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MODELING THERMAL FLUX FROM HOT ROCK INTO FLUID: IMPLICATIONS FOR GEOTHERMAL ENERGY

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INTRODUCTION

Geothermal energy supplies less than 2% of the renewable energy produced in the United States in large part because traditional system requirements limit geographic availability (Sharmin et. al., 2023). Traditional systems require Hot Wet Rock (HWR) reservoirs, meaning geothermal reservoirs with sufficient heat, permeability, and fluids to extract enough thermal energy to produce electricity (Sharmin et. al., 2023). This is a significant geographical limitation because most geothermal reservoirs in the United States with sufficiently high heat flows lack the fluids and permeability necessary to extract thermal energy using traditional methods. One method to reduce this limitation is through Enhanced Geothermal Systems (EGS), which only require a high geothermal gradient to be energetically favorable. EGS typically rely on increasing the permeability of a thermal reservoir through hydraulic fracturing, which is pumping fluids under a high-pressure differential such that fractures form in the reservoir, increasing the hydraulic conductivity (Moska et. al., 2021). However, hydraulic fracturing can cause induced seismicity due to the extensive drilling and increase pore fluid pressure introduced (Gaucher et. al., 2015). Therefore, it is advantageous to implement EGS in regions with preexisting weaknesses in the subsurface, such that lower intensities of hydraulic fracturing are required.

Normal fault damage zones are promising locations for EGS because of the elevated geothermal gradients associated with normal faults and the preexisting weaknesses present in the damage zone. A normal fault damage zone is the area of intensely fractured rock adjacent to a normal fault that increases in fracture number and intensity as the fault forms and evolves (e.g., Peacock and Sanderson, 1996; Choi et al., 2016). The Basin and Range region of the western United States has many normal faults with extensive damage zones, making these regions promising for EGS.

Because of the difficulties of elucidating subsurface fracture geometry and the expense required to complete a detailed field survey, we use computational modeling in MATLAB to simulate the thermal flux from a geothermal reservoir into the working fluid of an EGS to extract the thermal energy required for the generation of electricity. An additional motivation for using MATLAB for this computational modeling is economic accessibility. There are designer programs on the market that model hydraulic fracturing and thermal and fluid flow which are typically used in industry. However, these programs are costly, making them inaccessible for most institutions, especially for small research programs. One motivation for this project is to apply widely available software, MATLAB, to develop a protocol that can take the place of these more expensive software. In this project, we aimed to answer two primary research questions:

1. How does the fracture geometry of a geothermal reservoir affect the amount of energy extracted from the system?

2. Do normal fault damage zones have a fracture geometry that is effective for geothermal energy extraction?

BACKGROUND

Geothermal Energy Production

Traditional systems consist of hot wet rock (HWR), meaning they require high permeability, a seal, fluids, and high heat flow. Most HWR reservoirs are located

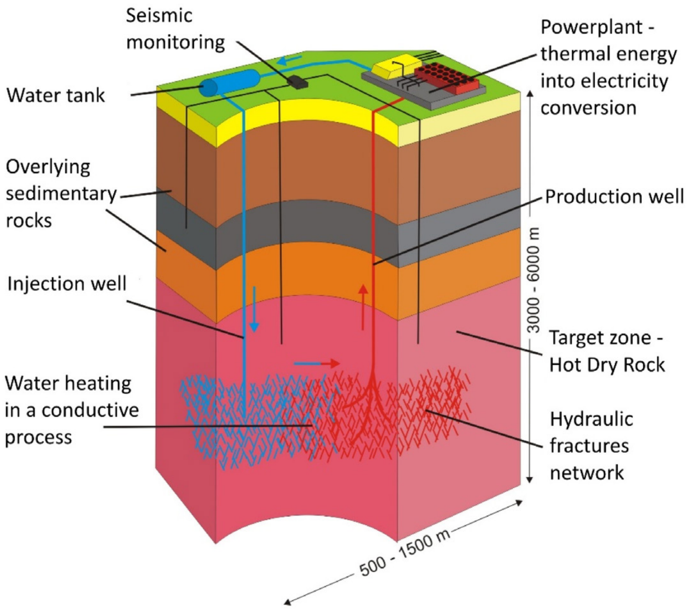

Figure 1. Diagram of an EGS plant (from Moska, 2021).

