to the IDDP-1 well (Thorgilsson et al., 2018). This supports the theory that water is, by a mechanism such as the CDM, circulated deep in the systems. The resulting heat transport could explain the existence of geothermal systems above magmatic sources.

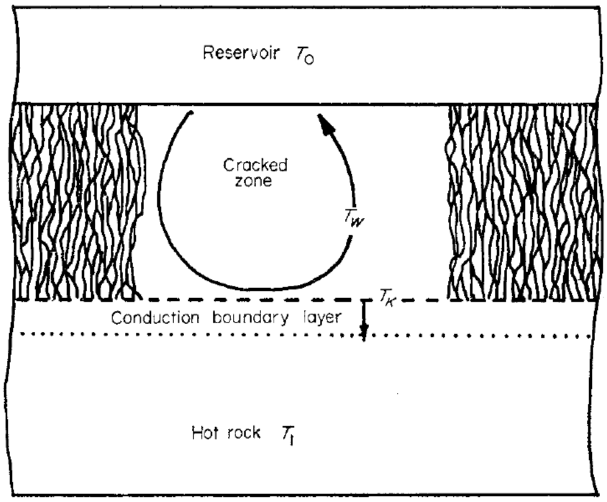


**Figure 2: Lister's 1D cracking front model where reservoir $T_0$ and hot rock $T_1$ is supplied at time equals 0. From Lister (1974).**

Results of simple calculations show that the process could contribute significantly to the heat output of the IDDP-1 well (Halldórsdóttir et al., 2019). These results however depend on the assumption that either: 1) the permeability near the bottom is due to CDM process only, or 2) that the heat flux is due to CDM process only. This is considered unlikely and further thermomechanical modelling of the conditions above the intrusion is needed. In the future, the ongoing SiGS project will investigate this by modelling the processes that lead to the alterations of permeability above crustal heat sources.

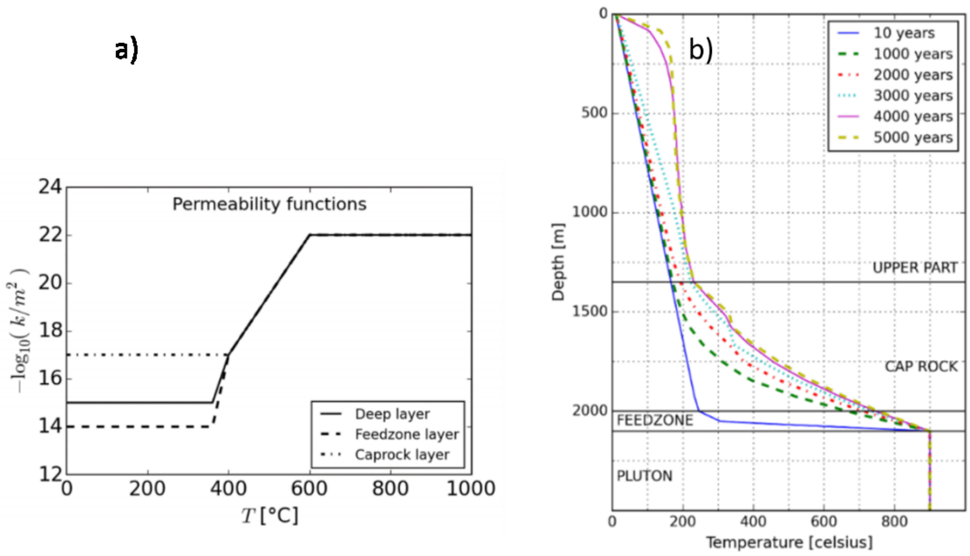


**Figure 3: Variations of permeability with depth in numerical models, with a) temperature and b) represented by different formation type, i.e. upper part, cap rock, feedzone and pluton, in the Krafla DRG project's case study. From Thorgilsson et al. (2018).**

### 2.2 Thermoelastic Contraction

The core of the CDM theory, for volcanic geothermal systems, is that a cracking front moves into the poorly permeable, conductive layer that seals off the magma from the permeable rock of the reservoir (shown as "Conduction boundary layer" in Figure 2). Existing fractures open or new ones form by cracking of this boundary layer. Water from the hydrological system above then circulates in the fracture, causing temperature to drop in a volume surrounding the fracture as is shown schematically in Figure 4. This cooling results in thermal stress and contraction of the rock, which in turn causes the cracking front to penetrate further into the conductive layer. Therefore, the migration of the cracking front downwards in the system can also be represented as a cooling front moving downwards.

The complete effect is then that the cracking moves downwards into the conductive layer, the magma cools from above and the conductive boundary layer of the magma progresses downwards, leaving a cracked, permeable zone (Figure 2), where water is circulating and transferring heat from the boundary layer of the magma to the geothermal system (Figure 1). This process enhances heat transfer from the hot boundary rock of the magma, resulting in more heat transfer from the heat sources than if the conductive layer would remain uncracked. In the latter case, heat would be transferred only by conduction through the layer that will thicken over time due to solidification of the rock. This process of heat conduction alone is too slow to explain the existence of geothermal systems above magmatic heat sources (Bodvarsson, 1982; Bjornsson et al., 1982).

