Introduction

Geothermal energy has been recognized as a significant source of energy for variable uses in many countries due to its cleanness, reliability, sustainability, and other promising features (Pandey et al., 2018). One of the most common geothermal energy originates as a consequence of deep faults providing permeable fluid pathways in combination with topography-induced hydraulic head gradients driving flow of meteoric water (Alt-Epping et al., 2021). The meteoric water infiltrates mountains with high elevations and goes down to contact the deep host heat from the shallow crust. Then the warm water driven by hydraulic gradient and buoyancy, travels through the permeable pathway and may come out from the system through some vents.

However, most of the geothermal reservoirs are located at relatively deep depths and mountain areas, and the lack of deep and subsurface data makes it challenging for us to qualify the geological structure, which inhibits us from further utilizing the geothermal energy (Taillefer et al., 2018). Fortunately, it has been realized that shallow available data obtained from field studies can be used to constrain the geological structure subsurface. This is due to the temperature distribution and the water field is sensitive to reservoir properties, operating parameters, and coupling various processes. Among these factors, permeability is critical because it highly affects the water flow pathway and then convection heat transfer patterns. Therefore, the measurable temperature around the vents is always associated with the permeability structure.

In this study, integrated heat and water flow modeling is performed to study the heat transport and water flow patterns in a synthetic hydrothermal system. The goal of this study is to calibrate the permeability of the granite to make the temperature of the vent of the fault fit the average known vent temperature at hydrothermal systems in Boise.

Model Description

Figure 1 shows the model setup. This synthetic model is built based on the real geological setting in Boise. It consists of four geological rocks, granite, fault, rhyolite, and impermeable layer. The initial properties of different rocks used in this simulation are in Table 1. We assume the properties are given by the priors. The meteoric water infiltrates into the system via the inflow area and goes down. It contacts the heat source at the bottom of the model and then comes out of the system via the vent of the fault on the top layer and the boundary at the right. The implementation of boundary conditions is shown in Figure 2. The inflow area has a 5 km length along the *x* direction. 20°C Water flows into the system via the inflow area, and the entire top layer is applied a 20°C constant temperature boundary. The reason is that 20°C is a good estimation of air temperature in the real world. The vent of the fault is assigned a heat-dependent boundary, and the right boundary is assigned another heat-dependent boundary. The general head boundary can be represented by equation (1):

$$Q_d = C(h - h_1) \tag{1}$$

where Q_d is the fluxes across the boundary, C is the conductance of the boundary, h_1 is the head threshold, and h is the total head at the boundary(Chen et al., 2023).

The boundary applied at the vent allows water to pass in both directions, and the boundary applied at the right side only allows water to leave the system. Also, a drain boundary, which allows water to leave the system once the calculated total head exceeds its corresponding elevation, is applied at the inflow area.

When the constant infiltration rate at the inflow area exceeds the hydraulic conductivity of the inflow area, the rejected infiltration will leave through the drain boundary with a very small hydraulic conductance. A constant heat flux 90 mW/m^2 is applied at the bottom of the model. All water leaves the system with temperature calculated at its corresponding cell. Except for the boundary conditions mentioned, other boundaries are applied no flow and no heat exchange boundary.

The goal of this study is to investigate how different permeabilities of the granite impact the temperature distribution and water flow in the system. The temperature at the vent is usually accessible, so we focus on how it varies with different permeability structures. Therefore, in the future, we can use this knowledge derived from how model responses are caused by the permeability structure to infer the permeability structure upon we have vent temperature information in the field.