near tectonic boundaries or magmatic bodies (e.g., Barbier, 2002). However, most non-magmatic heat sources in the United States are concentrated in deeper hot dry rock (HDR) reservoirs that lack the fluids, permeability, and seal of HWR reservoirs. HDR reservoirs can be formed by uplift that increases the geothermal gradient of a region and often occur near faults.

Enhanced Geothermal Systems (EGS) extract energy from HDR reservoirs, greatly increasing the geographic availability of geothermal energy in the United States, especially because so many normal faults in the Basin and Range Province are associated with high heat flows. EGS uses directional drilling and hydraulic fracturing into HDR reservoirs to increase the thermal reservoirs' permeability. Cold fluid is pumped into the reservoir at depth by an injection well, and hot fluid is drawn out by an extraction well (Fig. 1). Upon reaching the surface, the hot fluid can be used for heating or may flash to steam, due to the lack of overburden pressure; this thermal energy can be used for heating or for electricity generation, depending on the system (Sharmin et. al., 2023).

Structural Controls

A fault damage zone is the volume of intensely fractured rock that surrounds a fault because of fault-altered stress fields. This rock is considerably weaker than rock further away from the fault, and these fractures may enhance permeability; however, it is difficult to predict how far these zones can extend from the fault plane (e.g., Peacock and Sanderson, 1996; Choi et al., 2016). Previous research has asserted that elucidating the subsurface geometry of a fracture zone is essential in estimating the geothermal potential of a region because the fracture geometry and type determines the fluid flow rate (e.g., Anderson and Fairley, 2008). Previous research has also established that damage zone fracture geometry relies on the dominant fault geometry and fault interactions. Not only is geothermal potential higher in fault proximal damage zones (Fig. 2A), but it is higher in locations where the strike of a fault changes (Fig. 2B), two faults interact across a linked transfer zone (Fig. 2C), or multiple faults share transfer zones (Fig. 2D) (e.g., Faulds and Hinz, 2015).

In this study, we investigate the viability of the implementation of EGS systems in normal fault damage zones because normal faults are often associated with high geothermal gradients, and the natural fracturing that characterizes damage zones could reduce the intensity of hydraulic fracturing necessary to reach sufficient permeability.

METHODS

Model Workflow and Assumptions

The first step in the modeling process was to assume a fracture geometry that we could use to construct and validate the model. Our assumed geometry represents a hot reservoir in previously intact rock that was then hydraulically fractured to create a cylindrically shaped permeable reservoir with permeability decreasing towards the outer rim of the cylindrical reservoir (Fig. 3). The cross-sectional scale of the modeled fractured

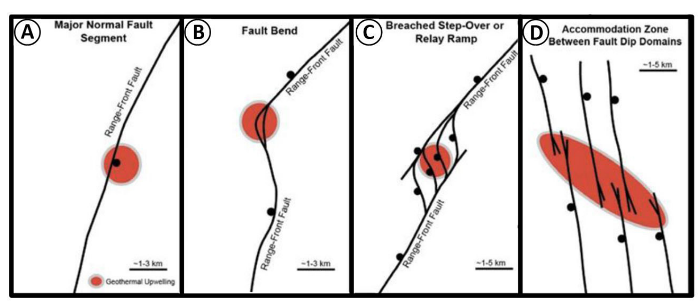

Figure 2. Common fault-related structural settings for geothermal systems in the Great Basin region (adapted from Faulds and Hinz, 2015).