Drilling into superheated formations in Reykjanes has revealed extensive fluid losses at depth for reasons that are not fully understood. A possible mechanism is that, as in the CDM process but on much shorter timescale, the introduction of cold drilling fluids leads to thermo-elastic contraction of the rock that opens fractures to significantly enhance the fluid injectivity.

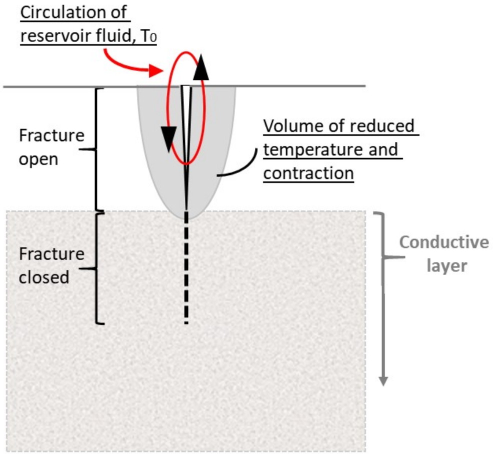


**Figure 4: Circulation of water in an existing fracture and volume of reduced temperature in the rock enclosed. Adapted from Lister (1974) and Axelsson (1985).**

2.2.1 Numerical approaches

Numerical simulations can be employed to give further insight into the thermomechanical problem of CDM. Of particular interest are simulation tools based on Discrete Fracture Matrix (DFM) model principles, which offer high resolution of dynamics in fractures and of fracture-matrix interaction (Berre et al., 2018). DFM models can incorporate hydro-thermomechanical processes and accommodate dynamic fracture permeabilities. In the future, the ongoing project will investigate this approach by employing the open-source simulation tool PorePy (Keilegavlen et al., 2017), which is based on DFM principles.

## 3. PERMABILITY BELOW 3 KM IN THE IDDP-2 WELL

Drilling operations for well IDDP-2 began by deepening of existing production well RN-15 in the northeast part of the production field (Figure 5). The well was drilled down to 3000 m and a new production casing was cemented down to 2932.4 m (Weisenberger et al., 2016). The well was drilled vertically from 2500 m down to 2750 m, and below that drilled directionally to the southwest to intersect the main upflow zone of the Reykjanes system. The bottom of the well is at a vertical depth of about 4500 m, situated 738 m southwest of the wellhead. The well track and location of main feed zones as detected during drilling are shown in Figure 5. The well reached supercritical conditions (reservoir with water temperatures above 374˚C and pressure above 222 bar) in January 2017 (Fridleifsson et al., 2017). After completion of the well in February 2017 the well was stimulated by injection of cold water resulting in the induced micro-seismicity further discussed in Section 4.

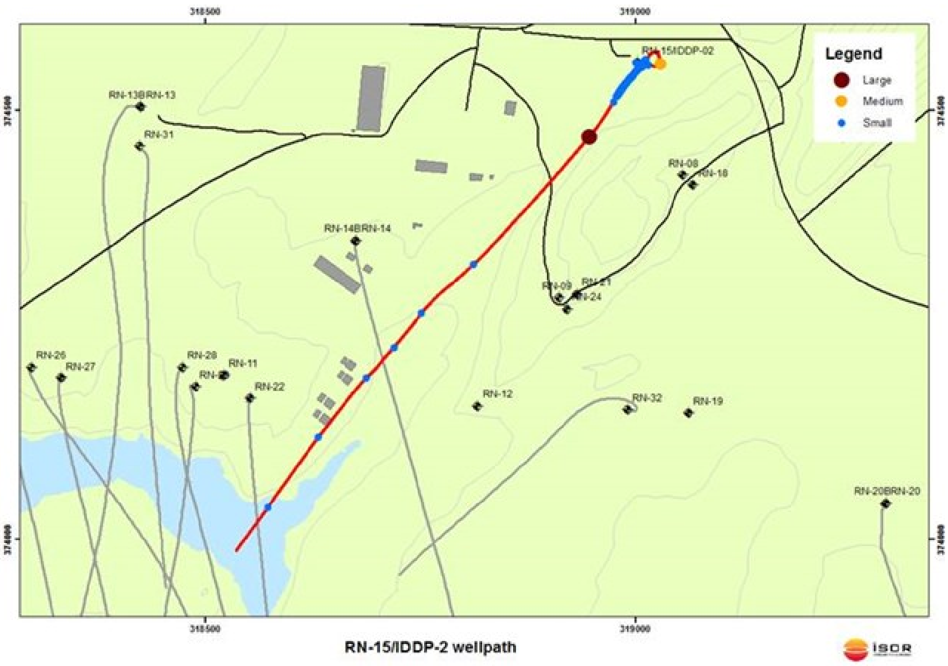


**Figure 5: Location of RN-15/IDDP-2 and main feed zones as reported in ÍSOR drilling report (Weisenberger et al., 2017).**

