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Modelling the Deep Roots of Volcanic Geothermal Systems

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ABSTRACT

The basic idea on the nature of volcanic geothermal systems hasn't changed much the last half a century and it is generally assumed that their heat sources are cooling magma chambers or intrusions. The heat-transfer from these roots up to shallower levels is poorly understood, however, as heat conduction is much too slow to explain the intense heat transfer involved. About half a century ago a heat-transfer process was proposed (CDM = convective downward migration) during which a cooling front, driven by convecting water, migrates into the hot rock through fractures that open up due to thermo-elastic contraction. This still appears to be a valid idea, but the question is whether the heat sources may also be shallower, smaller intrusions (dikes or sheets, etc.) or both. In the latter case the heat sources would be more dispersed than massive magma chambers and more accessible to circulating water. The deep roots have lately experienced renewed interest. This is because of their hypothetically great potential, small environmental impact of harnessing them (smaller surface imprint) and due to recent advances in exploration and drilling technologies. In Iceland the drilling of the IDDP-1 well in the Krafla geothermal field, NE-Iceland, in 2007-2008, which unexpectedly encountered magma at 2.1 km depth, has been followed by intensified scientific activity. This includes the Deep Roots Geothermal (DRG) project, which among other purposes aims at advancing modelling methods for simulating physical processes in the roots, with the purpose of illuminating the overall process controlling the upwards heat transfer from the roots as well as advance the methods for conventional geothermal reservoir modelling. The modelling part of the DRG project has involved the application of available software to various hypothetical models, relevant for increased understanding of geothermal activity around intrusions. A new equation-of-state (EOS) for iTOUGH2/TOUGH2 developed in the project is extremely valuable as it extends the applicability of the software, which is widely used within the geothermal industry, to much higher pressure and temperature, and consequently greater depth, than has been possible. The project also involved a study of the applicability of other software for deep roots modelling, including a comparison of 2D vs. 3D modelling configuration. The geothermal industry will greatly benefit from both increased understanding and improved modelling tools. Deep roots research in Iceland is continuing beyond the DRG-project, e.g. through several international research projects and deep drilling.

1. INTRODUCTION

The nature of the heat sources of volcanic geothermal systems (often called the roots), and of the heat transfer from the heat sources up to shallower levels (geothermal reservoirs), has for long been a matter of speculation. The link between volcanic activity and hot springs and fumaroles has been known for centuries and chemical studies in Iceland in the 19th century revealed the meteoric origin of geothermal fluids, even though the result was not widely known. The understanding of the nature of geothermal resources didn't really start advancing, however, until their large-scale utilization started during the 20th century concurrently with deep drilling. The basic idea on the nature of volcanic geothermal systems hasn't changed much during the last half a century, perhaps because direct access into the roots of the systems for observational purposes has been limited. Yet it is generally assumed that their heat sources are cooling magma chambers or intrusions. A speculative sketch of the structure of a volcanic geothermal system, as it is imagined to be today, is shown in Figure 1.

The deep roots have lately experienced renewed interest. This is because of their hypothetically great potential, small environmental impact of harnessing them (smaller surface imprint) and due to recent advances in exploration and drilling technologies. The IDDP-1 well was drilled in the Krafla geothermal field, NE-Iceland, in 2007-2008. It was to be drilled to a depth of 4 to 5 km, but unexpectedly drilled into magma at 2.1 km depth. The well discharged superheated steam (450°C well-head temperature) delivering power of more than 30 MW_e. This demonstrated that the deep roots of geothermal systems can be more complicated than anticipated and that huge amounts of energy can be harnessed by drilling close to (or into) magma. This was followed in Iceland by intensified scientific activity, e.g. the Deep Roots Geothermal (DRG) project, which among other purposes aims at advancing modelling methods for simulating physical processes in the roots, with the purpose of illuminating the overall process controlling the upwards heat transfer from the roots as well as advance the methods for conventional geothermal reservoir modelling. The DRG-project also involves geological studies of extinct, exposed volcanic geothermal systems, geophysical exploration of active systems and design of the components (well-heads, casings, etc.) of deep geothermal wells that can withstand the high temperatures, pressures and flow-rates expected (e.g. of superheated steam) as well as detrimental chemical content. The modelling part of the DRG project, which is the purpose of this paper, has involved the application of available software to various hypothetical models, relevant for increased understanding of geothermal activity around intrusions. A new equation-of-state (EOS) for iTOUGH2/TOUGH2 developed is extremely valuable as it extends the applicability of the software, which is widely used within the geothermal industry, to much higher pressure and temperature, and consequently greater depth, than has been possible. The project also involved a study of the applicability of other software for deep roots modelling, including a comparison of 2D vs. 3D modelling configuration.

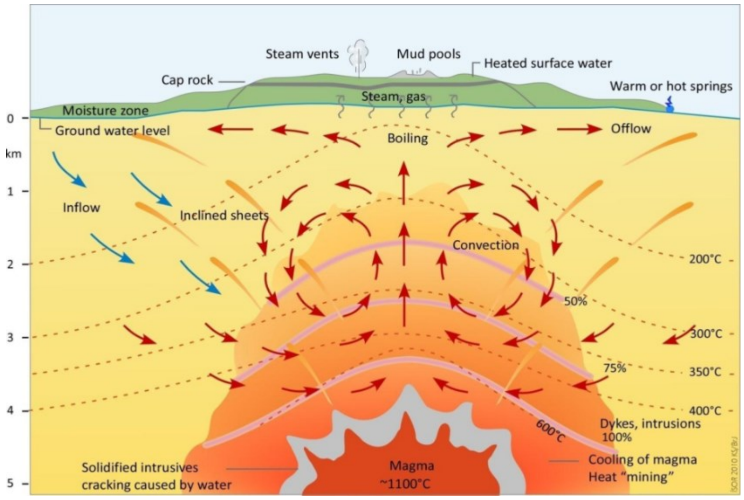

Figure 1: A sketch of the likely inner structure of an active volcanic geothermal system (© K. Saemundsson).

This paper starts out with a background review of the present knowledge of the deep roots and earlier work in that respect, as well as a review of the DRG project. This followed by a presentation of the DRG model development and modelling work along with some of the main results. The paper is concluded by a summary of the main results.

2. BACKGROUND

2.1 Deep roots of volcanic geothermal systems

The heat transfer from the deep roots of volcanic geothermal systems, up to shallower levels, is a complicated process involving flow of magma, flow of fluids (two-phase and/or supercritical water), heat transfer as well as thermo-elastic rock mechanics and chemical processes. Scientists have e.g. realized that heat conduction alone is much too slow a process to explain the extremely high rate of this heat transfer. If the heat flow from a cooling hot intrusion (either solidified or still partly molten), into a convective geothermal system were predominantly by heat conduction the thickness of the layer separating the two systems would grow with time and the heat transfer through this layer would soon be much too slow to maintain the geothermal system above. Therefore, Bödvarsson (1982; based on ideas as old as from the 50's) and Lister (1974) proposed a process termed convective downward migration (CDM) that can explain this rapid heat transport. In the process a cooling front migrates into the hot rock through fractures that open up due to thermo-elastic contraction by cooling of the rock (Figure 2). In the CDM-process the thermal energy derived from the cooling intrusions is transported upwards by convection from the roots up to the geothermal system and, consequently, through that towards the surface. These authors estimated CDM-rates of the order of 1 – 10 m/year, rates which are likely to depend mostly on temperature-, pressure- and stress-conditions. Such rates, furthermore, result in much more rapid heat extraction than through conduction alone, with extraction rates which are in a general agreement with estimated heat-flow in volcanic geothermal systems.