cylinder is 200 meters in diameter, consistent with the scale of hydraulic fracturing used in both EGS systems and oil & gas production (David Clay, *pers. comm.*). The length of the reservoir from injection borehole to extraction borehole was set at 2,000 m, also consistent with real-world EGS. We assumed that the fluid would enter the reservoir at room temperature (300 K) and be extracted at 500 K, a typical temperature used in electricity generation (e.g., Sharmin et. al., 2023). We assumed that fractures initiated by EGS would propagate outward from the borehole in an elliptical shape, resulting in a star-like appearance in cross-section (Fig. 3b). We split the cylindrical shell into five concentric rings for computational convenience. We created images of these concentric ring cross-sections in Adobe Illustrator and processed them in MATLAB. We used an image-processing program in MATLAB to count the number of dark pixels to light pixels in each concentric ring to create a ratio of intact rock (dark pixels) to fractured rock (light pixels) that would govern rock permeability in a real system.

Governing Equations

We calculated the permeability of each concentric ring by taking the weighted average of the ratio of fractured rock area, θ, to intact rock area, 1 - θ, using values of 2×10^{-11} m^2 for the permeability of intensely fractured rock, p_f, and of 5×10^{-15} m^2 for the permeability of intact rock, p_R (Equation 1) (Zhang and Xie, 2019).

$$p = p_f\theta + p_R(1 - \theta) \tag{1}$$

We used this permeability to calculate the cross-sectional velocity of the fluid, ϖ, according to Darcy's Law as a function of the permeability, p, with an applied pressure differential, ΔP, of 20 MPa and the horizontal length, L, of 2000 m (Equation 2). These values are consistent with literature and real-world EGS (Zhang and Xie, 2019; David Clay, pers. comm.).

$$v = \frac{\rho}{\eta L}\,\Delta P \tag{2}$$

Where the viscosity, η, is an empirical function of temperature, T, and lithostatic pressure, P, where R is the molar gas constant (Likhachev, 2002).

$$\eta = \eta_0 \exp\left(4.423\times10^{-4}P + \frac{4.753 - 9.565\times10^{-4}P}{R\,(T - 139.7 - 1.24\times10^{-2}P\,)}\right) \tag{3}$$

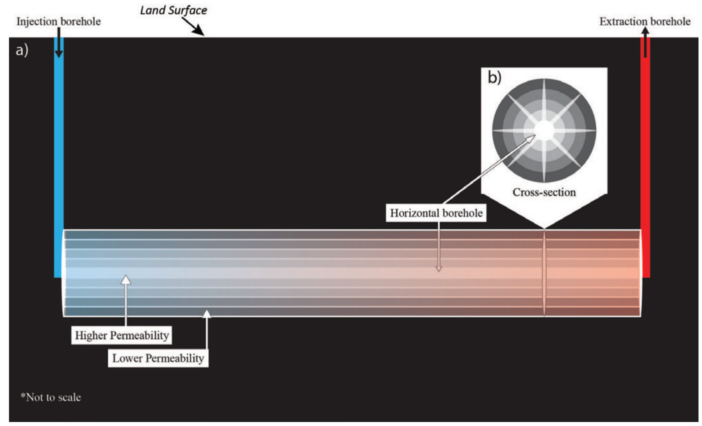

Figure 2. Overview of a simplified EGS a) Diagram of a cross-sectional view of the fracture geometry for a simplified EGS. The working cold fluid would flow down the injection borehole, through the hydraulically fractured reservoir, and out the extraction borehole as a hot fluid to be used for energy production. b) Proposed cross-sectional geometry of the horizontal run. The horizontal borehole is in the center, and we assume the primary forced fractures from the star formation shown.

