Modeling the Deep Roots of Geothermal Systems

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ABSTRACT
This paper discusses the challenges associated with modeling high enthalpy geothermal systems and magmatic intrusions. In reservoir modeling, the heat sources are commonly assumed to be below the model’s depth range and only incorporated into the model by choosing appropriate boundary conditions. However, the heat sources extend up to shallower depths in high enthalpy geothermal systems as indicated by wells that have been drilled into magma or very hot formations. Thus, it is of interest to improve current field scale numerical models by incorporating magmatic intrusions and the entire water circulation into the modeling scheme. A discussion of the difficulties related to modeling high enthalpy systems is provided in this paper. Various flow simulators were studied to find a simulator that could model supercritical conditions caused by the high pressures and temperatures at the deep roots of geothermal systems. A magma chamber was modeled and the thermal transfer between the magma chamber and the hydrostatic reservoir was investigated. The flow simulator cannot describe the system in full detail but the goal is for the model to capture the essence of the system. That way, the ability to answer questions relevant to the field management of magmatic geothermal systems can be improved.

1. INTRODUCTION
The high temperature geothermal power plants in Iceland are located in active volcanic zones where the heat sources consist of cooling magma bodies intruding into the continental crust. These magmatic intrusions can extend up to a relatively shallow depth as indicated by a geothermal well drilled into magma in the Krafla geothermal field in Iceland at a depth of 2.1 km (Fridleifsson et al., 2010). A geothermal well was also drilled into a very hot formation in the Nesjavellir geothermal system at the Hengill central volcano in 1985 and it is believed to have reached supercritical temperatures at a depth of 2.2 km (Steingrimsson et al., 1990). In addition to Iceland, superheated steam has been encountered in a few places around the globe, e.g. at Larderello in Italy, The Geysers in California, Matsukawa in Japan, and at Tatun volcano in Taiwan (Truesdell and White, 1973). These encounters with very hot temperatures at a drillable depth indicate that the heat sources extend up to a depth shallow enough to greatly influence the hydrology and thermal behavior in the reservoirs. However, in today’s standard modeling practices the magma intrusions are not included in the reservoir model. Instead, the model is driven by appropriate boundary conditions at the bottom of the model. These models, such as the comprehensive 3-D model of the greater Hengill volcano in SW-Iceland made by Bjornsson et al. (2003), assume that the heat sources are below the model’s depth range. As we start drilling deeper it becomes evident that these assumptions are not valid and in order to better understand the magmatic geothermal systems the heat sources must be incorporated into the modeling scheme.

The process by which heat is transferred from the heat sources to the surface can be complex and difficult to model. There are various unknowns such as the depth range of the water circulation and how the heat transfer between the groundwater and the magma bodies take place. In addition, modeling challenges are present due to supercritical temperatures and the time varying spatial distribution of the heat sources. There are several simulators capable of modeling supercritical temperatures, such as the U.S. Geological Survey simulator HYDROTHERM (Hayba and Ingebritsen, 1994) and the HOTHZO extension to the STAR simulator (Pritchett, 1995) but both simulators are limited to regular rectangular or radial computational grids. An implementation of the Complex System Modeling Platform CSMP++ (Weis et al., 2014) has been made to account for supercritical conditions. Codes developed based on the TOUGH2 code (Pruess, 1991) include the EOS1SC equation of state module by Brikowski (2001), the supercritical equation of state module by Kissling (2004), and the AUTOUGH2 code developed at the University of Auckland (Croucher and O’Sullivan, 2008). There are various assumptions and simplifications used when modeling hydrothermal systems using these simulators as summarized by Ingebritsen et al. (2010). Hence, these simulators will not be able to describe the magmatic systems in full detail but the objective is to be able to understand these systems better and to answer questions relevant to the field management.

