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Hydrology of a Supercritical Flow Zone Near a Magmatic Intrusion in the IDDP-1 Well – Insights from Numerical Modeling

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ABSTRACT

The contact zone between a magmatic intrusion and circulating meteoric fluids is of great interest both for understanding the thermal stucture and hydrological controls of high-enthalpy geothermal systems as well as for improving the future prospects of geothermal power production at near-magmatic temperature and pressure conditions. While there have been numerous complex conceptual and numerical models for this zone, they share in common a sharp drop in permeability at temperatures above the brittle-plastic transition temperature, which produces a boundary across which heat is transferred conductively from the intrusion to meteoric fluids. In addition, studies have recognized that non-linear changes in temperature- and pressure-dependent fluid properties play a critical role in optimizing energy transport. We report numerical simulations of the transient evolution of fluid flow and heat transport in high-enthalpy geothermal systems around cooling intrusions, including the deep, 'supercritical' roots. We employ the CSMP++ fluid flow and heat transport code, and analyze the temperature, pressure, enthalpy, phase state distribution, as well as the contribution of magmatic fluids. For a relatively shallow magma chamber (~2 km depth) and assuming that the onset of permeability reduction occurs above 550°C (reasonable for basalt), the simulations predict that large fluxes of a single-phase fluid of vapor-like density (superheated steam or supercritical fluid, depending on the external hydrostatic pressure) will be present around the intrusion. These results of fluid phase distribution, temperature and fluid enthalpy above the intrusion are generally consistent with observations from the Iceland Deep Drilling Project, Well 1 (IDDP-1), and indicate that such hydrological models may be useful for informing future geothermal exploration at near-magmatic conditions.

1. INTRODUCTION

The deeper (>2 km), very high enthalpy (up to >3000 kJ/kg) parts of volcanic geothermal systems have received growing attention as potential targets for future geothermal exploration. The ratio of buoyancy to viscous forces in pure water increases by roughly an order-of-magnitude near and above the critical point, permitting extremely high rates of mass and energy transport (Yano and Ishido, 1998; Friðleifsson et al., 2014). However, little is known about the hydrology of geothermal systems at the high temperatures (>375 °C) and pressures (>220 bars) necessary for supercritical fluids. This is partially due to the fact only a few wells have been drilled to such conditions, and have obtained seemingly conflicting observations, with some wells encountering very high rates of mass and energy transport and others nearly impermeable conditions (Fournier, 1991; Muraoka et al., 1998). More quantitative insight into the fluid phase state distribution and temperature/pressure conditions around a cooling intrusion could be provided by numerical modeling, but only relatively recently have numerical simulation codes advanced to the point where they can adequately simulate multiphase, near-critical fluid flow up to near-magmatic conditions (see Ingebritsen et al., 2010, for a review).

More recently, direct observations about the conditions likely to be encountered around a cooling intrusion were provided by The Iceland Deep Drilling Project, which drilled well IDDP-1 at the Krafla geothermal field into a magma intrusion at ~ 2 km depth (Elders et al., 2014). Drilling began in 2009 and the well underwent heating and flow testing until July 2012, when it had to be shut down due to faulty wellhead equipment and corrosion damage. During the flow tests, the borehole produced superheated steam with a wellhead temperature of 450 °C and enthalpy of up to 3150 kJ/kg and indicated a potential electricity output of 15-40 MWe. Axelsson et al. (2014) estimated on the basis of temperature measurements obtained during drilling that the fluid was derived from a ~45 m thick permeable layer above a cooling intrusion. However, the factors governing recharge and heat transfer between the fluid and the intrusion were unclear.

In a different study currently under preparation, we identify the main factors governing the deep hydrology of geothermal systems to be system-scale permeability, the brittle-ductile transition temperature and the depth to the top of the intrusion. For the Krafla geothermal system, these three parameters can be constrained reasonably well. Based on hydrological studies, the permeability at Krafla has been estimated to be approximately 10^{-15} m^2 (Bodvarsson et al., 1984). Geophysical studies have estimated the depth to the top of the heat source to be 2-3 km (Brandsdottir et al., 1997), and these estimates seem to be confirmed by the experience of the IDDP. Based on these estimates, the objective of this study is to compare model predictions against the observations acquired by the IDDP, both to get a sense of the plausibility of our current models as well as to inform future efforts to explore for supercritical geothermal resources.