The ideas of these two authors appear to be in general still valid. The question is, however, whether the heat sources are deep magma chambers or shallower, smaller intrusions (dikes or sheets, etc.) or a combination of both (see Figure 1). In the latter case the depth of the heat sources would not be as deep as in the case of massive magma chambers, which were earlier assumed as the main heat sources, and they would be more dispersed. In the latter case access to the heat sources by circulating water would be much easier by circulation of water through permeable rocks surrounding the shallower intrusions. Another question relates to the role of magmatic fluids and/or fluids released from reheated altered rocks.

With the advent of more efficient modelling methods during the last decade or so, modelling of the roots of geothermal systems has become more common. Reviewing this comprehensive work is beyond the scope of the present paper, but the reader is, in particular, referred to the work of Ingebritsen et al. (2010) and the more recent work of Scott et al. (2015 and 2017).

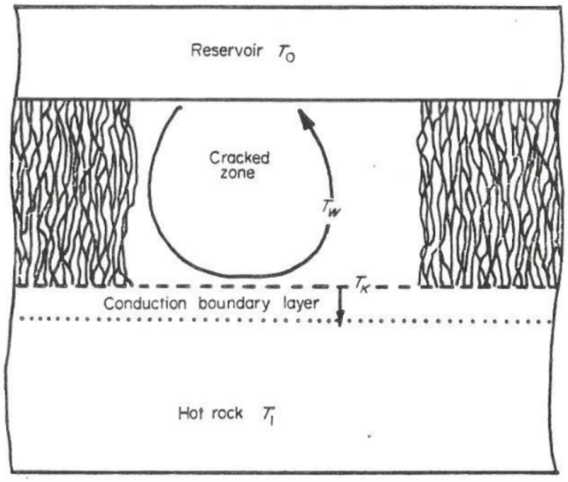

Figure 2: Lister's (1974) visualization of the convective downward migration (CDM) process.

2.2 The GEORG DRG project

The deep roots of volcanic geothermal systems have lately experienced renewed interest. This is because of the hypothetically much greater potential of deep geothermal resources due to higher temperature and pressure and possibly super-critical conditions, due to smaller environmental impact of harnessing deep root resources (smaller surface imprint) and because of recent advances in exploration and drilling technologies. The Iceland Deep Drilling Project (IDDP), which aims at drilling into the roots of three volcanic geothermal systems with a focus on both scientific and technical aspects, is an example of this renewed interest (see http://iddp.is/).

There is considerable scientific activity on-going in Iceland towards increasing the understanding of the deep roots; for geo-scientific purposes, to help increase the understanding of the lower boundary conditions (BC's) of conventional geothermal reservoirs and because of potential future use. The Deep Roots Geothermal (DRG) project, which was jointly funded by the GEORG Research Group, the three main power companies of the country, Landsvirkjun, Reykjavík Energy and HS-Orka, the National Energy Authority of Iceland, Iceland GeoSurvey, University of Iceland, Reykjavík University and Vatnaskil Engineers, was a comprehensive, large scale project focussing on the deep roots, ongoing from the middle of 2014 up to late 2017. It had the following multiple purposes (Ingólfsson et al., 2016):

- Study of geology and structure of exposed extinct volcanic geothermal systems.
- Geophysical study of active systems by comprehensive analysis of micro-seismicity.
- Monitoring of crustal deformation and gas emission.
- Advancement of modelling physical processes in the roots of volcanic geothermal systems and advancing methods of reservoir modelling for geothermal resource management.
- Material selection and design of the components (well-heads, casings, etc.) of deep geothermal wells that can withstand the high temperatures, pressures and flow-rates.
- Design of a power process for energy utilization and material recovery of high enthalpy geothermal steam.

The aim of the project was to understand the relationship of water and magma in the roots of volcanoes and how heat is transferred into geothermal systems to maintain their energy. State of the art technology was applied in deformation surveying, resistivity sounding, seismic monitoring, petrology and geochemistry. In addition, new modelling methods were evaluated and developed for use in simulating heat transfer in high temperature geothermal systems. Furthermore, the design of wells and well heads for high temperatures was a focus of the project, as well as methods for utilizing superheated steam from greater depths.

The research work was divided into three separate, but interconnected, parts; (1) exploration, (2) modelling and (3) utilization, with the modelling part described in more detail below. The DRG-project lasted about 4 years and resulted in interesting results and highly important research tools (Ingólfsson et al., 2016).

The DRG-project involves cooperation with the international research community, both from Europe and the USA, as well as links with other international research projects. The project consortium consists of a team of individuals from universities, research institutes, energy companies and engineering companies, building a strong bond between the academia and industry. The DRG project had, furthermore, synergy with, and was linked to, other international projects such as the Swiss COTHERM project, IPGT-partnership work, the ICDP Krafla Magma Drilling Project (KMDP), and the EU supported projects; IMAGE, DEEPEGS, FUTUREVOLC and DESRUMBLE to name some.

For information on the other two parts of the DRG-project (parts (1) and (3)), the reader is referred to Kaldal et al. (2016), Gudjónsdóttir et al. (2017) and Kim et al. (2018), for examples.

3. DRG MODELLING WORK

The aim of part (2) of the DRG project was to aid in the advancement of the methods that can be applied in the modelling of the physical processes occurring in the roots of volcanic geothermal systems, with the purpose of illuminating the overall process controlling the upwards heat transfer from the heat sources as well as improve and advance the methods that are applied in conventional geothermal reservoir modelling for geothermal resource management. The heat transfer from the roots up to shallower levels is a complicated process involving flow of magma, flow of fluids (two-phase and/or supercritical water), heat transfer as well as thermo-elastic rock mechanics and chemical processes. In conventional models of geothermal reservoir, used for assessing capacity and for management purposes during utilization, heat-sources are idealized as steady inflow of mass and energy, at relatively shallow depth, at the bottom of the models. There is, however, need to incorporate the heat sources more accurately in the models, both as specific intrusions in contact with the fluid circulation in the geothermal systems below the production reservoirs and their highly transient nature. Part (2) of the DRG project is extensively based on general conceptual models emerging from part (1) of the project.

Part (2) of DRG was split up in two parts with one part assigned to a postdoctoral scholar based in the USA and the other mainly assigned to two geothermal reservoir modelling specialists at Iceland GeoSurvey (ÍSOR) and Vatnaskil Consulting Engineers, respectively.

The first part was devoted to the upgrading of industry standard reservoir modelling software intended for detailed well-by-well analysis, (which Hydrotherm and CSMP++, evaluated under the second part, are not, see below) for the modelling of the extreme physical conditions deep in volcano-geothermal systems. After initial screening of available software, the iTOUGH2/TOUGH2 package was chosen for further development. A large, and highly significant part of the work, included the development of a new supercritical equation-of-state module EOS1sc for iTOUGH2/TOUGH2 (see below).

The second part was devoted to training and application of the Hydrotherm and CSMP++ reservoir modelling software, both applicable to volcanic geothermal systems, in cooperation with the COTHERM project operated at ETH in Zurich, Switzerland. An initial phase of the work was devoted to testing the applicability of the two software-packages to real volcano-geothermal situation, mainly through testing the software on idealized models of intrusive activity in deep permeable formations. Later the work shifted to modelling of actual conditions, e.g. in the Krafla geothermal system in NE-Iceland, in particular near the IDDP-1 well. Eventually, work under this second part focussed on using iTOUGH2/TOUGH2 with the new EOS1sc and other high-temperature related modifications for comparable modelling. Some significant results are presented in Chapter 4 below.

