Enhanced fluid convection and heat transfer near the bottom of the IDDP-1 well in Krafla, NE Iceland

Sæunn Halldorsdottir[1,2], Gudni Axelsson[1], Inga Berre[2,3] and Eirik Keilegavlen[2]

[1] ÍSOR, Grensásvegur 9, 108 Reykjavík, Iceland

[2] University of Bergen, Allégaten 41, 5007 Bergen, Norway

[3] NORCE, Fantoftvegen 38, 5072 Bergen, Norway

saeunn.halldorsdottir@uib.no

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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 thermoelastic contraction induced by cooling of the rock. The heat sources are believed to be cooling magma chambers or intrusions and this process transports thermal energy, derived from the cooling intrusions, upwards to the geothermal systems by convection. The CDM process has been implemented in numerical models by increasing the model-permeability near the heat sources, and the resulting heat transport could explain the existence of geothermal systems above magmatic sources.

Herein, a previous conceptual model of a magma intrusion close to the bottom of the IDDP-1 well is revisited (Axelsson et al., 2014). It is used to set up a new conceptual model of a CDM process active above a magmatic intrusion. The conceptual model presented is used to discuss the CDM process and its possible effect on heat transfer close to the IDDP-1 well. The work is part of an ongoing study of proposed conditions that enhance permeability and favour convection by opening of fractures above crustal heat sources.

1. INTRODUCTION

The first well of the Iceland Deep Drilling Project (IDDP) was drilled in the Krafla geothermal area between 2008 and 2009 by Landsvirkjun (National Power Company of Iceland). The drilling was stopped in June 2009 after encountering rhyolite magma at 2100 m depth (Elders et al., 2014). After completion of the well in July 2009 it was submitted to cold water injection until August the same year, when it was allowed to heat-up and then finally discharged in March 2010. The well was intermittently discharged from March 2010 until July 2012. During this period the measured discharge temperature was as high as 440 °C (Ingason et al. 2014) and the electrical power potential between 25 and 36 MWe (Gylfadóttir et al., 2012; Ingason et al., 2014). During the long-term discharge testing the well became the hottest well in the world at the time, see Fig. 1.

The Krafla geothermal area is in NE Iceland, located in the caldera of the Krafla central volcano. Geothermal electric power generation started in 1978 and since 2000, the total installed capacity of the Krafla geothermal power plant has been 60 MW_e. The latest eruption of the volcanic system, the Krafla fires, starting in 1975 and lasting until 1984, disturbed the development of the power plant and it was not until 2000 that the total installed capacity reached the originally planned 60 MW_e. The conceptual model of the geothermal system is described by Mortensen et al., (2009) and Weisenberger et al. (2015). Landsvirkjun is the operator of the power plant and developer of the geothermal concession.

Figure 1: Production test of IDDP-1, the worlds hottest well at the time it was tested between 2010 and 2012. Photo: Landsvirkjun – National Power Company of Iceland.

A probable location of the magma chamber of the most recent volcanic eruption, has been mapped, in particular by MT/TEM resistivity data and natural seismicity data (Mortensen et al., 2009). Based on this data it is unlikely that the magma encountered in IDDP-1 is the top of the Krafla magma chamber. It is more likely that the well hit a magmatic intrusion, not detected by the geophysical data, at shallower depth. This is also supported by modelling of temperature conditions near the bottom of the well by Axelsson et al. (2014), concluding that the produced superheated steam could result from an intrusion of 50-100 m thickness if emplaced during the Krafla volcanic episode 35–40 years ago. This previous conceptual model of an intrusion is revisited in the present study for theoretical modelling of processes transmitting heat from the intrusion to the geothermal system above.

Based on a lithological model of the IDDP-1 well, a permeable layer is located above the magma intrusion (Figure 2). The existence of this permeable layer could enhance convection of water in the hot rock above the intrusion, increasing the heat transfer from this shallow heat source, explaining the high enthalpy produced from the well.