2. METHODS

This study employs the fluid flow and heat transfer simulation code Complex Systems Modelling Platform (CSMP++). The computational method has been described previously (Matthai et al., 2007) and has recently been benchmarked against hydrothermal fluid flow simulation platforms HYDROTHERM and TOUGH2 (Weis et al., 2014), with all tests showing a close correspondence within the ranges of conditions over which the applicability of the codes overlap.

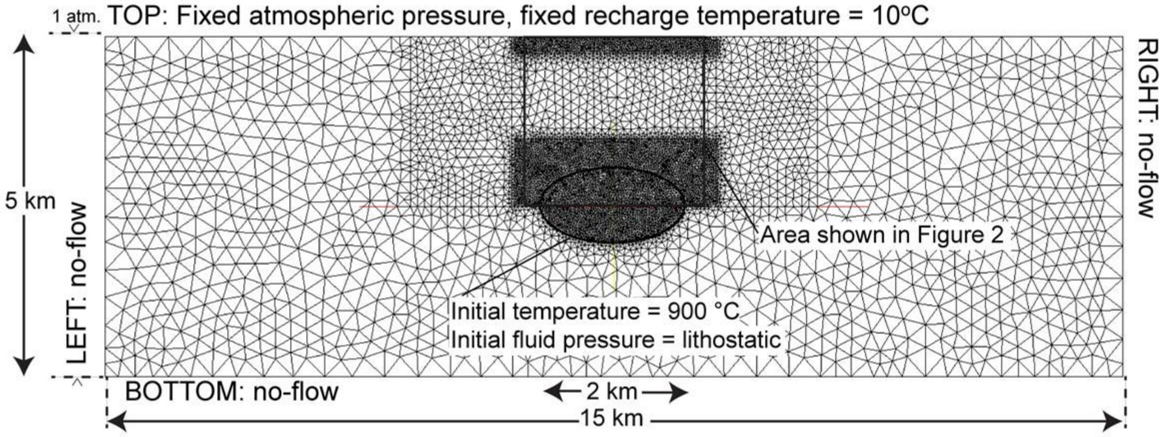

Figure 1. Model set-up, finite element discretization and boundary conditions.

2.1 Model set-up

The model set-up consists of a 2 km wide, 1 km thick idealized elliptical heat source centered at 2.5 km depth (top at 2 km depth) in a hydrostatically-pressured porous medium 5 and 15 km in vertical and horizontal extent (Figure 1). The computational domain consists of roughly ~15,000 finite elements, with a higher density of elements towards the heat source. Rock and fluid properties are listed in Table 1 and Table 2, respectively. The fluid is assumed to be pure water according to the equation of state of Haar et al. (1984). Initially, the porous medium is saturated with water and thermally equilibrates with a basal heat flux of 100 mW m^{-2} (corresponding to thermal gradient of ~45 °C/km assuming a thermal conductivity of 2.25 W m^{-1} C^{-1}). The temperature in the heat source is set to 900 °C and the fluid pressure lithostatic. The left, right and bottom boundaries are no-flow, while the top boundary is treated as open, allowing fluids to discharge or recharge as needed in order to maintain a constant pressure of 1 bar. Although similar symmetrical 2-D models have commonly used a half-space model in order to reduce computational effort, the full elliptical geometry of the heat source is included in order to avoid artifacts associated with setting a no flow boundary across the plane of symmetry going through the center of the ellipse. The temperature at the top boundary is allowed to vary based on the enthalpy of upflowing fluids, or in the case of recharge, the recharging liquid has a fixed temperature of 10 °C. The rock and fluid are assumed to be in thermal equilibrium at all times.

Table 1. Initial rock properties used in this study.