In previous work, HYDROTHERM has been used to model multiphase groundwater flow near cooling plutons at 900°C as described by Hayba and Ingebritsen (1997). Yano and Ishido (1998) used the HOTHZO extension to the STAR simulator to predict pressure transients in deep geothermal reservoirs at supercritical pressures. The TOUGH2 based simulators have also been used to model geothermal reservoirs at supercritical temperatures as demonstrated by Croucher and O’Sullivan (2008). They showed that the EOS1SC equation of state module for TOUGH2 and AUTOUGH2 give similar results for the geothermal five-spot problem described by Pruess (1991) with initial temperatures at 400°C.

The objective of this research project is to investigate ways to model magmatic geothermal systems and develop a model of the Hengill geothermal system in Iceland. The current field scale numerical model will be improved by including the heat source in the model and using inverse approach to determine some of the unknown properties as well as to test hypothesis on how heat is transported into the geothermal reservoirs. In this paper, the preliminary work of this project is described which includes investigating the applicability of using simulators AUTOUGH2 and HYDROTHERM to simulate magmatic geothermal systems.
with the heat sources and the entire water circulation included. The paper first discusses the existing modeling challenges and various flow simulators are compared. Then, a cooling magma chamber is modeled and the heat transfer between the magma chamber and the surrounding formation is studied. The advantages and disadvantages of using HYDROTHERM to model magmatic geothermal systems are discussed. A similar case of a magma chamber is modeled using AUTOUGH2 and the advantages and disadvantages of using AUTOUGH2 compared to using HYDROTHERM are studied.

2. MODELING CHALLENGES

The main challenge associated with modeling flow at the high temperature and pressure conditions observed in magmatic geothermal systems is the treatment of the highly non-linear fluid properties. The phase diagram for pure water using the IAPWS-97 formulation is shown in Figure 1 with the critical point represented by an asterisk. The gradients in fluid properties become very large near the critical zone so these properties can change drastically with small changes in temperature and/or pressure. Hence, convergence can be difficult, especially under high velocities. The existing flow simulators capable of simulating supercritical simulation use different thermodynamic formulations to describe the thermodynamic conditions. At a given point, the thermodynamic conditions are described in terms of a few variables called ‘dependent variables’. In HYDROTHERM and STAR, pressure and enthalpy are used as the dependent variables to uniquely specify the thermodynamic state of the fluid in the single- and two-phase regions as well as in the supercritical region. Hence, switching dependent variables when crossing phase region boundaries is avoided but the dependent variables are not the same as the thermodynamic formulation used so look-up tables must be used to determine flow properties. The TOUGH2 based codes use different thermodynamic formulation, TOUGH2 uses the IFC-67 formulation (IFC, 1967) but in AUTOUGH2 the IFC-67 formulation was superseded by the IAPWS-97 formulation (Wagner et al., 2000). The dependent variables are the same as those of the thermodynamic formulation so they depend on the phase region. In AUTOUGH2, pressure and temperature are used as dependent variables for liquid and vapor, pressure and gas saturation are used in the two-phase region, and density and temperature are used in the supercritical region. The IFC-67 and IAPWS-97 formulations both operate for up to 800°C and 100 MPa, the HOTH2O extension to STAR operates in the same temperature and pressure range but HYDROTHERM can simulate temperatures up to 1200°C and pressures up to 1,000 MPa.

Restrictions on numerical grid components, is another important factor to consider when choosing which simulator to use to model magmatic geothermal systems. Finite difference (FD) method is used in HYDROTHERM and STAR but integrated finite difference (IFD) method, formally equivalent to a finite volume (FV) method, is used in the TOUGH2 based codes. The FD method is limited to rectangular or radial grids, hence imposing restrictions in representing complex geometry. As a result, modeling magmatic intrusions that are small scaled compared to the reservoir would be inefficient because it requires a large part of the reservoir to be modeled with relatively small elements. The IFD method allows for more geometrical flexibility and the possibility of using discrete elements to represent the intrusions. The applicability of the FD based code, HYDROTHERM, and the IFD based code AUTOUGH2 are studied further in the following sections.

Figure 1: Phase diagram for pure water using the IAPWS-97 formulation covering the range 0-800°C for temperature and 0-100 MPa for pressure.