3.1 New supercritical equation of state for TOUGH2

The main achievement under the first part of the modelling part of the DRG-project was the development of a new equation-of-state module, termed EOS1sc, for the iTOUGH2/TOUGH2 numerical modelling software, as already mentioned. The purpose was to provide forward and inverse modelling capabilities at supercritical conditions. As a verification exercise, test cases of five-spot geothermal problems and of a cooling pluton were studied. The IAPWS-IF97 and IAPWS-95 thermodynamic formulations were examined, and results of EOS1sc were compared with those of other simulators. Advantages of EOS1sc over current geothermal simulators include higher operational range for pressure and temperature, better accuracy, higher computational speed, and the inverse modelling capabilities. This work and the outcome are described in detail by Magnúsdóttir (2014) as well as Magnúsdóttir and Finsterle (2015a, 2015b, 2015c). The work of the first part also involved testing of the module by applying it to synthetically generated production and response data and simplified but real case studies.

After the formal involvement of the postdoctoral scholar in the DRG-project was completed in early 2016, some further related work was intermittently performed. This included adding an option to iTOUGH2/TOUGH2 to use temperature dependent rock properties, mainly permeability, which allows the user to model various conditions present in magmatic geothermal reservoirs, e.g. the brittle-ductile transition. Some further improvements have also been made to the EOS1sc-module, see Magnúsdóttir and Jónsson (2018) at the present workshop. These new capabilities of iTOUGH2/TOUGH2 have been successfully applied to further theoretical and real cases, as described below.

3.2 Hydrothermal reservoir simulators used for deep roots modelling

Three different hydrothermal system simulation packages were used in this work: Hydrotherm, CSMP++, and iTOUGH2/TOUGH2 with the new additions referred to above. All these programs share the ability to be able to simulate fluid in the range of temperatures and pressures expected close to magmatic intrusions. However, most of the cases that we describe in this paper were modelled using CSMP++ and iTOUGH2. Following is a short description of each program.

3.2.1 Hydrotherm

USGS' Hydrotherm is an open source multiphase finite difference simulation program written in FORTRAN (see https://water.usgs.gov/nrp/hydrotherm/). It can handle calculations with pure water phases up to temperatures of 1200°C and pressures up to 1000 MPa. To solve the relevant differential equations a finite difference scheme on a square/cube lattice is used. It can handle both 2D systems and 3D systems through a Linux terminal input. But for the 2D version there is also available, in Windows, a convenient and simple graphical interface.

3.2.1 CSMP++

CSMP++ is multiphase finite element reservoir simulation package that can handle temperatures up to 1000°C and pressures up to 500 MPa (see http://www.ie.unimelb.edu.au/matthai/tools/). Its equation of state module can handle H_20-NaCl fluids as well as pure water.

CSMP++ is composed of a C++ library and uses a finite element – finite volume scheme to solve the relevant differential equations. The version of the library that was used for this work only handled 2D simulations, although 3D simulations are also supported by the CSMP++ code.

The fact that CSMP++ is a library, providing tools to solve fluid and heat flow equations from which a program is constructed, makes it very flexible and customizable. The program handles large projects robustly. It can model temperature and pressure dependent permeabilities. The program can model rock fracturing at high pressure and fracture closing at high temperature because it includes a memory feature so that the permeability is not only described as a function of the pressure and temperature, but also as a function of the rock's history.

3.2.2 iTOUGH2/TOUGH2

iTOUGH2/TOUGH2 is a simulation program package for multi-dimensional fluid and heat flows in porous and fractured media, which is widely used in geothermal reservoir engineering. The software implements the finite volume method to solve the partial differential equations of fluid mechanics which works both on regular and irregular grids. The program includes several equation of state modules that can simulate either pure water, or water with other compounds (carbon dioxide, air, brine, salt, oil, radionuclides, chemical tracers, etc.). Recently, the equation of state module for pure water was upgraded to the IAPWS-IF97 formulation and can now simulate supercritical water, as already discussed. Temperature and depth dependent permeability features have also been added to the software.

4. RESULTS

A number of features and scenarios regarding fluid transport around a magmatic intrusions were explored. These presented in this paper are divided in two groups: theoretical case studies and site specific cases.

4.1 Theoretical case studies

Here we present two theoretical studies of magmatic intrusions. The first is a 2D model that showcases the flexibility of CSMP++. In the model the cap rock is made to evolve dynamically with the temperature, crudely simulating the effects of clay alterations on permeability. Also in the same model, time dependent permeability change within the same simulation is tested. In the other case, we investigate the behavior of convection circulation cells in the transition from a semi-2D magma intrusion to a fully 3D magma intrusion. Here we use iTOUGH2 with its new supercritical equation of state module.

4.1.1 Dynamic modelling of a system in CSMP++

One of the possible conceptual models of the Krafla geothermal system is that at some point the permeability increased in the upper part (Weisenberg, et al., 2015) of the system. Here we explore how the natural state of a Krafla-like system could have evolved dynamically with a two-dimensional CSMP++ model. Models of dynamic high temperature geothermal system with sudden changes are usually rather unstable. So in order make complete runs the finite element mesh was made course and the background permeability somewhat lower ($k = 3\times10^{-16}$ m²) than what is thought to occur in the Krafla system (Weisenberg, et al., 2015). These changes help average out sudden changes in temperature and pressure and slows down the evolution of the system. The permeability is made temperature dependent as can be seen in Figure 3. There we see that the permeability drops by an order of magnitude on the temperature interval from 100°C to 200°C. This drop will crudely model the formation of a dynamic cap-rock due to clay alteration. Also, brittle-ductile transition is set to occur between 600°C and 700°C. This is in the lower end where the brittle-ductile transition is thought to happen for basalt, (Violay, et al., 2010).

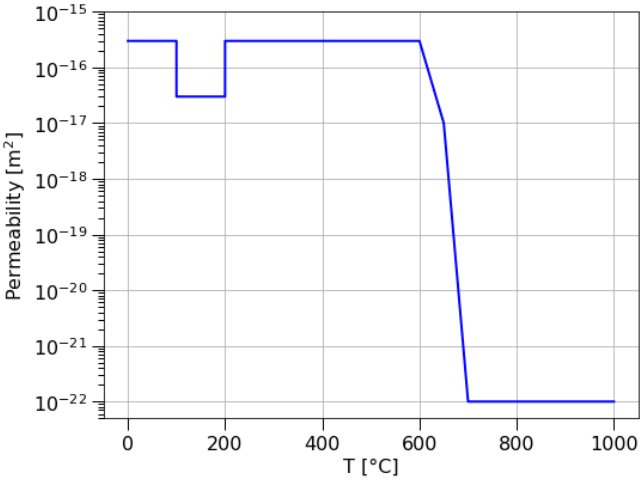

Figure 3: Permeability as a function of temperature. Between 100°C and 200°C we have a sudden drop to simulate the formation of cap-rock due to clay-alteration. The brittle-ductile transition is set at the temperature interval from 600°C to 700°C

Figure 4 shows the permeability of the system at various times. Also plotted in Figure 4, are temperature contour lines and fluid velocity vectors. The temperature at the contour lines start at 50°C for the uppermost line and increment by 50°C downward between lines. The model was made to be 10 km wide and 5 km deep. The top of the model is put at 500 m above sea-level (m a.s.l.) and the bottom at 4500 m below sea-level (m b.s.l.). The upper part of the system starts at 200 m a.s.l. and goes down to 1500 m b.s.l. The initial temperature profile is a linear 100°C/km gradient. At the bottom we maintain a 210 W m^{-2} heat flux throughout the simulation. In Figure 4 (a) we see the system at the start of the simulation. The magma intrusion is not yet present and we have lower permeability, representing the cap rock, where the temperature is in the range from 100°C to 200°C.

After 100 years a 900°C magma is injected into the system. The magma intrusion comes in as a 100 m wide and 2 km high column. Figure 4 (b) shows the system after 200 years. There we see that the magma is starting to heat up its surroundings.