Increasing circulation losses below 3.0 km depth in the IDDP-2 well, and a total loss of circulation from around 3.2 km depth indicate the high permeability at this depth, with several more permeable zones identified in ÍSOR's well reports down to around 4.6 km slant depth (Weisenberger et al., 2017). The main feed zones can also be determined by analyzing the logged temperature in the well shown in Figure 6. The figure shows the two temperature logs from January 2017 that confirmed the supercritical conditions at the bottom of the well. Feed zones are detected at about 3400 m, 4250 m, 4350 m and 4550 m slant depth. This clearly indicates permeability below the conventional production field in Reykjanes but prior to the drilling of the IDDP-2 well the deepest production wells had reached a depth of about 2500 m.

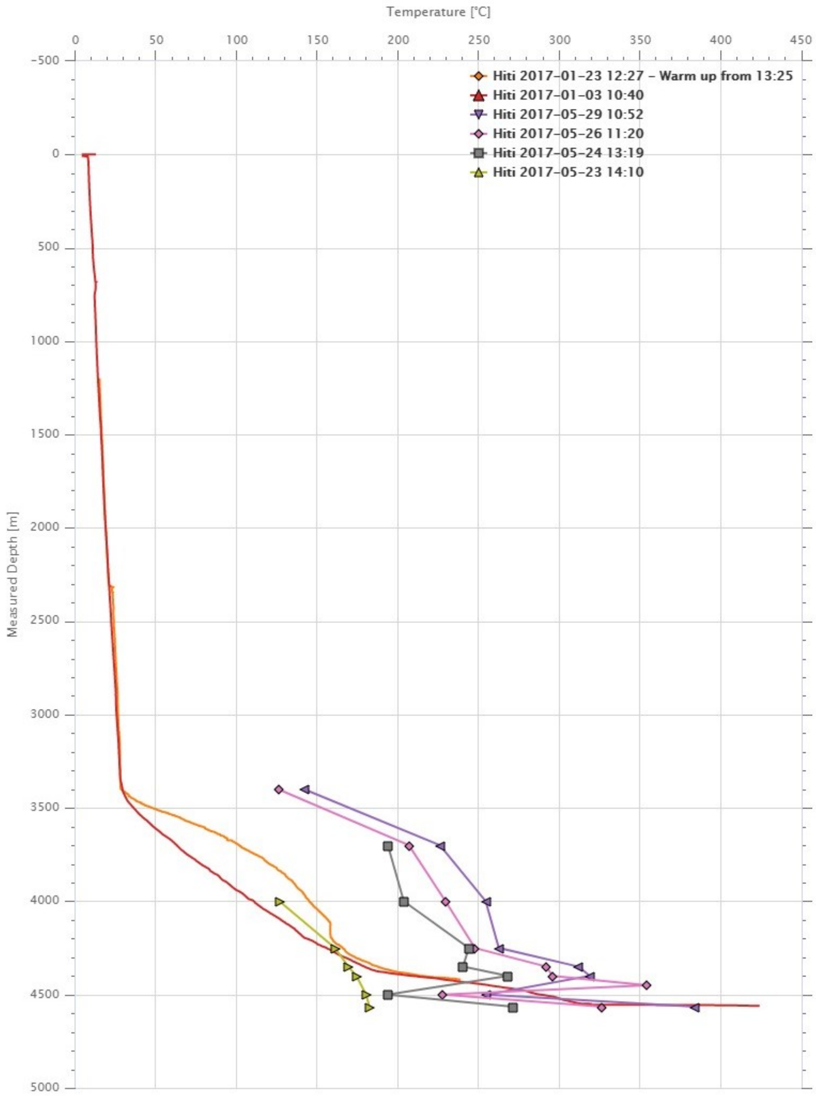


**Figure 6: Temperature logs in IDDP-2 at the end of drilling in January 2017 confirming supercritical conditions as well as temperature measured during short warm up in May 2017 used to estimate the final temperature at depth (Fridleifsson et al., 2017, Fridleifsson et al., 2018).**

The figure also shows temperature measured on the 23rd, 24th, 26th, and 29th May 2017, in a weeklong heat-up interval during the stimulation program (Fridleifsson et al., 2018). A Horner plot estimate using these temperature series gives an estimate of the formation temperature at the bottom to be at least 535°C (Tulinius and Níelsson, 2020).