Initial rock property	Host rock	Magma chamber	Unit
Temperature	+45°C/km depth	900	°C
Porosity	0.1	0.05	-
Permeability	10^{-14} – 10^{-15}	10^{-22} (where T>500°C)	m^2
Heat capacity (isobaric)	880	Temperature-dependent	J/kg°C
Compressibility	10^{-20}	10^{-20}	/bar
Density	2,750	2,750	kg/m^3
Thermal conductivity	2.25	2.25	W/m°C

Although the 'background' permeability of the host rock is assumed to be uniform, a key feature of our model is a temperature-time-dependent permeability. This simulates the effect of thermoelastic stresses on the transition from brittle-dominated deformation, which permits fracture permeability to be maintained, and ductile-dominated deformation, which causes fractures to close and permeability to be dramatically reduced (Fournier, 1999). As adopted by previous studies (Hayba and Ingebritsen, 1997), we assume that permeability decreases in a log-linear fashion from the background value to essentially zero. Hayba and Ingebritsen (1997) assume that the brittle-ductile transition begins at 360 °C , but this value may depend on the rock type and the strain rate (Fournier, 1999). Violay et al. (2012) recently investigated the temperature of the brittle-ductile transition in basalt and estimated a value of 550 ± 100 °C for non-glassy basalt under reasonable confining pressures for shallow crustal magma chambers. Therefore, in this study, permeability begins to be reduced from the background value at 550 °C.

2.2 Computational method

The governing equations of multi-phase mass and energy conservation are solved using a continuum porous medium approach with pressure-enthalpy-based formulation for energy transport implemented in a Control Volume Finite Element Scheme (CVFEM). Weis et al. (2014) describes the computational method in detail, so only a brief review will be presented here.

An extended two-phase form of Darcy's law is used:

$$v_i = -k \frac{k_{ri}}{\mu_i} \ (\nabla p - \rho_i g) \tag{1}$$

where v is the Darcy velocity of phase i, k denotes permeability, k relative permeability, μ viscosity, p total fluid pressure, ρ fluid density, and g acceleration due to gravity. A linear relative permeability model with a liquid residual saturation of 0.3 and vapor residual saturation of zero is adopted, implying there is little interaction between the liquid and vapor phase (Wang and Horne, 2000).

Conservation of pure water fluid mass is described by the following equation:

$$\frac{\delta(\varphi(S_l \rho_l + S_v \rho_v))}{\delta t} = -\nabla \cdot (v_l \rho_l) - \nabla \cdot (v_v \rho_v) + \mathrm{Q}_{\mathrm{H2O}} \tag{2}$$

where S refers to the volumetric saturation of phase i and Q_{H2O} denotes a source term. Conservation of energy accounts for diffusion of heat in the rock and advection of enthalpy by the fluid:

$$\frac{\delta((1-\varphi)\rho_r h_r + \varphi(S_l \rho_l h_l + S_v \rho_v h_v))}{\delta t} = -\nabla \cdot (K \nabla T) - \nabla \cdot (v_l \rho_l h_l) - \nabla \cdot (v_v \rho_v h_v) + \mathrm{Q}_{\mathrm{e}} \tag{3}$$

where the subscript r refers to the rock, h_i denotes the specific enthalpy of the phase indicated, K is thermal conductivity, T is temperature and Q_e is a source term. By assuming that heat transfer by conduction occurs almost entirely within the rock mass, while heat transfer by advection happens exclusively by fluids, the advection-diffusion type equation of energy conservation can be split into a parabolic diffusion and hyperbolic advection part. As a result of operator splitting, rock and fluid can heat or cool at different rates, and extra steps need to be taken to insure that the rock and fluid in a control volume are in thermal equilibrium at all times. This is performed by changing temperature at a constant pressure and redistributing the total enthalpy between rock and fluid at each modeling time step until they each have the same temperature. Due to potential discrepancies between the mass of fluid in the pore volume prior to thermal equilibration and the thermodynamic densities of the fluid after equilibration, thermal equilibrium leads to a pressure source term that can be of critical importance when crossing phase boundaries (Weis et al., 2014).