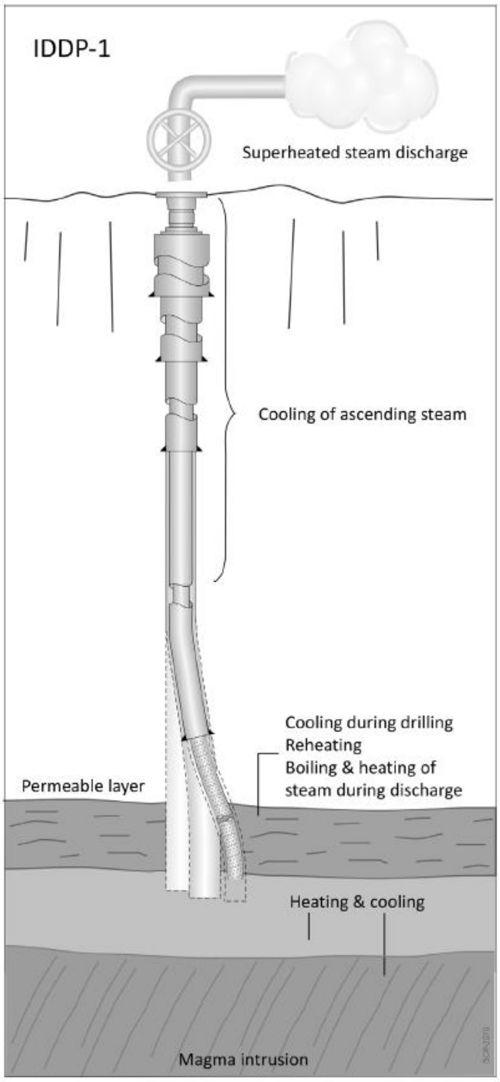

Figure 2: IDDP-1 well in Krafla was drilled into a permeable layer before hitting a magma intrusion. From Axelsson et al. (2014).

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. 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 (Figure 6). 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 that the first to be a rather unlikely mechanism for hydrothermal systems in Iceland.

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, upwards to the hydrothermal systems. Figure 3 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 contraction. The contraction is driven by 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. This 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 7 (b)). 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.

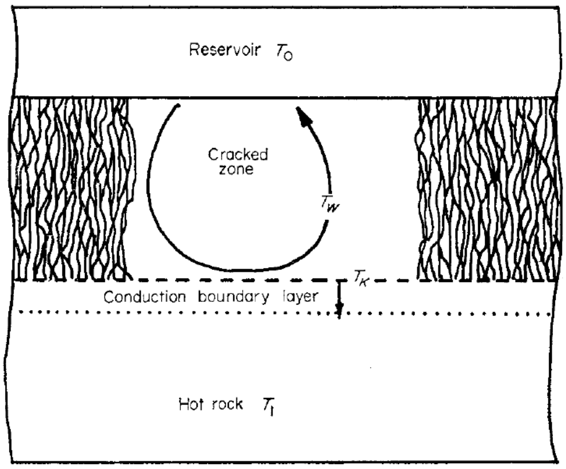

Figure 3: Lister's 1D cracking front model where reservoir T_0 and hot rock T_1 is supplied at time equals 0. From Lister (1974).

The CDM process has been approximately incorporated in numerical models of volcanic geothermal systems by increasing the permeability near the heat sources. 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 4, or by inserting a horizontal layer of high permeability overlaying a low permeable hot boundary layer representing the heat source, i.e. the FEEDZONE and the PLUTON in Figure 5. The model examples investigated in the present study are products of the Deep Roots of Geothermal System (DRG) project (Ingólfsson et al., 2016). Case studies have used data sets obtained during drilling and testing of the IDDP-1 well in Krafla geothermal system (Thorgilsson et al., 2018). In the models both approaches to altering the permeability deep in the system (depicted in Figure 4 and Figure 5) 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. This supports the theory that water is, by a mechanism such as the CDM, circulated deep in the systems and the resulting heat transport could explain the existence of geothermal systems above magmatic sources.

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 of the magma from the permeable rock of the reservoir (shown as "Conduction boundary layer" in Figure 3). Existing fractures open up 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 7 (b). 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 seen 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 3), where water is circulating and transferring heat from the boundary layer of the magma to the geothermal system. 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.