## 4. SEISMIC EVENTS INDUCED DURING DRILLING AND STIMULATION OF IDDP-2

Since 2013, ÍSOR, on behalf of HS Orka Ltd., has operated a permanent network of ten seismic stations on the Reykjanes Peninsula, i.e. from Reykjanes to Svartsengi, with seven of the ten stations in a dense network around the Reykjanes geothermal field. In addition, on-line data from four seismic stations of the Icelandic national seismic network (SIL network), operated by the Icelandic Met Office, are available. Moreover, two temporary networks have been operated at Reykjanes since 2013. The IMAGE network was operated from April 2014 to August 2015 with a total of 54 additional seismic stations (Blanck et al., 2018), 30 on-land and 24 Ocean Bottom Seismometers (OBS). The second one was a temporary seismic network of nine additional stations, installed by ÍSOR and KIT in Reykjanes from October 2016 to September 2017, to monitor seismic activity during drilling and stimulation of the IDDP-2 well within the framework of the DEEPEGS project (Gaucher et al., 2016).

The seismic monitoring at Reykjanes since 2013 has provided a large and highly valuable dataset for understanding the structure and dynamics of the Reykjanes geothermal system, as the area is micro-seismically very active. Around 6200 earthquakes occurred in and around the Reykjanes geothermal field from January 2013 to August 2018, with the majority of $M_L \leq 2.0$ in magnitude (Gudnason, 2018). Earthquake activity in the uppermost 2 km in Reykjanes, i.e. at reservoir depths, is concentrated below the production field and most likely associated with the geothermal activity and production, while earthquake activity outside the production field is generally located below 3 km depth.

The depth of earthquakes from January 2013 confirms earlier observations that the brittle-ductile boundary below Reykjanes is generally at 5.5–6 km depth. However, from 2013 to 2016, an aseismic body was evident between 3 and 6 km depth, below the central core of the production field in Reykjanes. The nature of this aseismic body below the production field was unknown, and there is no past evidence for seismic activity within this presently aseismic body. One of three hypotheses put forward to explain this aseismic body (Gudnason et al., 2015) was that temperature within this aseismic body is high enough (600°C ± 100°C) to prevent stress accumulation to result in faulting, i.e. that the brittle-ductile boundary is at close to 3 km depth below the production field.