3. RESULTS

A snapshot of the state of the system after 2500 years of evolution is shown in Figure 2. This time was chosen for the snapshot because it is sufficiently large for the model to reach a state of pseudo-equilibrium in the vicinity of the heating zone above the heat source. An intensely boiling upflow zone has developed over the center of the intrusion. Because the hydrostatic pressure at the depth of the intrusion is less than the critical pressure (220 bars), the system is boiling all the way from the top of the intrusion to the surface, as indicated by the near-horizontal 300 °C. However, in the central base of the upflow zone, the fluid enthalpy is greater than 2 MJ/kg, and single-phase fluid (superheated vapor) with a vapor-like density exists. Significantly, temperatures and enthalpies in the core of this zone are near 400 °C and 3 MJ/kg, even though the brittle-ductile transition temperature is 550 °C.

The change in fluid properties near and within the impermeable intrusion are shown in more detail in Figure 3. Increasing temperatures above 550 °C towards the intrusion cause the rock permeability to decrease from the background value to effectively zero within a 100 meter thick zone. Fluid pressure through the permeable region corresponds to a hot vaporstatic gradient. Once temperature causes permeability to decrease to less than 10^{-17} m^2, the fluid pressure increases sharply to near-lithostatic values. Above the brittle-ductile transition, the fluid enthalpy is dominantly controlled by the temperature gradient, with pressure making an increasing contribution once permeability is below10^{-17} m^2. The vapor pore velocity increases very rapidly from zero to $3*10^{-5}$ m/s (950 m/year) within a very sharp zone above the brittle-ductile transition. However, once temperature decreases below ~425 °C, it decreases slightly and then increases at a lower rate.

4. DISCUSSION AND CONCLUSIONS

In combination with the measurements made during drilling and flow testing, our models allow us to constrain the thermo-hydrological conditions encountered at the IDDP-1 well. The temperature and fluid enthalpy in the core of the zone of superheated steam (~450 °C and 3.1 MJ/kg) between 2-2.1 km depth match very nicely measured values of temperature flow tests of the IDDP-1 well which were obtained from permeable aquifers located at a similar depth. These values make sense in terms of the 'fluxibility' hypothesis (Jupp and Schultz, 2000), which posits that fluid properties within magma-driven hydrothermal systems will reflect conditions at which overall advective heat transport can be maximized. Additionally, it suggests that our selection of parameters (depth to top of intrusion, background system-scale permeability, and brittle-ductile transition temperature) may be appropriate for the downhole conditions of IDDP-1. It is expected that the effects of permeability changes due to chemical reactions (mineral precipitation or dissolution) and rock mechanical factors would be superimposed on this overall system structure as revealed by these models. Weis et al. (2012) showed that such factors can act stabilize a transition zone between vapor-like fluids and external liquid-like fluids in a porphyry copper regime. The same principles are likely valid for dry basaltic magmas, but this needs to be investigated in greater detail.