As time progresses further the heat from the magma starts a large convection cell at the centre and drives the cap-rock up into a dome like structure, see Figure 4 (c). Also, we see formation of smaller convection cells to sides as time progresses. These smaller secondary convection cells could be the result of the two dimensional nature of the system, see section 4.1.1 below. The convection cells tend to be rather stable as the cap-rock acts as "blanket" over the system and the flow is maintained by the heat-flux from below. The formation of the dome in the cap-rock also helps stabilizing the system by pinning down the large convection cell at the centre.

After 6000 years we abruptly increase the background permeability in the upper system. The temperature dependence of the permeability remains similar to what is shown in Figure 3 for the upper system. With the increased permeability a new pair of small convection cells form in the upper layer and the cap-rock dome deforms into a more box-like shape. These new arrangement of convection cells also seems to be robust and maintains its structure for at least another 6000 years, see Figure 4 (d). We can therefore assume that the system shown in Figure 4 (d) can be regarded as a natural steady state.

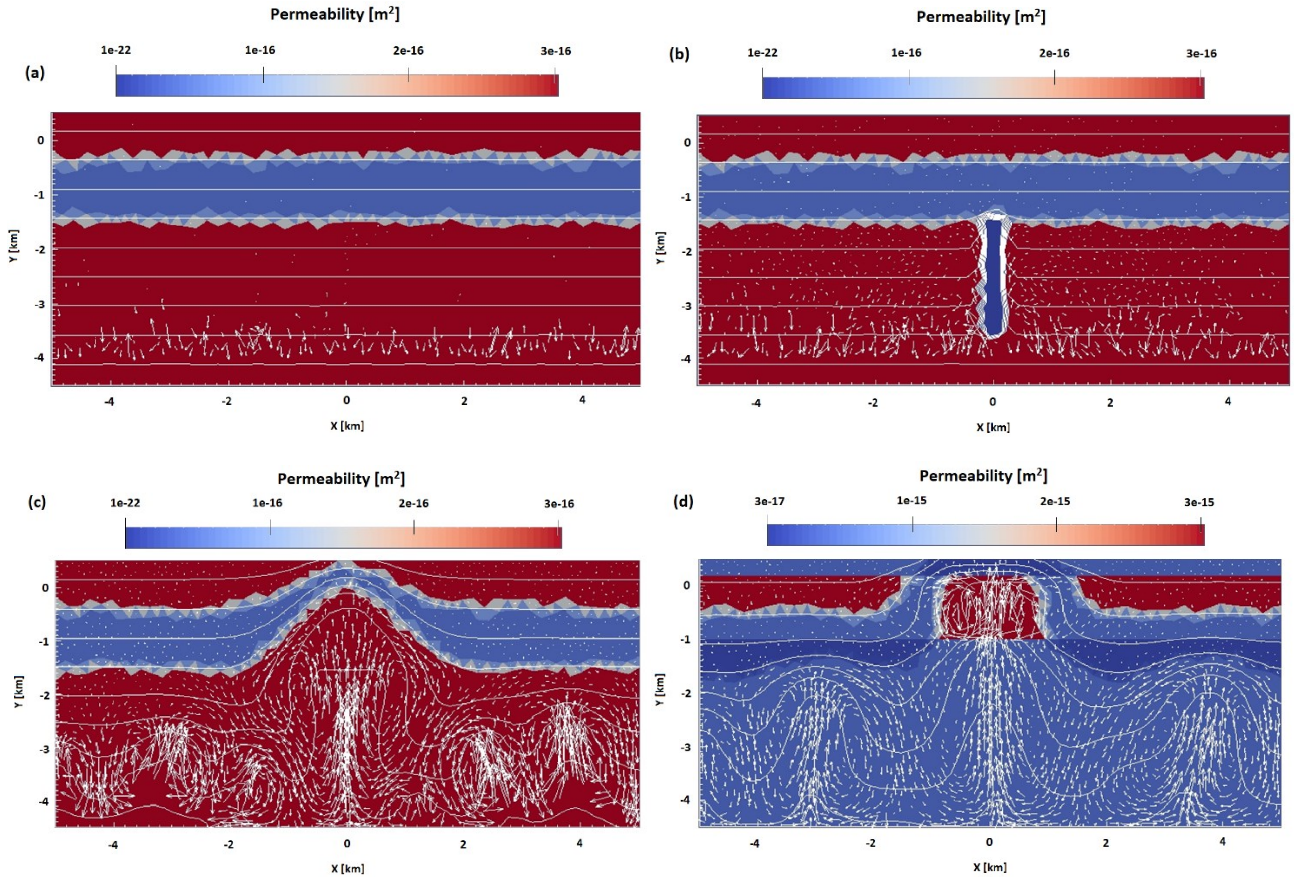

Figure 4: Snapshots of the system at various times. The color indicates the permeability. The white contour lines give the temperature starting from 50°C at the uppermost line and increasing by 50°C between lines. Fluid velocity is given by the white arrows. In (a) we see the system after 100 years or just before the magma injection. Figure (b) shows the system at 200 years, which is shortly after the injection. The heat from the magma starts a system of convection cells that drives up the cap rock. This can be seen in (c) which shows the system after 6000 years. After 6000 years the permeability of the upper system is abruptly increased by an order of magnitude. This forms new convection cells in the upper system. This system is also rather stable as can be seen in (d) which shows the system after 12000 years (Note the change of the colour scale).

The change in the temperature profile of the system caused by the sudden increase of permeability of the upper system can be seen in Figure 5. Temperature profiles at various distances from centre are plotted just before the change and 2000 year after the change. We see in Figure 5 (b) that the temperature profile 300 m from the centre has developed a steep curve in the upper level and even a slight temperature inversion 600 m from the centre, see Figure 4 (c).

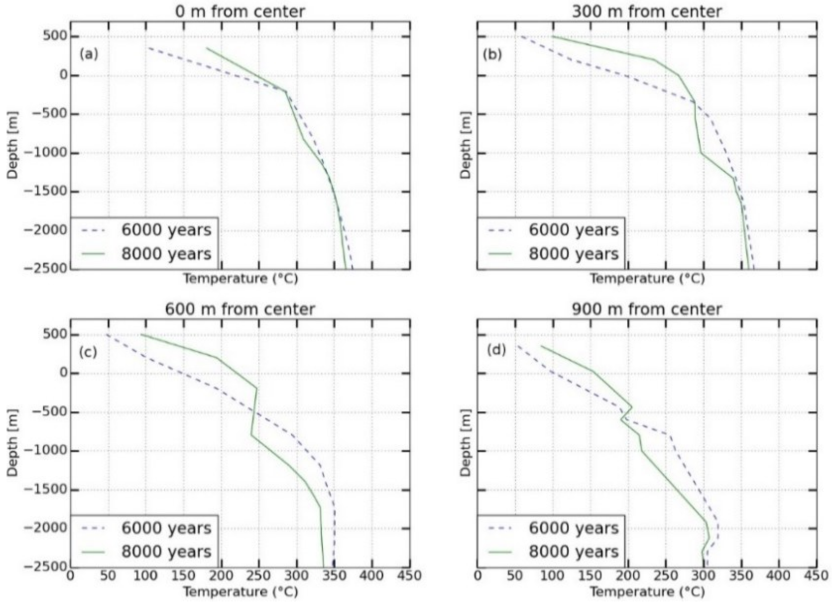

Figure 5: Temperature profiles of the system just before the increase of permeability of the upper system (blue dashed lines) and 2000 years after the increase (green solid lines). Figure (a) shows the profile at the centre, (b) 300 m from the centre, (c) 600 m from the centre, and (d) 900 m from the centre.