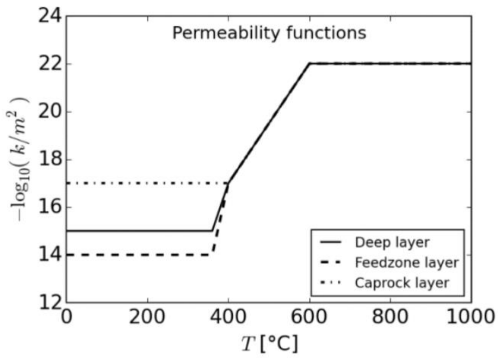

Figure 4: Variations of permeability with temperature in the Krafla DRG project's case study. From Thorgilsson et al. (2018).

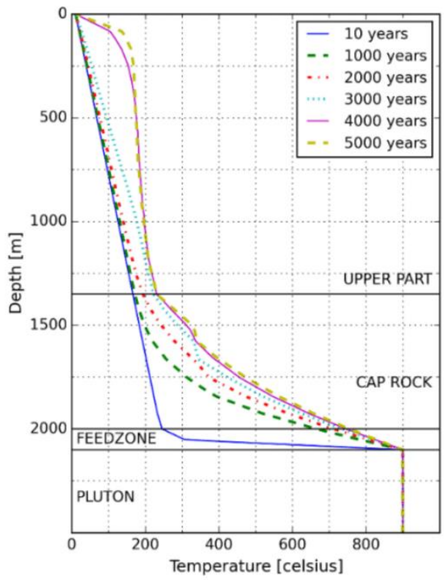

Figure 5: Variations of permeability represented by different formation type, i.e. upper part, cap rock, feedzone and pluton, in the Krafla DRG project's case study. From Thorgilsson et al. (2018).

3. MODEL OF INTRUSION CLOSE TO THE BOTTOM OF IDDP-1

The present study considers the conceptual model of Axelsson et al. (2014) of an intrusion close to the bottom of the IDDP-1. As described in the previous section, the drilling of the first IDDP well was terminated at only 2100 m depth when rhyolite magma was encountered. Series of feed-zones associated with circulation loss during drilling were encountered between 2040 and 2080 m depth in the well, reflecting high permeability above the magma (Mortensen et al., 2014). This is depicted in Figure 2; on top of the magma there is a conductive, impermeable layer and in the solid rock above, formation of higher permeability supported by location of feed-zones and abundant alteration minerals (Mortensen et al., 2014).

For the purpose of modelling the temperature conditions above the intrusion, the model in Figure 6 was proposed in the previous study. In this model the magma-layer is of constant thickness and it cools and solidifies both from above and below, while heating up the surrounding rock (Axelsson et al., 2014). The present temperature of the magma intrusion is assumed 850°C, initial temperature of magma 950°C (liquidus temperature at the time of emplacement) and the initial temperature of the high permeable layer before intrusion is assumed 340°C (initial host rock). The original solid-liquid boundary of the intrusion at time of intrusion is shown in the figure together with its location at time, t, since the interface moves downwards as the magma solidifies.

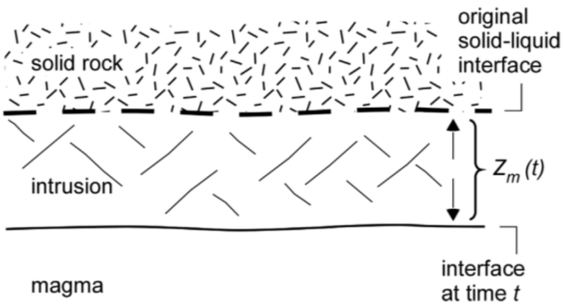

Figure 6: Conceptual model of an intrusion close to the bottom of the IDDP-1 well in Krafla. From Axelsson et al. (2014).