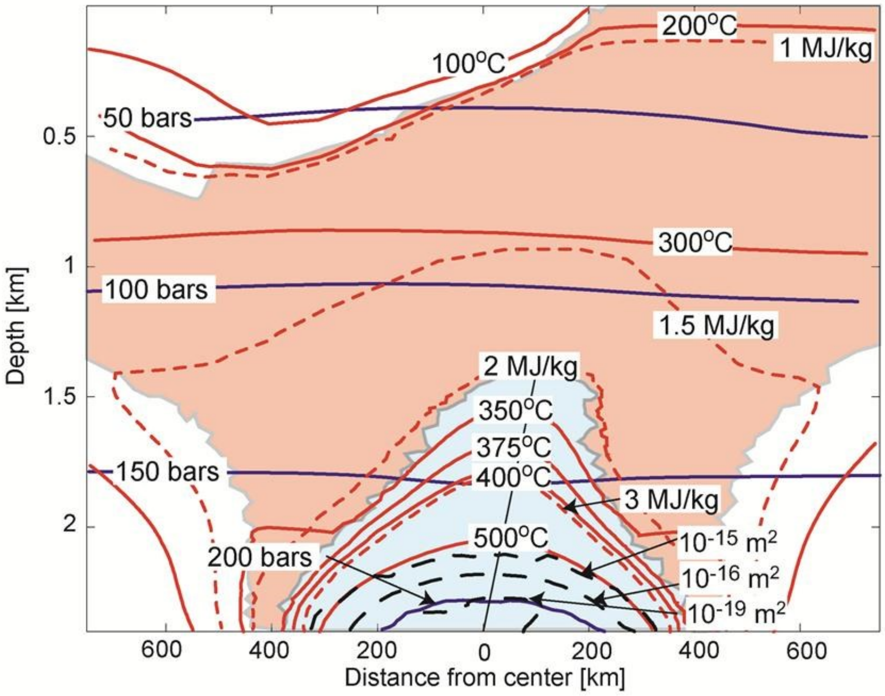

Figure 2. Snapshot showing the state of the system after 2500 years of evolution. Fluid pressure contours are shown by blue lines, temperature contours by red lines, enthalpy contours in dashed red lines, and permeability contours in dashed black lines. The red region represents zones of boiling, while the blue region represents a zone of a single-phase fluid with vapor-like density. White represents single-phase fluid with a liquid-like density.

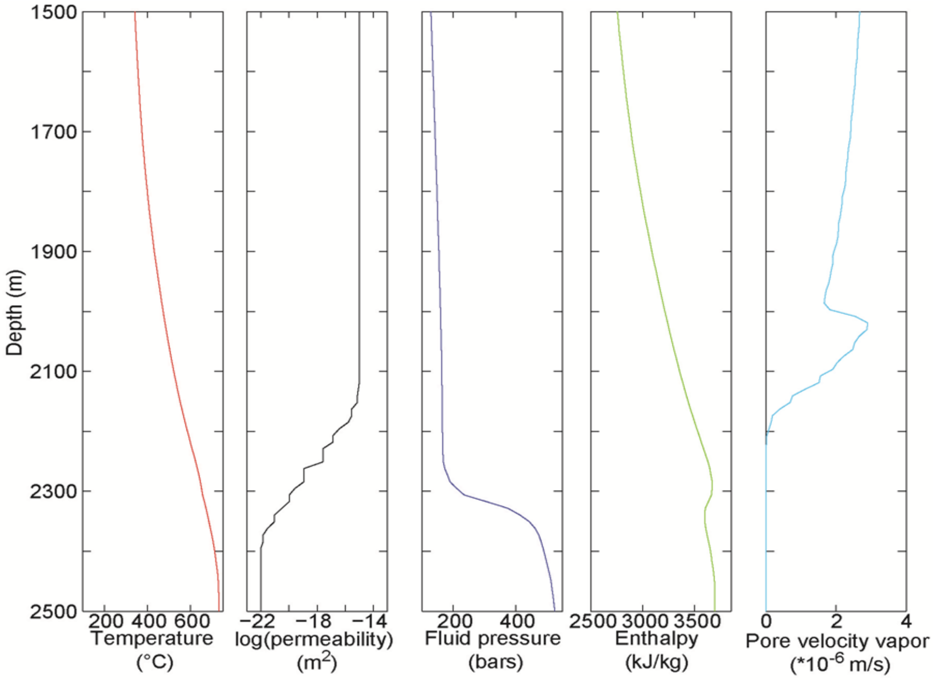

Figure 3. Changes in temperature, permeability, fluid pressure, enthalpy and pore velocity vapor in the zone of superheated steam above the intrusion, along the black line shown in Figure 2.

These models also provide basic insight into the hydrological structure of high-enthalpy geothermal systems. One of the surprising results from these numerical models is that fluid upflow zones are not near isenthalpic or isothermal, especially close to the base of the upflow. The main reason for the decrease in fluid temperature from 550 °C to ~350 °C and in fluid enthalpy from 3500 kJ/kg to ~2000 kJ/kg is believed to be variable mixing between lower-enthalpy meteoric fluids that were heated up at a greater distance from the intrusion and high-enthalpy meteoric fluids that reached temperatures >400 °C. Thus, fluid mixing can explain how deep, very high-enthalpy zones can exist even if the enthalpy of fluid in the natural state of the upflow zone is much lower. Future studies will employ passive tracers to quantify fluid mixing and better constrain flow behavior.