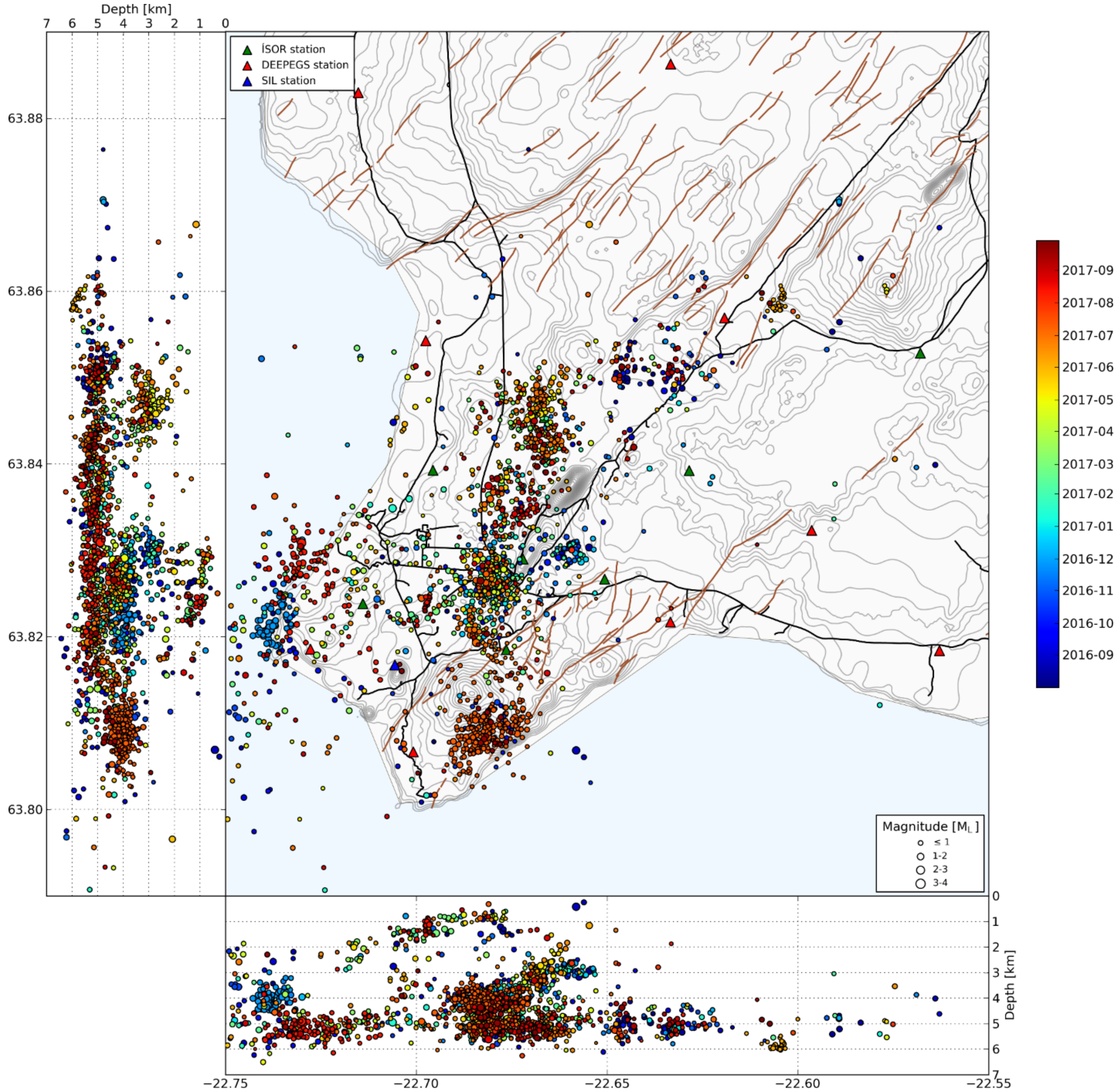


**Figure 7: Double-difference earthquake relocations in map view in Reykjanes from August 2016 to end of September 2017, colored by time and sized according to magnitude (Gudnason, 2018; Gudnason et al., 2020).**

Interestingly, since the IDDP-2 drilling started on the 12th of August 2016, seismicity has been induced within the eastern part of the previously postulated aseismic body, i.e. from 3.5 to 5.6 km depth (Gudnason et al., 2016, 2017). A double-difference earthquake relocation study, with a special focus on the period from September 2015 to August 2018, has been carried out on the data (Gudnason, 2018). Double-difference earthquake relocations in Reykjanes during drilling and stimulation of the IDDP-2 well, i.e. from August 2016 to end of September 2017, are shown in Figure 7. According to the double-difference earthquake relocations, the western part of the previously postulated aseismic body is still more or less aseismic below 3 km depth (Gudnason, 2018, Gudnason et al., 2020).

The high permeability in the IDDP-2 well is indicated by increasing circulation losses below 3.0 km depth and a total loss of circulation from around 3.2 km depth (Weisenberger et al., 2017). Several more permeable zones are identified down to around 4.6 km depth. All induced seismicity occurs just below the total loss of circulation, i.e. from 3.5 down to 5.6 km depth. The induced seismicity seems to group into two different fault zones, a northern one from 3.5 to around 4.7 km depth, and a southern one which seems to delineate a fault going from the bottom of the well to SE, striking NW-SE. These different fault zones are even more pronounced when looking at the double-difference locations of only earthquake swarms consisting of 10 or more earthquakes per day during this period (Gudnason, 2018, Gudnason et al., 2020).

A likely explanation for the induced seismicity is that the total loss of circulation of cold water (below 3.2 km depth) into the previously aseismic body during drilling, completion and stimulation of the IDDP-2 well has increased the strain rate sufficiently to make this volume seismically active (Guðnason et al., 2016). Therefore, the temperature of the previously aseismic body is almost at the brittle-ductile boundary for normal strain rates (Gudnason, 2018, Gudnason et al., 2020). This might open up possibilities to put better constraints on the temperature of the brittle-ductile boundary of basaltic crust in general. The fact that the western part of the previously postulated aseismic body is still more or less aseismic below 3 km depth might mean that the strain rate within that part is still sufficiently low to keep this volume aseismic.

## 5. TRACERS OF IDDP2 DRILLING FLUIDS IN REYKJANES PRODUCTION FIELD

Concentration of Cl, Na, Ca, B, SO4 in production fluids in Reykjanes geothermal field monitored by HS Orka and ÍSOR is detected decreasing towards the end of 2016 and during 2017 and then starts to recover to previously detected values in 2018 (Gałeczka and Óskarsson, 2019). This is most clearly depicted in the concentration of chlorite in well RN-12, shown in Figure 8, located centrally in the production field. However, measured silica concentration and calculated quartz temperature remains unaffected through 2016 and 2017 indicating that the pulse of drilling fluid has not caused significant cooling in the production field (Gałeczka and Óskarsson, 2019).

Drilling operation in the IDDP-2 well began in August 2016 and ended in January 2017 and it is likely that the lowering of chloride and other chemicals are the result of freshwater injected during drilling. The freshwater injection continues throughout 2017 and a large part of 2018 during the stimulation of the well but the amount of water injected is considerably less than during the drilling operation (Fridleifsson, 2018). The average injection rate during the almost 6 month period of drilling is estimated by Thorgilsson et al. (2020) to be almost 30 l/s.