The mathematical solution for the temperature evolution with time and distance above the magma boundary, presented by Turcotte and Schubert (1982), is given by

$$T(z,t) = T_0 + (T_m - T_0)\frac{erfc(z/2\sqrt{at})}{1+\mathrm{erf}(\lambda_2)} \qquad [1]$$

Where a is the thermal diffusivity defined by

$$a = \frac{k_s}{\beta\rho_s}, \qquad [2]$$

with k_s and β the permeability and rock heat capacity, respectively, ρ_s the density of the rock and the parameter λ_2 is determined by solving

$$\frac{L\sqrt{\pi}}{\beta(T_m - T_0)} = \frac{e^{-\lambda_2^2}}{\lambda_2(1+\mathrm{erf}(\lambda_2))}, \qquad [3]$$

with L the latent heat of melting of the magma. The location of the upper magma boundary moving downwards is given by

$$z_m(t) = -2\lambda_2\sqrt{at}. \qquad [4]$$

The parameters T_0, T_m are defined in Table 1 together with other parameters used in the calculations.

Fluid from the hydrological system above is circulated in the permeable layer and heats up by proximity to the thin layer of impermeable hot rock right above the magma. The bottom-hole temperature of IDDP-1 was estimated to 500°C corresponding to the maximum temperature of this highly permeable layer after the emplacement of the magma.

In the present study we are interested in linking this model of the temperature conditions with the possible CDM process and developing a conceptual model for the CDM process at the bottom of the IDDP-1 well.

Table 1: Parameters, symbols and values used in the temperature model calculations (Axelsson et al., 2014)

Parameter	Symbol	Value
Temperature of the magma intrusion	T_m	850°C
Initial (liquidus) magma temperature	T_l	950°C
Solidus temperature of magma	T_s	700°C
Initial host rock temperature	T_0	340°C

3.1 Model of a cracking front moving downwards into the hot rock at the bottom of the IDDP-1 well

This study is a part of an ongoing study aimed at evaluating the CMD process, described in section 2, close to magmatic geothermal heat sources. The first well of the IDDP project was drilled into magma, believed to be an intrusion of 50-100 m thickness and early modelling work has concluded that it may have been intruded at the time of the Krafla fires 35-40 years ago. Therefore, the field data available and obtained during drilling and testing of the IDDP-1 in Krafla make an excellent dataset to study conditions above shallow heat sources.

Taking the existing model from 2014 of the cooling intrusion already described, where the interface between the solid rock and the magma (Figure 6) moves downward with time described by equation (4), we attempt to place Lister's cracking front (Figure 3) there within. The core of the CDM is that the magma is sealed from the solid rock of the reservoir with a relatively thin non-permeable layer (Figure 3). The cracking front moves into this layer (Lister, 1974; Axelsson, 1986), which consequently will cool from above through small fractures into the layer, causes temperature to drop in a volume surrounding the fractures and the rock to contract. This is shown schematically in Figure 7 (b) and in Figure 7 (a) the conceptual models from Lister

(1974) and Axelsson et al. (2014) have been combined in a schematic to show the overall convective heat transfer processes in a volcanic geothermal system. If the hypothesis of the CDM process is valid, it can partly explain the existence of the permeable layer encountered above the magma during the drilling of the IDDP-1.

If it can be shown that this process is effective during production from the IDDP-1, for example by further thermomechanical modelling, knowledge of it can be used to design stimulation aimed at enhancing heat transfer and increasing productiveness of wells drilled into similar settings.