3. HYDROTHERM

A model of a cooling magma body in a hydrostatic reservoir studied by Hayba and Ingebritsen (1997) was reproduced in order to investigate the advantages and disadvantages of using HYDROTHERM to model magmatic geothermal systems. First, the groundwater flow near a cooling magma body at a temperature of 900°C was studied. Then, the effects of the pluton depth and size on the thermal behavior in the reservoir were examined to study the importance of including the magmatic intrusions in the models of magmatic geothermal reservoirs. Finally, the advantages and disadvantages of using HYDROTHERM to model these magmatic systems were summarized.

3.1 Model Description

Groundwater flow near a cooling pluton was investigated using HYDROTHERM. Vertical symmetry was assumed so only half of the system was modeled to increase efficiency. Hence, a pluton with a depth of 2 km and a half thickness of 0.5 km was modeled at
a depth of 2 km as shown in Figure 2. The overall dimensions of the two-dimensional model were 10 km × 4 km and the surface temperature and pressure were set constant at 20°C and 1 atm. The initial temperature of the pluton was set as 900°C and the pressure was defined approximately 10% less than lithostatic pressure. For the host rock, the initial temperature gradient was set as 20°C/km and the pressure was assumed to be hydrostatic. The left boundary is impermeable and insulating to represent the vertical plane of symmetry while the right boundary is set as an open boundary at 20°C/km and hydrostatic pressure. It is located far away from the pluton and does not have much impact on the temperature distribution. The bottom boundary is impermeable and has a constant heat flux of 63 mW/m² into the host rock but no heat flux into the pluton.

Figure 2: A numerical model of a cooling pluton using HYDROTHERM.

Hayba and Ingebritsen (1997) account for the effects of the brittle/ductile transition by decreasing the permeability at higher temperatures as shown in Figure 3. At temperatures below 360°C the permeability is set as 10⁻¹⁶ m² and at 360°C the permeability decreases log linearly to 10⁻²² m² at 500°C. Thus, it is assumed that the intrusion becomes brittle and that fractures develop as the pluton cools down, thereby making it more permeable. In addition, the latent heat of crystallization is accounted for by using Hanson and Barton’s approach (1989) so the heat capacity of the pluton is doubled, i.e. increased to 2000 J/(kg K), for temperatures between 900°C and 750°C. Other rock properties for the pluton and the host rock are summarized in Table 1.

Figure 3: Permeability as a function of temperature to approximate the effect of the brittle-ductile transition.

Table 1: Rock properties for the pluton and host rock

<table>
<thead>
<tr>
<th>Property</th>
<th>Pluton</th>
<th>Host rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity [%]</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Heat capacity [J/(kg K)]</td>
<td>1000 for T&lt;750°C, 2000 for T≥750°C</td>
<td>1000</td>
</tr>
<tr>
<td>Thermal conductivity [W/(m K)]</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Rock density [kg/m³]</td>
<td>2500</td>
<td>2500</td>
</tr>
</tbody>
</table>
3.2 Temperature Distribution
At the beginning of the simulation, immediately following the intrusion of igneous rock, the flow in the reservoir is dominated by thermal pressurization that drives the fluids away from the pluton. Figure 4 shows the temperature distribution 10 years after the intrusion with black lines representing the fluid flow vectors and black dots representing the tails of the vectors. Hayba and Ingebritsen (1997) discussed the influence of permeability on the thermal transfer in the reservoir. They showed that for host rock permeabilities equal to $10^{-16} \text{ m}^2$ thermal pressurization was only dominant during the first few hundred years but for lower permeabilities thermal pressurization is a significant force for several thousand years following the intrusion. Thus, the duration of thermal pressurization dominating the flow varies inversely with the permeability of the host rock but it does vary directly with porosity and the temperature contrast between the pluton and its host (Delaney, 1982). Hayba and Ingebritsen (1997) also showed that for host-rock permeabilities of $10^{-15} \text{ m}^2$ or greater, the heat transfer is advection dominated while it is conduction dominated for lower permeabilities.

![Temperature distribution](image)

Figure 4: Temperature distribution [°C] 10 years after the intrusion (dimensions are in km). Flow is dominated by thermal pressurization (dots represent the tails of flow vectors).