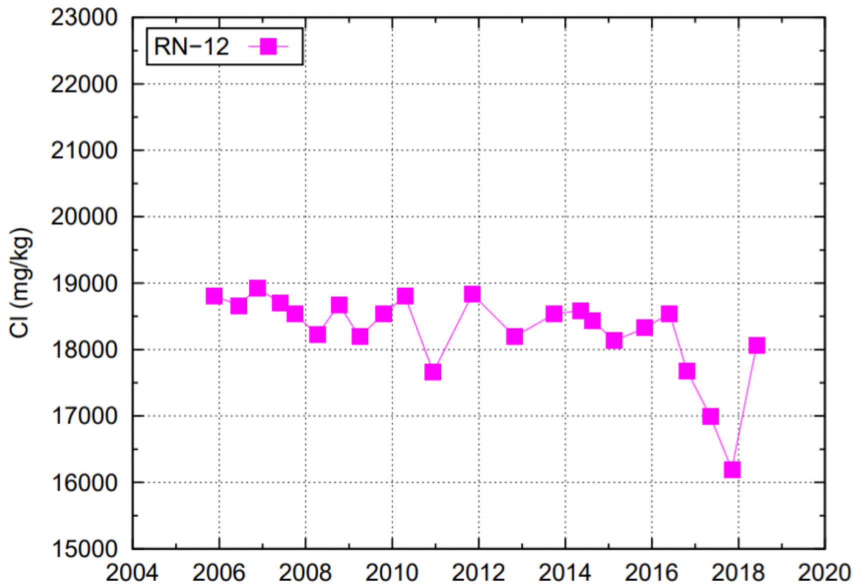


**Figure 8: Cl-concentration in fluid from production well RN-12 in Reykjanes field as reported in ÍSOR geochemical monitoring report (Gałeczka and Óskarsson, 2019).**

In a recent study a kind of reverse tracer analysis, using a naturally occurring tracer, has been carried out to investigate the effect of the freshwater pulse (5.5 months) injected during drilling of IDDP-2 on chloride concentration in production well RN-12 (Thorgilson et al., 2020). The results show that the chloride decline in well RN-12 is likely induced by the pulse of drilling fluid by flow through a fluid pathway between the deeper part of the IDDP-2 well and the Reykjanes production reservoir, with realistic values estimated for the dimensions of a fractures-zone corresponding to the pathway.

## 6. CONCLUSIONS

Increasing circulation losses below 3.0 km depth in the IDDP-2 well, and a total loss of circulation from around 3.2 km depth indicate high permeability below the proved production field in Reykjanes. Several feed zones can be identified from temperature measurements between 3200 and the bottom of the well, indicating that the deeper part of the Reykjanes geothermal system could be productive. This will however not be known before the anticipated production test of the well in fall 2019.

Double-difference earthquake relocations during the drilling and stimulation of the IDDP-2 well map out two different fault zones with different fault dynamics below 3 km depth (Gudnason et al., 2020). A northern one from 3.5 to around 4.7 km depth, and then a southern one which seems to delineate a fault going from the bottom of the well to SE, striking NW-SE mapping possible fluid pathways from the deeper parts of the system to the present production field above 2.5 km depth. Furthermore, a recent study show that the lowering of chloride detected in the production fluid is likely induced by the pulse of freshwater injected during drilling of the well (Thorgilsson et al., 2020). Thereby, proving that fluid pathways exist between the deeper part of the system and the production field.

The mapped faults zones provide input for numerical flow simulation such as carried out in the ERiS project (Berre et al., 2020). The mapped flow pathways will furthermore be used in the ongoing SiGS project to restrain thermo-mechanical and THM models of the proposed conditions that enhance permeability by opening of fractures. The results will be used in an ongoing study of the CDM process and possible effect on heat transfer close to the IDDP-2 well.

Whether or not the CDM process has any fault in opening up fluid pathways in the bottom part of the IDDP-2 will not be determined by field observations, but it is an interesting problem to be further investigated with numerical simulation. While there are indications of thermal stimulation, it is not so easy to draw links to the CDM process. At the same time, if we are close to the brittle ductile boundary in terms of temperature, as the result of Gudnason et al. shows, the colder fluids will change the characteristic of the nearby rock as well as force it to crack, similarly to the thermal stimulation mechanism in CDM, but an extreme version of it. By theory the process can increase the injectivity of the formation and numerical simulation, such as described in Section 2.2.1, can be used to investigate its effect on the heat transfer from the hot rock in the deeper part of the Reykjanes system. Either in a natural state, as a mechanism that transfers heat from the hot rock to the productive reservoir at shallower depth, or in an EGS system, knowledge of the process can be used to implement stimulation programs aimed at enhancing heat transfer from the hot rock to the productive parts of the system.

**REFERENCES**

Axelsson, G.: Hydrology and thermomechanics of liquid-dominated hydrothermal systems in Iceland. PhD-Thesis. Oregon State University, USA, (1985).

Berre, I., Doster, F. and Keilegavlen, E.: Flow in fractured porous media: A review of conceptual models and discretization approaches. Transport in Porous Media, 2018, https://doi.org/10.1007/s11242-018-1171-6

Berre, I., Trung-Dang, H., Duboeuf, L., Keilegavlen, E., Stefansson, I., Agustsson, K., Gudnason, E.Á., Halldorsdottir, S. and Oye, V.: Enhancing Geothermal Reservoirs – Modelling and Analysis of Hydraulic and Thermal Stimulation (ERiS Project). Proceedings of the World Geothermal Congress 2020. Reykjavík, Iceland, (2020).