In conclusion, this study exhibits the potential of the state-of-the-art fluid flow and heat transfer code CSMP++ to the study of the deep hydrological structure of volcanic geothermal systems. Reasonable confidence in the model predictions is justified by the fairly close correspondence between direct observations made at the IDDP and the predicted temperature and fluid enthalpy observed in this generic model. Future studies will focus on improving our understanding of the deep hydrology of geothermal systems by creating more advanced models including heterogeneous/anisotropic permeability, transient permeability changes due to mineral precipitation/dissolution, saline fluids, and more realistic heat source geometries, among other possible advancements. However, the present results suggest an understanding of the first-order controls on supercritical/superheated fluid reservoirs is at hand.

REFERENCES

Axelsson, G., Egilson, T., and Gylfadóttir, S. S., 2014, Modelling of temperature conditions near the bottom of well IDDP-1 in Krafla, Northeast Iceland: Geothermics, v. 49, p. 49-57.

Bodvarsson, G. S., Benson, S. M., Sigurdsson, O., Stefansson, V. and Eliasson E. T., 1984, The Krafla geothermal field, Iceland: 1. Analysis of well test data. Water Resources Research. V. 20:11, 1515-1530

Elders, W. A., Friðleifsson, G. Ó., and Albertsson, A., 2014, Drilling into magma and the implications of the Iceland Deep Drilling Project (IDDP) for high-temperature geothermal systems worldwide: Geothermics, v. 49, p. 111-118.

Fournier, R. O., 1991, The transition from hydrostatic to greater than hydrostatic fluid pressure in presently active continental hydrothermal systems in crystalline rock: Geophysical Research Letters, v. 18, no. 5, p. 955-958.

Fournier, R. O., 1999, Hydrothermal processes related to movement of fluid from plastic into brittle rock in the magmatic-epithermal environment: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 94, no. 8, p. 1193-1211.

Friðleifsson, G. Ó., Elders, W. A., and Albertsson, A., 2014, The concept of the Iceland deep drilling project: Geothermics, v. 49, p. 2-8.

Haar, L., Gallagher, J. S., and Kell, G. S., 1984, NBS/NRC Steam Tables, Washington D.C., Hemisphere, p. 320.

Hayba, D. O., and Ingebritsen, S. E., 1997, Multiphase groundwater flow near cooling plutons: J. Geophys. Res., v. 102, no. B6, p. 12235-12252.

Ingebritsen, S. E., Geiger, S., Hurwitz, S., and Driesner, T., 2010, Numerical simulation of magmatic hydrothermal systems: Rev. Geophys., v. 48, no. 1, RG1002.

Jupp, T., and Schultz, A., 2000, A thermodynamic explanation for black smoker temperatures: Nature, v. 403, no. 6772, p. 880-883.

Matthäi, S. K., Geiger, S., Roberts, S. G., Paluszny, A., Belayneh, M., Burri, A., Mezentsev, A., Lu, H., Coumou, D., Driesner, T., and Heinrich, C. A., 2007, Numerical simulation of multi-phase fluid flow in structurally complex reservoirs: Geological Society, London, Special Publications, v. 292, no. 1, p. 405-429.

Violay, M., Gibert, B., Mainprice, D., Evans, B., Dautria, J.-M., Azais, P., and Pezard, P., 2012, An experimental study of the brittle-ductile transition of basalt at oceanic crust pressure and temperature conditions: Journal of Geophysical Research: Solid Earth, v. 117, no. B3, p. B03213.

Wang, C.T., and Horne, R.N.: Boiling Flow in a Horizontal Fracture, *Geothermics*, **29**, (1999), 759-772.

Weis, P., Driesner, T., Coumou, D., and Geiger, S., 2014, Hydrothermal, Multi-phase Convection of H2O-NaCl Fluids from Ambient to Magmatic Temperatures: A new Numerical Scheme and Benchmarks for Code Comparison: Geofluids, (in press), doi: 10.1111/gfl.12080

Weis, P., Driesner, T., and Heinrich, C. A., 2012, Porphyry-Copper Ore Shells Form at Stable Pressure-Temperature Fronts Within Dynamic Fluid Plumes: Science, v. 338, no. 6114, p. 1613-1616.

Yano, Y., and Ishido, T., 1998, Numerical investigation of production behavior of deep geothermal reservoirs at super-critical conditions: Geothermics, v. 27, no. 5–6, p. 705-721.