4.1.2 Comparison of 2D vs. 3D modelling configuration

Simulations of magma injection in 2D often produces very strong and robust convection cells. Example of this can be seen in Figure 6. There is shown results from a 2D simulation done in Hydrotherm. The total system size is 10 km long and 5m deep. At the start of the simulation a thin 1000°C magma intrusion, 50 m wide and 3 km high, is placed at the bottom left of the system, see Figure 6 (a). The background system is uniform with a 100°C/km temperature gradient and a 250 mW/m^2 basal heat flux. Two systems with different values for the background permeability, 1×10^{-16} m^2 (0.1 mD) and 5×10^{-16} m^2 (0.5 mD) were simulates.

After 8000 years the two background systems produce very different outcomes. For the lower value, see Figure 6 (b), the effect is very localized. In sharp contrast, the system with the higher value for the permeability produces a cascading series of large convection cells where each cell kicks of a new cell to the right. This train eventually stretches throughout the system, see Figure 6 (c). In what follows we will examine if this appearance of strong convection cells survives in 3D simulations.

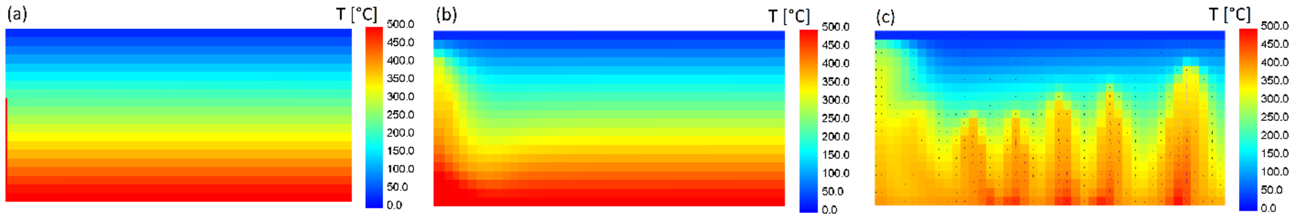

Figure 6: Temperature results for a thin magma intrusion in Hydrotherm for two different permeability values 1×10^{-16} m^2 and 5×10^{-16} m^2. The initial temperature profile for both permeability values is shown in (a), note the very thin magma intrusion on the left side. In (b) is the temperature result for the system with the lower permeability, 1×10^{-16} m^2 (0.1 mD), after 8000 years in (c) is the result for the higher permeability, 5×10^{-16} m^2 (0.5 mD), also after 8000 years.

We present a comparison of three different shapes of shallow magma intrusions: A pillar-like intrusion, limited dike-like intrusion, and a narrow and long dike-like intrusion. The last intrusion, the long dike-like intrusion, corresponds to a semi-2D system, while the others are fully three dimensional. We use iTOUGH2 with the EOS1sc module for the modelling. The system is three dimensional with equal side lengths of 2500 m. It is partitioned into cubes. Nearly all the cubes have a side lengths 100 m except at the top where the cubes are given disproportionally large volume to act as a boundary condition with a constant temperature of 20°C and a pressure of 1 atm. The temperature and pressure at the bottom is also fixed by giving the cubes at the bottom a disproportionally large heat capacity and zero permeability. The sides of the system have a no-flow boundary condition. The background rock has initially a temperature gradient of 100°C/km, a hydrostatic pressure gradient, 10% porosity, specific heat of 900 J/(kg°C), density of 2600 kg/m^3, and a permeability of 5.0×10^{-16} m^2 = 0.5 mD.

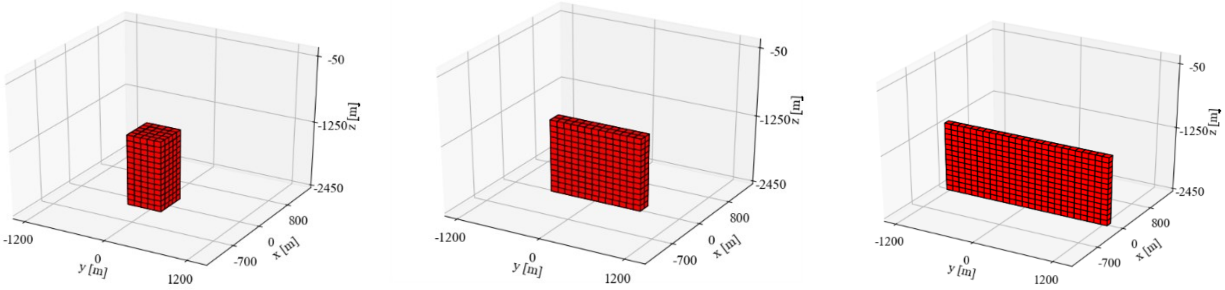

Figure 7: The three shapes of magma intrusions being compared: (Left) a pillar-like intrusion, (middle) a limited dike-like intrusion, and (right) a dike-like semi-2D intrusion. The limited dike-like intrusion has slightly more volume than the others, or roughly 4% more.

The intrusions all have nearly the same volume and have the geometrical dimension shown in Figure 7. The long dike intrusion stretches over the whole system, side to side, and acts as semi two dimensional system. At the beginning all the intrusions have the same temperature of 900°C, and twice the hydrostatic pressure. In all other respect the intrusions share the same physical features as the background rock.

In both the background rock and the magma intrusions, the permeability and specific heat is temperature dependent. The value of the permeability decreases log-linearly nine orders of magnitude between the temperatures 600°C and 700°C. This is to roughly simulate the ductile-brittle transition for basalt. The specific heat increases linearly by a factor of 2 from 750°C to 800°C in order to crudely account for the latent heat of the magma.

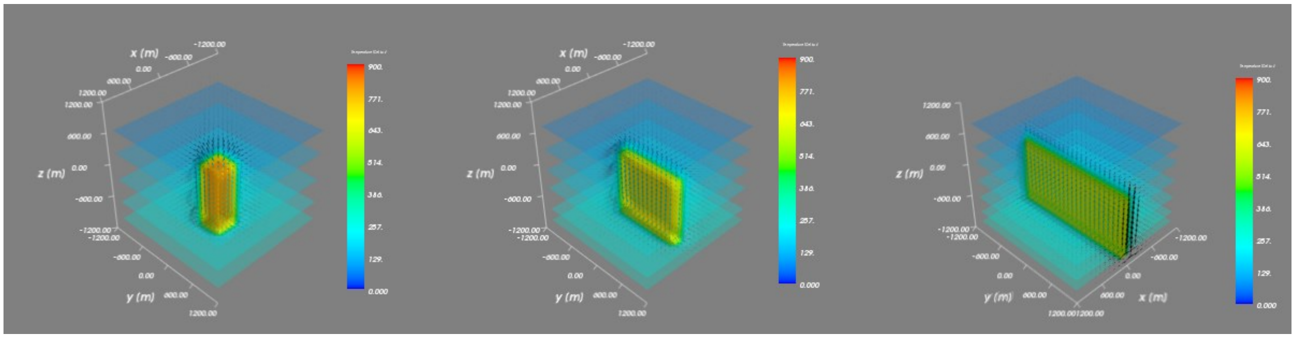

Figure 8: Temperature contours and total flow rate vectors for the intrusions after 200 years from start of simulation.

Figure 8 shows a 3D contour plot along with vectors showing the total rate of fluid flow in each element of all systems after 200 years. We notice, as would be expected, that the dike intrusions have cooled more than the pillar intrusion due to higher surface to volume ratio. But we also notice that due to inflow of cold water from the surrounding at the bottom that the heat of the intrusions are being eroded away at the bottom.