The temperature distribution in the reservoir was simulated for up to 60,000 years after the intrusion. The temperature distribution after 5,000 years, 30,000 years, and 60,000 years are shown in Figure 5. A density-driven convection system develops after the initial period of flow driven by thermal pressurization (Figure 4). However, the rock is relatively impermeable ($k = 10^{-16} \text{ m}^2$) so advective heat transport is minor and conduction is the dominant heat transfer mechanism. The corresponding results published by Hayba and Ingebritsen (1997) show similar conduction dominated heat transfer (Figure 6) although the temperature distribution is somewhat different from the results presented in this paper. The same goes for the maximum fluid velocities, compared in Table 2. The temperature distribution at 5,000 years was found to be sensitive to the exact location of the boundaries of temperature and pressure initial conditions near the pluton but the exact location of the boundaries was not as important for the thermal distribution after 30,000 and 60,000 years.

### Table 2: Maximum fluid-particle velocities for steam ($V_s$) and water ($V_w$)

<table>
<thead>
<tr>
<th>Time</th>
<th>Maximum fluid velocity</th>
<th>Maximum fluid velocity calculated by Hayba and Ingebritsen (1997)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000 years</td>
<td>$V_w = 0.95 \text{ m/year}$</td>
<td>$V_w = 1.4 \text{ m/year}$</td>
</tr>
<tr>
<td></td>
<td>$V_s = 0.27 \text{ m/year}$</td>
<td>$V_s = 1.1 \text{ m/year}$</td>
</tr>
<tr>
<td>30,000 years</td>
<td>$V_w = 1.19 \text{ m/year}$</td>
<td>$V_w = 0.47 \text{ m/year}$</td>
</tr>
<tr>
<td>60,000 years</td>
<td>$V_w = 0.21 \text{ m/year}$</td>
<td>$V_w = 0.12 \text{ m/year}$</td>
</tr>
</tbody>
</table>

A bug in the step function for the temperature dependence of the heat capacity of the pluton has been found in HYDROTHERM according to O. Abramov (personal communication, November 3, 2013) which could explain the difference in thermal distribution. In the case presented in this paper, a step function was mimicked by a very steep ramp function while the step function was used in the case published by Hayba and Ingebritsen (1997). Thus, in order to compare the results, a step function was used instead of the ramp function and the resulting temperature distributions are shown in Figure 7. The results match the results published by Hayba and Ingebritsen (1997) (Figure 6) well. The maximum fluid velocities also match well except at 5,000 years, but the results at that time were sensitive to the exact location of the boundaries of the pressure and temperature initial conditions.
Figure 5: Temperature distribution [°C] a) 5,000 years after the intrusion, b) 30,000 years after the intrusion, and c) 60,000 years after the intrusion (dimensions are in km).

Figure 6: Temperature distribution [°C] published by Hayba and Ingebritsen (1997) a) 5,000 years after the intrusion, b) 30,000 years after the intrusion and c) 60,000 years after the intrusion.
Figure 7: Temperature distribution [°C] when mimicking a step using a ramp function for temperature dependence of the heat capacity of the pluton a) 5,000 years after the intrusion, b) 30,000 years after the intrusion, and c) 60,000 years after the intrusion (dimensions are in km).

Table 3: Maximum fluid-particle velocities for steam ($V_s$) and water ($V_w$) for simulations shown in Figure 7.

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<tbody>
<tr>
<td>5,000 years</td>
<td>$V_w = 2.75$ m/year</td>
<td>$V_w = 1.4$ m/year</td>
</tr>
<tr>
<td></td>
<td>$V_s = 0.86$ m/year</td>
<td>$V_s = 1.1$ m/year</td>
</tr>
<tr>
<td>30,000 years</td>
<td>$V_w = 0.50$ m/year</td>
<td>$V_w = 0.47$ m/year</td>
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<td>$V_w = 0.12$ m/year</td>
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</tbody>
</table>
3.3 Effect of Pluton Size and Depth