We used the MATLAB PDE-solver software to construct a finite element model (FEM) to calculate the change in temperature over time according to the advection-diffusion equation (Equation 4).

$$\frac{\partial T}{\partial t} = \nabla \cdot (D_T\nabla T - v\,T\,) + R \tag{4}$$

Where the ∇T term corresponds to heat transferred through conduction, and the T term corresponds to heat transferred convectively. The R term is the source; in this model it corresponds to the hot rock surrounding the fractured reservoir. The thermal diffusivity, D_T, is a material-specific constant that indicates how easily heat is transferred in a material (Equation 5).

$$D_T = \frac{k}{\rho c_p} \tag{5}$$

Where k is the thermal conductivity, ρ is the density, and c_p is the specific heat capacity of the material. We calculated D_T for each ring in the reservoir using the same weighted average method as the permeability (Equation 1).

DATA AND RESULTS

We calculated the velocity of each concentric ring for multiple different temperatures ranging from 300 K to 500 K to see how the velocity would change in

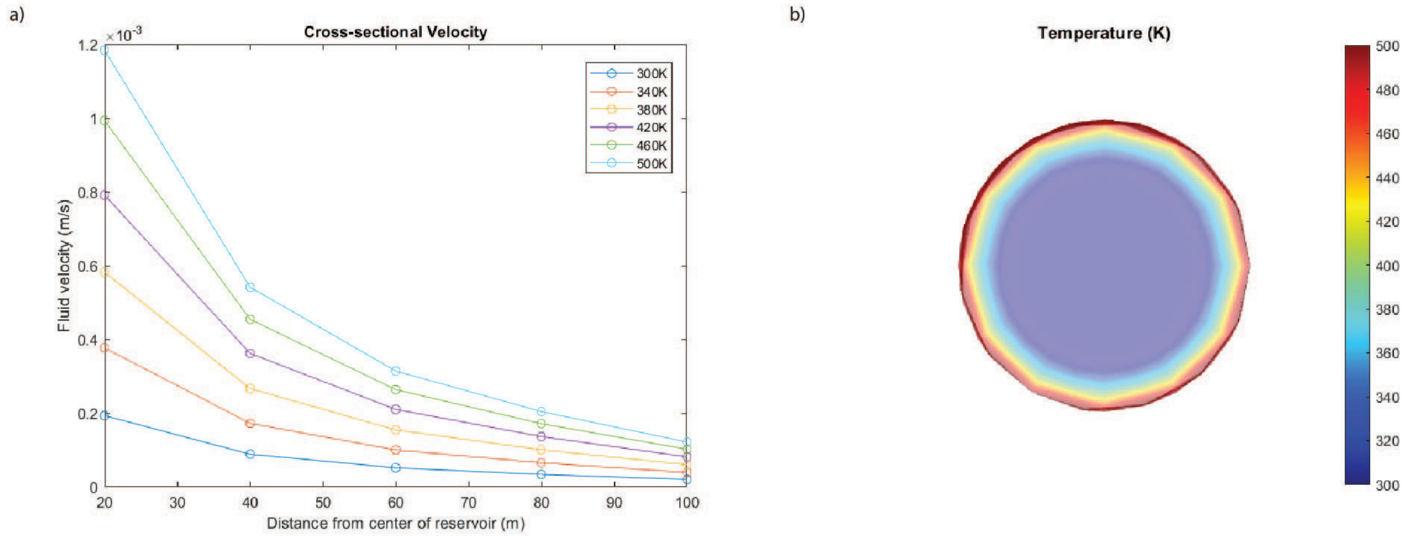

Figure 4. Preliminary results. a) Graph of cross-sectional velocity against distance from the center of the reservoir calculated at varying temperatures (Equation 2). b) Graph of the temperature of a cross-section of the reservoir from the PDE-Solver (Equation 4).

each region as the fluid gained thermal energy. We plotted these cross-sectional velocities as functions of the distance from the borehole (Fig. 4). We see that as the distance from the borehole increases, the velocity decreases as expected by the decrease in permeability at greater distances (Equation 2). On the other hand, as the temperature increases, the velocity of the fluid increases, as we would expect from the viscosity equation (Equation 3).