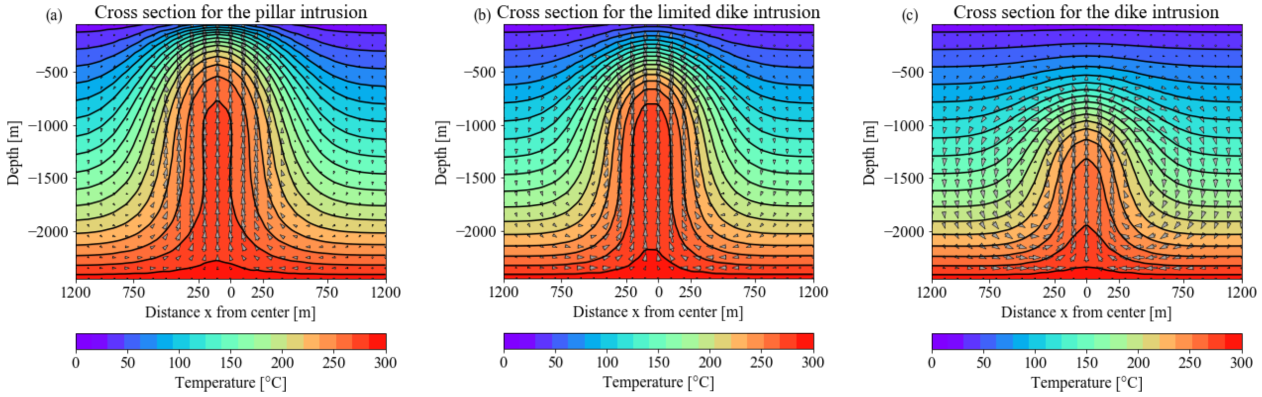

Figure 9: Temperature contours for the cross section along the x axis and through the middle of the systems after 5000 years for: (a) the pillar intrusion, (b) limited dike intrusion, and (c) dike intrusion. Also shown are fluid flow rate vectors in the cross section plane.

As the simulations progresses the three systems evolve in different ways. After 5000 years the temperature plumes have taken on semi-stable forms that are characteristic for each intrusion. In Figure 9 cross sections of the systems are shown in the xz-plane cutting the middle of the y-axis.

The case for the pillar intrusion after 5000 years is shown in Figure 9 (a). For this case we see a plume that rises with a large flow rate propelling it upward but not a clear formation of distinct convection cells as was the case for the long and narrow dike. Also, we see a sign of temperature inversion at the centre of the plume. The shape of limited dike is midway between the pillar system and the long dike system and is therefore a valuable case for comparison. The result for the limited dike system after 5000 years is shown in Figure 9 (b). It is interesting to see that it does show a plume and temperature profiles that are more in line with what we see in the pillar intrusion than for the long dike intrusion. Although, we see clearer sign of convection cells than for the pillar intrusion, the cells are not as clear and symmetric as for the long dike system. In Figure 9 (c) we have the case for the long dike intrusion. This system can be considered to be a semi-2D system. On the temperature contour figure we see an emergence of plume localized close to the original magma intrusion. Also, in the temperature contour figure we see two distinct convection cells on both sides of the intrusion. This is very typical of what expect from a 2D simulation. The plume does not rise much and maintains a bell curve shape.

For all three cases the semi 2D case, the long dike, seems to stand out in two ways. First, its plume does not rise like in the other cases. This could be because it has a large surface to volume ratio and smaller top surface area than the other cases. This makes the long dike lose heat faster and warm the total system more evenly. The other feature that stands out is the clear and symmetric convection cells. This is probably due to the 2D nature of the system. For the long dike the flux area for the upstream and the downstream are closer in size than for the limited dike and pillar system. Also, because the system is completely uniform in the y direction there is negligible flow in the y direction which enhances convection cells that lie in the xz-plane. The systems that are presented here are not large enough to produce secondary convection cells. But the weaker down flow of the intrusions with fully 3D structures would result in a severe dampening of the secondary convection cells for larger systems. This means that systems that do not possess semi-2D structures will have more localized effects than is indicated by 2D simulations.

4.2 Case studies for volcanic geothermal systems

Here we present two case studies where site-specific models come into play. The first case is a 2D model of magmatic intrusion in CSMP++ based on the stratigraphic information that we have for the site where IDDP-1 was drilled. The second case is a 3D model of random intrusions in a iTOUGH2 model based on the Hengill geothermal area.

4.2.1 CSMP++ model based on IDDP-1 stratigraphy

The original plan of the Deep Root Project in Krafla was to drill down to 4.5 km, to find super critical water. The magma was thought to be below 5 km. But the drilling of the well was stopped at 2.1 km because of magma intrusion. Two attempts were made to redirect the well, but all ended up at around 2.1 km (Pálsson et al., 2014). It is not known how wide the magma intrusion is. The model presented here is based on the stratigraphy description by Mortensen et al. (2014):

> *“The upper 1362 m of the well consist of basaltic lavas and hyaloclastite formations […]”*
>
> *“Below 1350 m depth IDDP-1 the well enters a dyke complex which extends to the bottom of the well at 2104 m depth, where the well encountered rhyolitic magma.”*
>
> *“The upper reservoir is isothermal at 170°C.”*

> *“The largest feed-zones […] were encountered below 2000 m depth […].”*
>
> *“All these wells [in the vicinity of IDDP-1] encountered large feed zones at or below 2000 m.”*
>
> *“[…] in the upper 1300 m of well IDDP1 few smaller feed zones were intersected […].”*
>
> *“[…] feed zones are scarce at 1350–2000 m depth. […] this interval may be characterized as representing a tight cap rock to the lower reservoir.”*
>
> *“[…] the estimated temperature of the magma encountered in IDDP-1 is ~900°C.”*
>
> *“Temperature recovery indicates that the reservoir temperatures approach 500°C near the well bottom, […]”*

A model was constructed based on the description given in the article (Figure 10). The model is 5 km deep and 10 km wide. The model is divided into layers: an upper layer (from the surface down to 1 350 m), a cap rock layer (from 1 350 m down to 2 000 m), a feed-zone layer (2 km to 2.1 km), and a deep layer (below 2.1 km). The upper layer, where the temperature is uniform at 170°C, was assigned a permeability of 10^{-14} m². The permeability was chosen so as to have convection in the upper layer. Below 1 350 m, temperature dependent permeability was used. The permeability functions, for each layer, are shown in Figure 11. For the ductile part (above 400°C), the three functions share the same properties. In the brittle region (below 400°C), the functions were defined so as to reflect the layers’ characteristics as described in the stratigraphy article. The caprock layer was assigned a low brittle permeability of 10^{-17} m², to simulate the tight caprock. The feedzone layer was assigned the brittle permeability of 10^{-14} m²; and the deep layer was assigned a brittle permeability of 10^{-15} m². The top boundary was set to a constant temperature of 20°C; and the bottom was assigned heat sources averaging to a heat flux of 260 mW m^{-2}. The heat flux was chosen to obtain a temperature of 600°C at the bottom of the model. The magma intrusion, at the centre, is 200 m wide and 3 km high. Its initial temperature was set to 900°C. Because the permeability is temperature dependent, the intrusion is automatically assigned a low initial permeability of 10^{-22} m².