The effect of the size and depth of the cooling pluton previously studied was investigated but with rock permeability increased to $10^{-15} \text{ m}^2$ to account for advection dominated heat transfer. Figure 8a shows the temperature distribution 5,000 years after the intrusion for the pluton previously studied, i.e. with dimensions $0.5 \times 2 \text{ km}$ at a depth of $2 \text{ km}$. Figure 8b shows the temperature distribution for a pluton with a double thickness, i.e. with dimensions $1 \times 2 \text{ km}$ and at a depth of $2 \text{ km}$, and in Figure 8c the temperature distribution is shown for a pluton located deeper in the reservoir, i.e. a pluton with dimensions $0.5 \times 2 \text{ km}$ located at a depth of $3 \text{ km}$. In figure 9, the same cases are shown 15,000 years after the intrusion.

Figure 8: Temperature distribution [°C] 5,000 years after the intrusion for a) a pluton of dimensions $0.5 \times 2 \text{ km}$ at a depth of $2 \text{ km}$, b) a pluton of dimensions $1 \times 2 \text{ km}$ at a depth of $2 \text{ km}$, and c) a pluton of dimensions $0.5 \times 2 \text{ km}$ at a depth of $3 \text{ km}$.
Figure 9: Temperature distribution [°C] 15,000 years after the intrusion for a) a pluton of dimensions 0.5 × 2 km at a depth of 2 km, b) a pluton of dimensions 1 × 2 km at a depth of 2 km, and c) a pluton of dimensions 0.5 × 2 km at a depth of 3 km.

Advection is the dominant heat transfer mechanism in these cases due to a higher rock permeability which results in more rapid temperature changes than observed earlier for the conduction dominated heat transfer. Increasing the thickness of the pluton (Figures 8b and 9b) causes a change in the flow pattern due to more heat being added to the system. Instead of the upwelling plume rising only from the center of the pluton, it is also rising at the top of the outer corner of the pluton which results in a different temperature distribution than observed for a thinner pluton. The depth of the pluton does not affect the flow pattern as much as the thickness of the pluton, but when the pluton is located deeper in the reservoir (Figures 8c and 9c) the rock near the surface does not heat up as fast and not to the same temperatures because the pluton must heat more volume of overlying rock. These results have shown the large effect a magmatic intrusion has on the hydrothermal behavior of the geothermal system. Thus, it is important to include the heat sources of the systems in the reservoir models when predicting the thermal behavior of the system.
3.4 Applicability of Using HYDROTHERM to Simulate Magmatic Systems

The main reason for reproducing the model of a cooling pluton by Hayba and Ingebritsen (1997) was to get familiar with HYDROTHERM and investigate the advantages and disadvantages of using HYDROTHERM to model the deep roots of magmatic geothermal systems. The main advantage of using HYDROTHERM is that the simulator can be used to model supercritical conditions with temperatures up to 1200°C and pressure up to 1,000 MPa. Modeling such high temperatures could be crucial when studying magmatic geothermal systems where the heat source could be a magma chamber or multiple intrusions with temperatures ranging from 700°C to 1200°C. The brittle-ductile transition could be approximated as well as the latent heat of crystallization because of the possibility of using temperature dependent rock properties. Another advantage is the easy-to-use graphical user interface allowing the user to set up the grid and reservoir properties in easy steps and to watch the change in reservoir properties as they are calculated.

The main disadvantage of using HYDROTHERM is that the code uses finite-difference formulation which limits the computational grid to regular rectangular elements. Although, the requirement of using structured grids did not cause problems when modeling a simple rectangular pluton, it does cause restrictions in representing complex geological structures and topography often observed in geothermal reservoirs. Another disadvantage is that only pure water can be simulated using HYDROTHERM. Hence, it would not be possible to account for salt present in the brine, and implementing tracer transport would likely be difficult. However, in cases where the geological structure is simple and pure water assumptions are valid, HYDROTHERM could be effectively used to study the hydrothermal system.