Blanck, H., Jousset, P., Hersir, G. P., Ágústsson, K. and Flóvenz, Ó. G.: Analysis of 2014-2015 on and off shore passive seismic data on Reykjanes Peninsula, SW-Iceland. Journal of Volcanology and Geothermal Research, (2018), submitted.

Bjornsson H., Bjornsson S. and Sigurgeirsson Th.: Penetration of water into hot rock boundaries of magma at Grímsvötn. Nature, 295, (1982), 580–581.

Bjornsson S. and Stefánsson V.: Heat and Mass Transport in Geothermal Reservoirs, in: Advances in Transport Phenomena in Porous Media, NATO ASI Series (Series E: Applied Sciences), vol 128, Bear J. and Corapcioglu M.Y. (Eds), Springer, Dordrecht (Bj1987).

Bodvarsson, G.: Terrestrial energy currents and transfer in Iceland. Continental and Oceanic Rifts, 8, (1982), 271-282.

Bodvarsson, G.: On thermal activity in Iceland, Report of the Iceland Drilling Authority (Jarðborunardeild Raforkumálaskrifstofunnar), (1948), 76 pp.

Elders, W.A., Fridleifsson, G.Ó. and Pálsson, B.: Iceland Deep Drilling Project: The first well, IDDP-1, drilled into magma. Geothermics 49, (2014), 1.

Friðleifsson, G. Ó., Elders, W. A. and Albertsson, A. The concept of the Iceland deep drilling project. Geothermics 49, 2–8 (2014)

Fridleifsson, G., Elders, W. A., Zierenberg, R. A., Stefánsson, A., Fowler, A. P. G., Weisenberger, T. B., Mesfin, K. G. (2017). The Iceland Deep Drilling Project 4.5 km deep well, IDDP-2, in the seawater-recharged Reykjanes geothermal field in SW Iceland has successfully reached its supercritical target. Scientific Drilling, 23, 1-12. DOI: 10.5194/sd-23-1-2017

Fridleifsson, G.Ó., Elders, W.A., Zierenberg, R.A., Fowler, A.P.G., Weisenberger, T.B., Mesfin, K.G., Sigurdsson, Ó., Níelsson, S., Einarsson, G., Óskarsson, F., Gudnason, E.Á., Tulinius, H., Hokstad, K., Benoit, G., Nono, F., Loggia, D., Parat, F., Cichy, S.B., Escobedo, D. and Mainprice, D.: The Iceland Deep Drilling Project at Reykjanes: Drilling into the root zone of a black smoker analog, Journal of Volcanology and Geothermal Research, 2018, https://doi.org/10.1016/j.jvolgeores.2018.08.013

Fridleifsson, G.Ó., Albertsson, A., Stefánsson, A., Thórólfsson, G., Mesfin, K.G., Sigurdsson, K., Sigurdsson, Ó., Gíslason, Th., 2019. The Reykjanes DEEPEGS Demonstration Well – IDDP-2. Proceedings European Geothermal Congress 2019, The Hague, Netherlands, (2019).

Gaucher, E., Coppo, N., Gudnason, E. Á., Haaf, N., Darnet, M., Karlsdóttir, R., Köpke, R., Wawrzyniak, P., Ágústsson, K., Schill, E., Óskarsson, F., Níelsson, S. and Weisenberger, T. B.: Analysis and Design of Methods to Control the Stimulation Experiments, including Seismicity and Tracers. Prepared for DEEPEGS Geothermal, KIT Report, (2016), 40 pp.

Gudnason, E.Á., Ágústsson, K., Gunnarsson, K. and Flóvenz, Ó.G.: Seismic Activity on Reykjanes December 2014 to November 2015. Iceland GeoSurvey, Reykjavík (2015), report, ÍSOR-2015/068. 31pp.

Gudnason, E. Á., Ágústsson, K. and Gunnarsson, K.: Seismic Activity on Reykjanes December 2015 – November 2016. Iceland GeoSurvey, Reykjavík (2016), report, ÍSOR-2016/090. 45 pp.

Gudnason, E. Á., Ágústsson, K. and Gunnarsson, K.: Seismic Activity on Reykjanes December 2016 – November 2017. Iceland GeoSurvey, Reykjavík (2017), report, ÍSOR-2017/093. 51 pp.

Gudnason, E. Á.: Double-Difference Earthquake Relocations in Reykjanes. Iceland GeoSurvey, Reykjavík (2018), report, ÍSOR-2018/055, 33 pp.

Gudnason, E.Á., Köpke, R., Gaucher, E., Ágústsson, K., Níelsson, S. and Kohl, T.: Seismic Monitoring During Drilling and Stimulation of Well RN-15/IDDP-2 in Reykjanes, SW-Iceland. Proceedings of the World Geothermal Congress 2020, Reykjavík, Iceland, (2020).