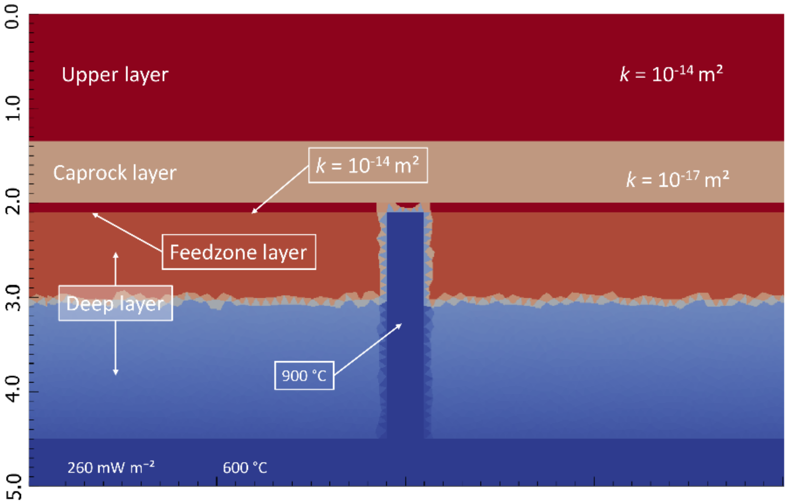

Figure 10: CSMP++ model based on the IDDP-1 description by (Mortensen et al., 2014). The figure shows the permeability and temperature in the initial state.

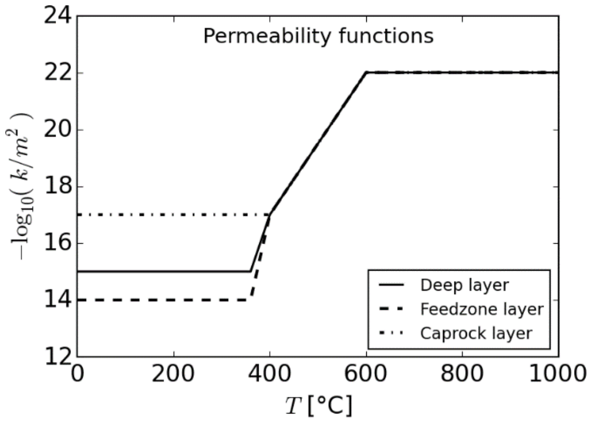

Figure 11: Temperature dependent permeability functions used for the three layers below 1350 m.

CSMP++ was first used to create a background steady state without the pluton. Then the model was run, with the pluton, to simulate 5000 years. At the beginning of the run, the temperature, above the pluton, is that of the steady state and the background heat flux (Figure 12); the gradient is 0.12°C/ m. During the first 2 000 years, the heat from the pluton gradually penetrates into the caprock; little change is observed in the upper layer. After around 2 000 years, the heat has crossed the caprock and the temperature in the upper layer begins to rise. After 3 000 years, convection is visible only at the bottom of the upper layer. After 4 000, the convection has reached the top of the reservoir; the temperature is the upper layer is almost uniform, around 200°C. During the next 1 000 years, the temperature rises slightly at the top of the upper layer, but it changes little overall.

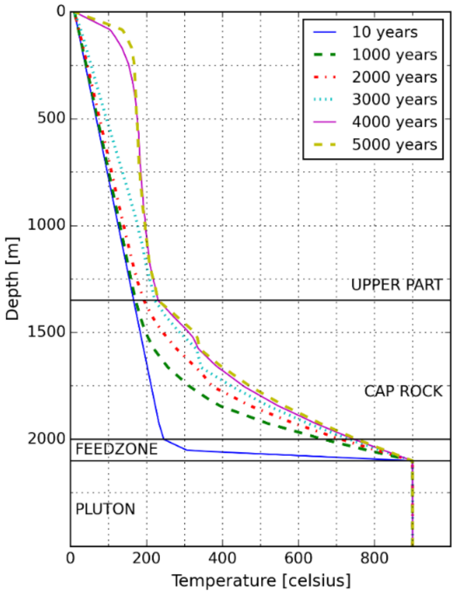

Figure 12: Temperature versus depth at the centre of the model, in and above the pluton.

4.2.2 Modelling of random magma intrusions with iTOUGH2 and EOS1

This case study involves a continuation of the work of Gunnarsson and Aradóttir (2014), using the tools developed in this project for high temperature and pressure, not available during the original work. The study involves comparing two ways of introducing heat in 3D models. In the first model the heat is introduced into the system via steady heat sources at the bottom of the system. This is often done in TOUGH2 models to simulate heat coming from the deep roots of the geothermal system, which are assumed to be below the model. The second model introduces this heat as a series of random magma intrusions that appear in the volume that is being modelled.

The model is 20 km long, 10 km wide and 3.4 km deep. Vertically, the model is divided into 17 layers. Layers close to the top are 100 m or 200 m thick; near the bottom, the layers are 300 m and 400 m thick. The top and bottom layers are inactive, and used as constant pressure and temperature boundaries. Thus, the active part of the model in 3 km thick. The elements are 230×230 m^2 at the centre of the model and 500×500 m^2 closer to the edges.

The reservoir is defined as the part of the model where the rock is permeable enough so that convection dominates the heat transfer. The reservoir 9.9 km×3.2 km. The permeability in the reservoir is 15×10^{-15} m^2. A small area at the centre, has higher permeability of 5×10^{-13} m^2. The reservoir is surrounded and capped by impermeable rocks. Outside the reservoir, the permeability is 10^{-18} m^2. Vertically, the permeable reservoir starts at -800 m and extends down to the bottom of the active model at -3000 m. The permeability in the bottom layer and cap rock (above -800 m) is 10^{-18} m^2. In the reservoir, the porosity is 0.12, and in the impermeable rock outside the porosity is 0.01.

4.2.2.1 Heat sources and steady state

A common method to create natural-state, is to add heat source to the reservoir bottom layer, and run the model run until a steady state is reached. In this example, heat sources were placed to entirely cover the reservoir bottom layer. The heat rates were scaled to provide a uniform heat rate per unit area. The heat rates were also adjusted to obtain a roughly uniform temperature of 300°C, at the centre of the model. Figure 14 (a) shows the temperature profile at different locations. Figure 13 (a) shows the temperature horizontal distribution at -1050 m. The heat flux through the reservoir bottom layer (combining the heat from the model bottom layer and sources) is 35 MW, or 1.1 W m^{-2}.

4.2.2.2 Random magma intrusions

The new equation of state module developed by Lilja Magnúsdóttir (see above), can simulate temperature up to a 1000°C. The module was used here and attempts were made to create a natural state by simulating intrusion of hot magma into the reservoir. This was performed by using command 'RESTART' in iTOUGH2 to reset the temperature and pressure of some randomly chosen elements at the bottom of the reservoir. All the intrusions have the same shape. They are made of vertically aligned elements in the three bottom layers at -3200 m, -2900 m, and -2550 m. The intrusions were simulated by resetting the selected elements' temperature to 800°C, and pressure to 75 MPa. The horizontal locations and times at which the resets occurred were chosen randomly. In its initial state, prior to the intrusion, the reservoir temperature is roughly 90°C.

The scenario was set up to simulate 200 intrusions in 10,000 years. Figure 14 (b) shows the temperature profiles of the reservoir. Around 7000 years are necessary to reach the temperature of around 300°C. Figure 13 (b) shows a map of the temperature at -1050 m, after 7 000 years. The result is like the one obtained by using constant head sources (Figure 14 (b) and Figure 13 (b)), but the model with intrusions has a less regular temperature distribution.