We then calculated the temperature of the fluid at a time near the midpoint of the time the fluid would spend in the reservoir using the MATLAB PDE Solver (Equation 4) (Fig. 4). We set the interior of the reservoir to begin at 300 K and the exterior to remain constant at 500 K and modeled the reservoir warming up due to radial diffusion. Because of the boundary conditions of this model, we see that the edges of the reservoir warm up more quickly than the interior.

However, the rate at which the interior warms up is underestimated because this model assumed only laminar flow (purely horizontal velocity) and doesn't take radial convection into account. A more computationally intense model would account for more mixing in the reservoir due to turbulent flow as the fluid flows through rough fractures, and radial convection as the high temperature fluid flows away from the lower boundaries due to lower density than the cold fluid. By applying the velocity results to the temperature results, we see that the distance from the center of the reservoir is inversely related to the velocity but positively related to the change in temperature. This means that the fluid is likely to move uniformly across the cross-sectional rings until the interior is sufficiently heated.

CONCLUSION

We made a preliminary model that illustrates the relationship between fracture geometry, fluid velocity, and thermal energy for the purpose of evaluating geothermal potential in a normal fault damage zone. To assert meaningful conclusions, this model would need to be improved in a number of ways. Firstly, we would need to incorporate radial advection to more accurately estimate the thermal flux. Secondly, one would have to run this model with more complicated geometries that more accurately correspond to existing EGS systems and compare the results with field data to validate the model. Lastly, we would investigate fracture geometries more representative of normal fault damage zones, likely incorporating the anisotropic fracture networks of normal fault damage zones. These corrections would elucidate the geothermal potential of normal fault damage zones by comparing the thermal flux calculated to the thermal flux required for electricity generation.

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REFERENCES

Anderson, T., and Fairley, J., 2008, Relating permeability to the structural setting of a fault-controlled hydrothermal system in southeast Oregon, USA: Journal of Geophysical Research, v. 113, B05402, doi:10.1029/2007JB004962.

Barbier, E., 2002, Geothermal energy technology and current status: an overview: Renewable and Sustainable Energy Reviews, v. 6, 1-2, p. 1-65, ISSN 1364-0321. https://doi.org /10.1016/S1364-0321(02)00002-3.

Choi, J-H., Edwards, P., Ko, K., and Kim, Y-S., 2016, Definition and classification of fault damage zones: a review and a new methodological approach: Earth Science Reviews, v. 152, p. 70-87.

Faulds, J., Hinz, N., 2015, Favorable Tectonic and Structural Settings of Geothermal Systems in the Great Basin Region, Western USA: Proxies for Discovering Blind Geothermal Systems: World Geothermal Congress 2015, Melbourne, Australia.

Likhachev, E., 2003, Dependence of Water Viscosity on Temperature and Pressure [translated from Zhurnal Tekhnichesko œ Fiziki, Vol. 73, No. 4, 2003, pp. 135–136]: Technical Physics, v. 48, No. 4, pp. 514-515.

Moska, R., Labus, K., Kasza, P., 2021, Hydraulic Fracturing in Enhanced Geothermal Systems—Field, Tectonic and Rock Mechanics Conditions—A Review: Energies, 14, 5725. https://doi.org/10.3390/en14185725.

Peacock, D.C.P., and Sanderson, D.J., 1996, Effects of propagation rate on displacement variations along faults: Journal of Structural Geology, v. 18, p. 311 –320.

Sharmin, T., Khan, N., Akram, M., and Ehsan, M., 2023, A State-of-the-Art Review on Geothermal Energy Extraction, Utilization, and Improvement Strategies: Conventional, Hybridized, and Enhanced Geothermal Systems: International Journal of Thermofluids, v. 18, 100323, ISSN 2666-2027, https://doi.org/10.1016/j.ijft.2023.100323.

Zang, J., Xie, J., 2020, Effect of reservoir's permeability and porosity on the performance of cellular development model for enhanced geothermal system: Renewable Energy, v. 148, p. 824-838, ISSN 0960-1481 https://doi.org/10.1016/j.renene.2019.10.168.