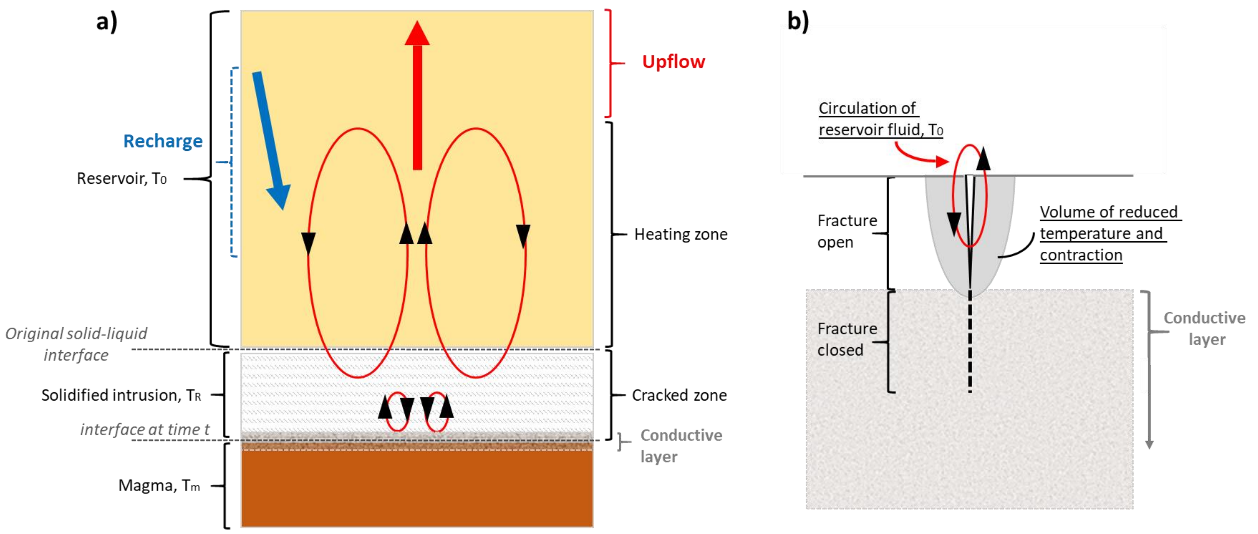

Figure 7: a) Conceptual model of a CDM process above a magmatic intrusion close to the bottom of the IDDP-1 well in Krafla. b) Circulation of water in an existing fracture and volume of reduced temperature in the rock enclosed. Adapted from Lister (1974), Axelsson (1985) and Axelsson et al. (2014).

4. THERMOMECHANICAL PROBLEM

Modelling of the CDM in a volcanic geothermal system is a thermomechanical problem since it involves both thermal contraction of the rock and cracking, or mechanical fracture of the rock. Modelling of the thermal contraction in a rock with existing fractures has already been solved mathematically but offers an interesting problem to investigate numerically.

Axelsson (1985) offers a solution to the thermoelastic part of the 2-D problem and shows that CDM is likely to be an active part in heat mining from the crust below low temperature systems in Iceland. The interesting part of his solution is that mathematically it is not restricted to low temperature environment. However, to treat the problem as purely thermoelastic, disregarding fracture, he needs to assume that the process is ongoing in a setting with already existing fractures and at stable conditions, which is hardly ever the case for high temperature systems located in volcanic centres. Nonetheless, as pointed out by Axelsson and earlier by Bodvarsson (1982) and Bjornsson et al. (1982) there exists a way to evaluate this complicated thermomechanical problem for high temperature environment as thermoelastic, if we consider the process within quasi stable settings, for example above an intrusion were a system of vertical fractures in a horizontal layer already exist, for example due to an ongoing CDM mechanism or other pre-existing geological settings. As the time passed since the intrusion is long enough so that the heat transmitted by conduction is minimal.

The basic equations governing the quasi-static linear thermoelastic response of homogeneous and linear Hookean solids follow (Axelsson et al., 1985):

$$\mu\nabla^2\bar{u} + (\lambda+\mu)\nabla\nabla\cdot\bar{u} = 3\alpha k\nabla(\Delta T) \qquad [5]$$

where μ and λ are the Lame constants of the solid,

$$k = (3\lambda + 2\mu)/3$$

and $\bar{u}$ is the vector of the displacement caused by the change in temperature (ΔT). In the model of Axelsson the thermoelastic stress is balanced against other stresses, including hydrostatic stress in the fracture, weight of the overburden and regional stress, to give the minimum thermal stress causing the volume to contract, described such that

$$K_{\Delta T} = -K_P\text{, with} \qquad [6]$$

$$K_{\Delta T} \sim -\alpha k \Delta T \text{ and } K_P \sim \mathrm{p(z)} + \mathrm{P(z)}$$

where p(z) is the hydrostatic stress and P(z) other stresses including weight of the overburden and regional stress. The simplest way of estimating the heat transfers due to CDM in volcanically active areas have been offered already by Bodvarsson in 1982 as an alternative to Listers complicated (Lister's own words) mathematical solution. Bodvarsson estimates the minimum temperature difference for the thermal stress to outweigh other forces keeping the fracture closed by considering this simple relation derived by evaluating equations (5) and (6):