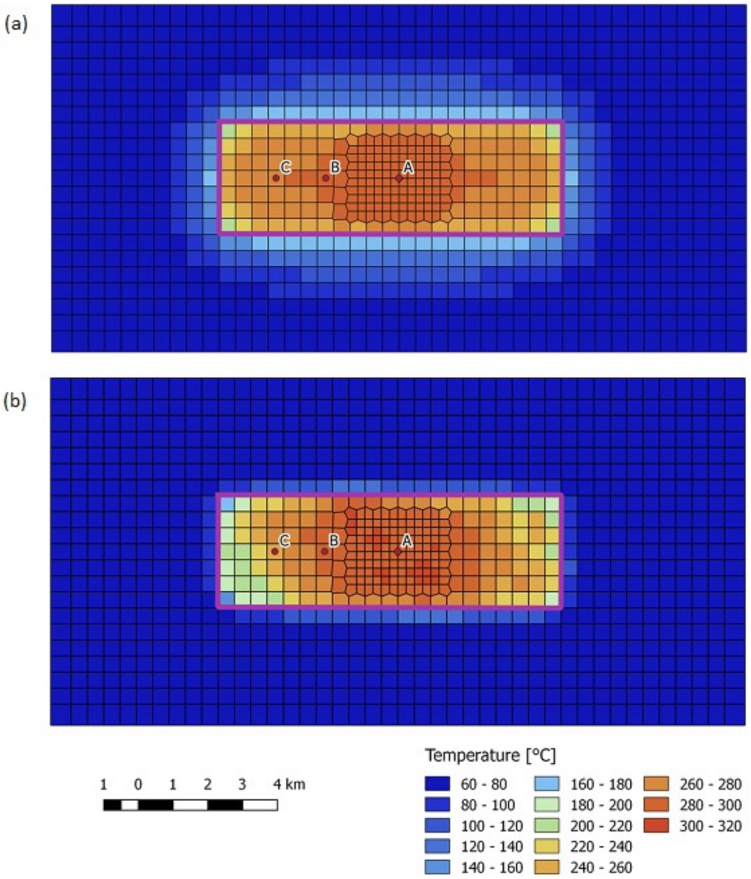

Figure 13: Mesh and temperature at -1050 m. Convection occurs inside the purple rectangle where the rock permeability is 15×10^{-15} m². Outside the rectangle, where the permeability is 10^{-18} m², heat is transferred by conduction. The model is 20 km×10 km. The (purple rectangle) permeable area is 9.9 km×3.2 km. In (a) the result of the steady state model is shown and in (b) for the random intrusion model.

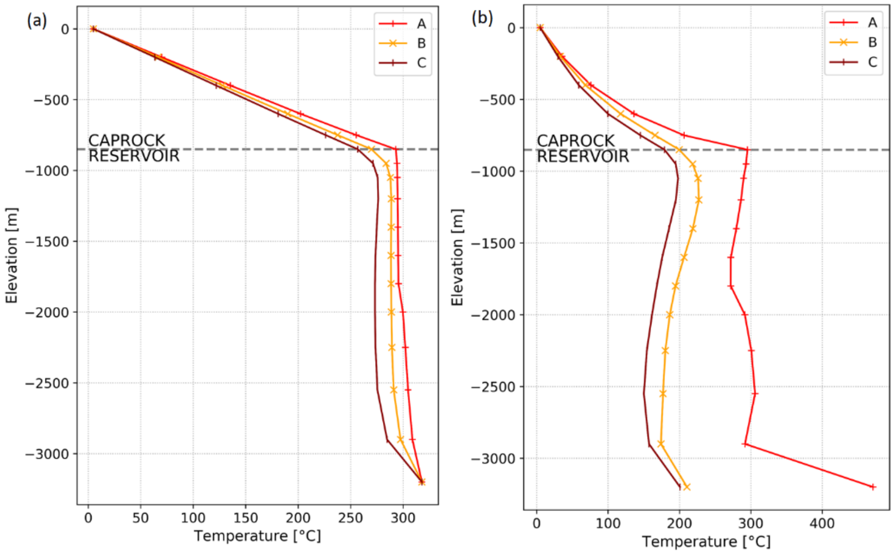

Figure 14: Temperature profiles for (a) a steady state model and (b) for a random intrusion model. The locations (A, B and C) of the temperature profiles can be seen in Figure 13.

Natural states similar to the ones generated using constant sources, can be created by modelling the random intrusions of magma into the reservoir. However, the intrusion method resulted in a reservoir with a more irregular temperature distribution. The intrusion method also took significantly longer. With such a small model, generating a steady state takes using constant heat sources takes a few minutes. Modelling the water in supercritical conditions, the plutons and the complex convection patterns they induce required a few days to a couple of weeks.

5. CONCLUSIONS

The modelling part of the Deep Roots Geothermal (DRG) project, funded through the GEORG research group in Iceland, was aimed at advancing modelling methods for simulating physical processes in the roots of volcanic geothermal systems, with the purpose of illuminating the overall process controlling the upwards heat transfer from the roots as well as advancing the methods for conventional geothermal reservoir modelling. The following are the most significant results:

- A new equation-of-state (EOS) for iTOUGH2/TOUGH2 developed in the project is extremely valuable as it extends the applicability of the software, which is widely used within the geothermal industry, to much higher pressure and temperature, and consequently greater depth, than has been possible.
- Temperature dependent rock permeability has been incorporated in TOUGH2/iTOUGH2, yet outside the DRG-project. This makes the software package more versatile and makes it resemble Hydrotherm and CSMP++ in deep-root applicability.
- Several modelling case studies were modelled as part of the project, with four of these presented in this paper. Two of the cases are theoretical and two site specific, where the effects of magmatic intrusion evolution in a geothermal system were investigated. Two reservoir simulators were mainly used, CSMP++ and iTOUGH2 with the newly incorporated supercritical equation-of-state module. Both reservoir simulators were found to perform well in simulating the supercritical hydrothermal systems created by the magmatic intrusions.
- The first case was a theoretical model that incorporated a dynamic cap rock and time depended features in permeability. This was modelled with CSMP++ and showcased the flexibility by which a model can be set up with the reservoir simulator.
- The second case, also theoretical, was a comparison of convection cells that are created by semi-2D shaped intrusions and 3D shaped intrusions. This was modelled using iTOUGH2 and its new supercritical equation-of-state and temperature dependent permeability option. The main findings were that convections cells tend to be more localized for a 3D shaped intrusion than for a 2D shaped intrusions. Therefore, care must be taken when interpreting 2D model results that are supposed to simulate 3D systems.
- The third case was a site specific 2D model for the volcanic hydrothermal system in Krafla, N-Iceland modelled with the CSMP++ package. Krafla is the site of the IDDP-1 borehole, which encountered magma at relatively shallow depth. The IDDP-1 well, and its magmatic surroundings, were the focus of this case.
- The fourth case was a continuation of the work of Gunnarsson and Aradóttir (2014). That work focused on an iTOUGH2 model of the Hengill geothermal system in SW-Iceland, where heat was introduced into the system via random intrusions. In the old work the subcritical EOS1 equation of state was used, while in the current work the new supercritical equation of state module was used, by modelling the intrusions more accurately. The resulting temperature profile of the system was compared with a temperature profile for the same system, where heat was introduced via steady state heat sources at the bottom of the system. The random intrusion heat profile was shown to be comparable with the steady state heat source profile. This supports the

justification of using steady state heat sources instead of magmatic intrusions as a heat source, if the intrusions themselves are not the focus of the model simulation.

- With the upgrades made to iTOUGH2/TOUGH2 that simulation package is now well suited for the task of extending conventional industrial style well-by-well models down to greater depth. Furthermore, the software packages evaluated and used in this project have all proven to be applicable for the modelling of the deep roots of volcanic geothermal systems.
- The geothermal industry will benefit from the results of this work, even though many of the case studies are more of an academic nature than directly applicable to the production of geothermal energy at present. The benefit includes both increased understanding of the roots of volcanic geothermal systems and, in particular, the improved iTOUGH2/TOUGH2 modelling tools.

Deep roots research in Iceland is continuing beyond the DRG-project, e.g. through the cooperative DEEPEGS project, funded by the European Union's HORIZON 2020 programme. That project has e.g. been involved the drilling of the 4.7 km deep IDDP-2 well in Reykjanes, SW-Iceland, where a bottom-hole temperature of approximately 550°C has been inferred, indicating proximity to some kind of “roots”.

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