Halldórsdóttir, S., Axelsson, G., Berre, I. and Keilegavlen, E.: Enhanced fluid convection and heat transfer near the bottom of the IDDP-1 well in Krafla. Proceedings European Geothermal Congress 2019, The Hague, Netherlands, (2019).

Ingólfsson, H.P., Árnason, K., Axelsson, G., Franzson, H., Hreinsdóttir, S., Jónsson, M.Th., Saevarsdóttir, G.A., Gunnarsson, G., Júlíusson, E., Podgorney, R.P., Sigmundsson, F., and Gardarsson, S.M.: Deep roots of geothermal systems – A GEORG collaborative project. Proceedings European Geothermal Congress 2016, Strasbourg, France, (2016).

Kissling, W. M. and Weir, G. J. (2005). The spatial distribution of the geothermal fields in the Taupo Volcanic Zone, New Zealand. Journal of Volcanology and Geothermal Research, 145(1-2), 136-150

Keilegavlen, E., Fumagalli, A., Berge, R., Stefansson, I. and Berre, I.: PorePy: an open-source simulation tool for flow and transport in deformable fractured rocks. arXiv preprint arXiv:171200460 (2017).

Khodayar, M., Bjornsson, S., Guðnason, E.A., Nielsson, S., Axelsson, G. and Hickson, C. (2018) Tectonic Control of the Reykjanes Geothermal Field in the Oblique Rift of SW Iceland: From Regional to Reservoir Scales. Open Journal of Geology, 8, 333-382.

Khodayar, M., Nielson, S., Hickson, C., Gudnason, E.A., Hardarson, B.S., Gudmundsottir, V., Halldorsdottir, S., Oskarsson, F., Weisenberger, T.B., Bjornsson, S.: The 2016 Conceptual Model of Reykjanes Geothermal System, SW Iceland. Iceland GeoSurvey, Reykjavík (2016), report, ÍSOR-2016/072, 110 pp + maps.

Lister, C.R.B.: On the penetration of water into hot rock. Geophysical Journal International, 39, (1974), 465-509.

Gałeczka, I.M. and Óskarsson, F.: Reykjanes production field. Geochemical monitoring in 2018. Iceland GeoSurvey, Reykjavík (2019), report, ÍSOR-2019/005. 91 pp.

Scott, S, Driesner, T. and Weis, P.: A New Conceptual Framework for the Deep Roots of Magma-Driven Geothermal Systems. Proceedings of the Fourty-Second Workshop on Geothermal Reservoir Engineering, Stanford University, California, (2018).

Tulinius, H. and Níelsson, S.: How Hot Is the Deepest Part of the IDDP2 Well in Iceland? Proceedings of the World Geothermal Congress 2020, Reykjavík, Iceland, (2020).

Thorbjornsson, D., Halldórsdóttir, S., Franzson, S., Karlsdóttir, R., Friðriksson, Þ., Níelsson, S., Einarsson, G. M. E, and Óskarsson, F.: Reykjanes - conceptual model Updated to March 2014. Iceland GeoSurvey, Reykjavík (2014), report, ÍSOR 2014/049, 62 pp.

Thorgilsson, G, Axelsson, G, Berthet, JC, Magnúsdóttir, L, Árnason, K, Gunnarsson, G & Júlíusson, E: Modelling the Deep Roots of Volcanic Geothermal Systems. Proceedings of the Fourty-Second Workshop on Geothermal Reservoir Engineering, Stanford University, California, (2018).

Thorgilsson, G, Óskarsson, F., Gałeczka, I.M. and Axelsson, G.: Tracking Fluid Flow Between IDDP-2 and the Current Production Reservoir in the Reykjanes Geothermal System in SW-Iceland, Using Drilling Fluid as Tracer. Proceedings of the World Geothermal Congress 2020, Reykjavík, Iceland, (2020).

Weisenberger, T. B., Kästner, F., Níelsson, S., Hardarson, B. S., Kristinsson, B., Ingólfsson, H., Stefánsson, H.Ö., Jónasson, H., and Vilhjálmsson S.: Well Report – RN-15/IDDP-2, Drilling of Well RN-15/IDDP-2 in Reykjanes – Continuation of Phase 3 from 2509 m down to 3000 m, Iceland GeoSurvey, Reykjacík (2016), report, ÍSOR2016/053, 91 pp.

Weisenberger, T. B., Hardarson, B. S., Kästner, F., Gunnarsdóttir, S. H., Tulinius, H., Gudmundsdóttir, V., Einarsson, G. M., Pétursson, F., Vilhjálmsson, S., Stefánsson, H. Ö. and Níelsson, S.: Well Report RN-15/DEEPEGS/IDDP-2. Drilling in Reykjanes. Phases 4 and 5 from 3000 to 4659 m. Iceland GeoSurvey, Reykjavík (2017), report, ÍSOR-2017/016. 276 p. + Appendix B.

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