4. AUTOUGH2

The advantages and disadvantage of using AUTOUGH2 instead of HYDROTHERM to model a cooling intrusion were investigated. AUTOUGH2 does not have all the same features as HYDROTHERM so some properties previously modeled (Figure 2) could not be modeled using AUTOUGH2. The resulting pluton modeled with AUTOUGH2 was also modeled using HYDROTHERM for comparison and the applicability of AUTOUGH2 was discussed.

4.1 Cooling Pluton Simulated Using AUTOUGH2

AUTOUGH2 uses an integrated finite difference formulation, formally equivalent to a finite volume method, giving it flexibility to model irregular computational grids. However, for this case a structural mesh was used to make the comparison between AUTOUGH2 and HYDROTHERM easier. A few changes were made to the model shown in Figure 2. Temperature dependent rock properties cannot be modeled using AUTOUGH2. Thus, the permeability of the host rock was set constant to $10^{-16}$ m$^2$ instead of modeling the temperature dependent behavior illustrated in Figure 3, and the permeability of the pluton was set as $10^{-20}$ m$^2$. In addition, the temperature of the pluton was set as 750°C instead of 900°C because AUTOUGH2 cannot model temperatures higher than 800°C. The same case was modeled using HYDROTHERM and the temperature distribution 25,000 years after the intrusion was similar for both models, as shown in Figure 10. Due to the low permeability of the rock, the heat transfer is dominated by conduction.

Figure 10: Temperature distribution [°C] 25,000 years after the intrusion using a) AUTOUGH2, and b) HYDROTHERM.
4.2 Applicability of Using AUTOUGH2 to Simulate Magmatic Systems

The main advantage of using AUTOUGH2 to model magmatic geothermal systems is the possibility of using an unstructured grid which can be essential to represent complex geographical structures. In addition, the intrusions in magmatic geothermal reservoirs can be relatively thin and in order to model them efficiently, discrete elements could be used in AUTOUGH2. Multi-component fluids can also be modeled in AUTOUGH2 so tracer tests can be carried out and simulated to study the flow and other properties of the system. The main disadvantage of AUTOUGH2 is that temperatures higher than 800°C cannot be modeled but the temperature of the intrusions could reach up to 1200°C. Another disadvantage compared to HYDROTHERM is that the rock properties cannot be defined temperature dependent. Hence, the brittle-ductile transition cannot be approximated by increasing the permeability for lower temperatures to account for fractures developing when the intrusion becomes brittle. One option would be to run the AUTOUGH2 simulation for a short period at a time, have a program read the output temperature and update the permeability of the model before continuing the simulation but that approach would be quite inefficient. However, if the temperature of the intrusion is less than 800°C and the topography of the system is highly complex, it would be feasible to use AUTOUGH2 instead of HYDROTHERM to simulate the magmatic system.

5. CONCLUSIONS

Modeling challenges associated with modeling magmatic geothermal systems where temperatures can reach supercritical conditions were discussed. Two simulators both capable of modeling fluid at supercritical temperatures, HYDROTHERM and AUTOUGH2, were studied for modeling a cooling magma chamber. The effect of the pluton depth and size was shown to have large effects on the thermal transfer between the pluton and the host rock. Hence, it is important to include the heat sources in magmatic geothermal models to answer questions relevant to the field management of these magmatic systems. The advantages and disadvantages of each simulator were discussed. HYDROTHERM is restricted to using a rectangular grid while AUTOUGH2 is more flexible. Thus, AUTOUGH2 could be more applicable when modeling complex geometry or small scaled intrusions in large reservoirs where discrete elements could be efficient. HYDROTHERM can model a larger range in temperature and pressure than AUTOUGH2 and is capable of modeling temperature dependent rock properties which can be useful to approximate the effects of the brittle-ductile transition. The graphical user interface of HYDROTHERM is also easy to use but the simulator is limited to pure water while AUTOUGH2 can model multi-component fluid. Therefore, the applicability of each simulator depends on the properties of the reservoir being modeled, such as the fluid properties, topography, and temperature.

REFERENCES


Brikowski, T.H.: Modeling Supercritical Systems with TOUGH2: Preliminary Results Using the EOS1SC Equation of State Module, Proceedings, 26th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2001).