$$\Delta T > P_c/\alpha k. \qquad [7]$$

Where P_c represents other forces keeping the fracture closed. At 3 km depth in the Icelandic crust he estimates P_c to be of the order of 10^7 Pa and the minimum temperature difference for thermal contraction to be of the order of 10°C. After further assumptions, he arrives to the conclusion that the rate of migration for the CDM cooling front is in the range of 0.3 to 3 m/year. Then assuming that the average rate of heat transfer per unit area, from a fracture that has migrated a distance H into a hot boundary rock, is given by (Carslaw and Jaeger, 1959; Bodvarsson, 1982)

$$q = 2h_0\sqrt{av/H}, \qquad [8]$$

finds the rate to be 30 W/m^2 for the migration rate of 1 m/year. By this simple calculation it has been argued that CDM is a likely process for heat transfers in high temperature hydrothermal areas in Iceland. Similarly, also in 1982, Bjornsson et al. considers a simple heat balance and arrives the result that the average heat flux density for Grímsvötn is 50 W/m^2. From that conclusion they further derive the result that the average rate of water penetration into hot boundary rock to be 5 m/year.

4.1 Heat transfer and velocity of CDM cracking front near the bottom of the IDDP-1

We now turn our attention to the IDDP-1 site in Krafla, assuming that Axelssons et al.'s results from 2014 are correct and that the intrusion encountered was emplaced during the latest volcanic episode, i.e. the Krafla fires between 1975 and 1984. The previous study concluded that the minimum thickness of the permeable layer above the magma would be 45 m. This is also consistent with the lithology reported by Mortenssen et al. (2014) of a highly permeable layer at least 40 m thick above the magma. If we assume that the permeability is created by a cracking front, this makes the velocity of the front roughly 1.5 m/year which is an agreement with previous estimates of Bodvarsson (1982) and Bjornsson et al. (1982). They estimated the velocity of the CDM cracking front to be in the range of 0.3-3 m/year for high temperature hydrothermal systems in general and 5 m/year for Grímsvötn volcanic geothermal system in particular.

The conclusion of the long-term flow testing of the IDDP-1 well is that it can produce up to 50 kg/s of superheated steam. This is equivalent to 150 MW thermal since the measured enthalpy is close to 3000 kJ/kg (Gylfadóttir et al., 2012). If the heat released from the permeable formation in IDDP-1 is averaged over 600 m radius around the wellbore, this gives us an average heat flux density of about 130 W/m^2. Using equation (8) and solving for v/H we obtain

$$v/H = \frac{q^2}{4ah_0^2}. \qquad [9]$$

Inserting values for H between 50-100 m, the thickness of the permeable layer, into equation (9), gives the rate of the CDM in the range of 0.8-1.5 m/year.

4.2 Numerical approaches

As an extension of analytical calculations, numerical simulations can be employed to give further insight into the thermomechanical problem. Of particular interest here is simulation tools based on Discrete Fracture Matrix (DFM) principles, which offers 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.

5. CONCLUSIONS

In the present study, a previous conceptual model of a magma intrusion close to the bottom of the IDDP-1 well, in Krafla NE-Iceland, is revisited. The model is combined with conceptual model of the CDM process for heat transfer in volcanic systems to create a new conceptual model of a downward migrating CDM front above an intrusion. The model is used to discuss the CDM process and possible effect on heat transfer near the bottom of the IDDP-1 well. Results of simple calculations show that the process could contribute significantly to the heat output of the IDDP-1 well. 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 project will dig into this by modelling the processes that lead to the alterations of permeability above crustal heat sources.

If the CDM process is valid, it can partly explain the existence of the permeable layer encountered above the magma during the drilling of the IDDP-1. Furthermore, if this theory can be validated further by thermomechanical modelling, it will open up the door for knowledge of the process to be used to implement stimulation programs aimed at enhancing heat transfer from the hot boundary of the magma at superheated geothermal sites.

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