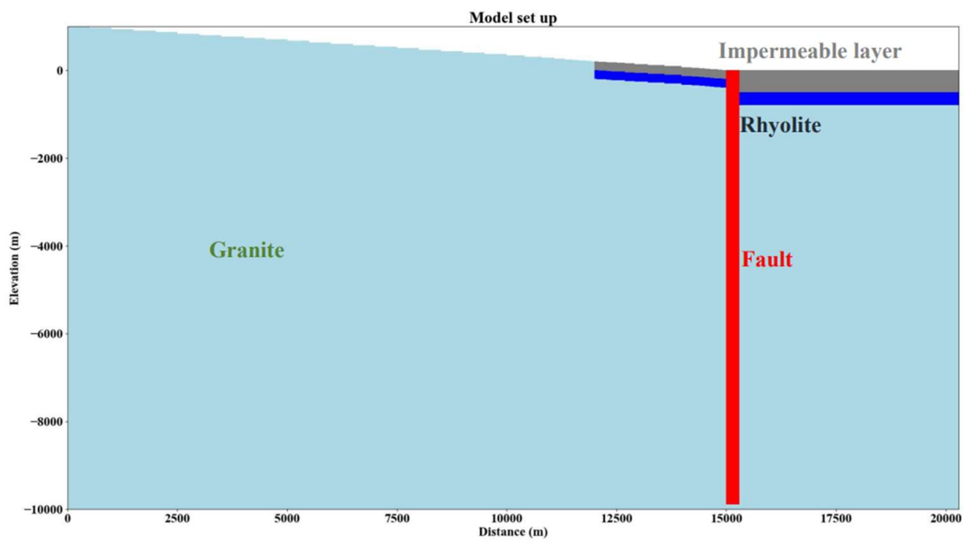

Figure 1 Model set up

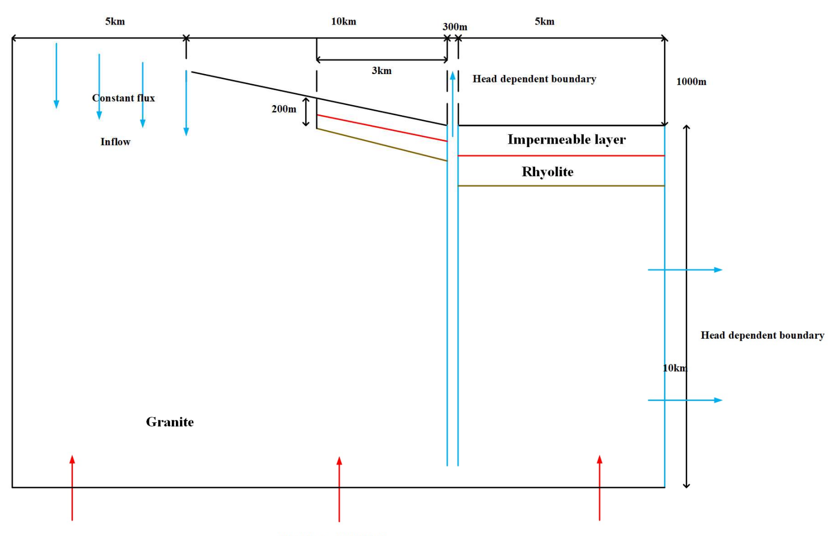

Figure 2 Model boundary conditions

Table 1 Material properties of different rocks used in the simulation

	Granite	Fault	Rhyolite
Permeability (m^2)	10^{-18}~10^{-15}	10^{-15}	10^{-14}
Heat capacity (J/K/kg)	790	800	700
Density (kg/m^3)	2600	3000	2300
Thermal conductivity (W/K/m)	3.0	4.0	2.5
Porosity (-)	0.05	0.2	0.2

Data needed

This study is simulated by MODFLOW. The main input data can be divided into four types, mesh, simulated time, thermal-related properties, and hydraulic-related properties.

Specifically, mesh properties contain the number of columns, rows, and layers. Also, it includes how to discretize the mesh and how to assign different permeabilities on cells. A well-defined mesh is very important for calculation accuracy and geological structure representation. Simulation time defines how long the model will run, and the total simulation time can be divided into multiple stress periods and apply different conditions in different periods. Thermal-related properties define parameters such as thermal conductivity, heat capacity, and heat flux that are essential to simulate heat transfer within the system. These properties are linked to the material characteristics of the granite, fault, rhyolite, and impermeable layers. Hydraulic-related properties define parameters such as permeability, porosity, and hydraulic conductivity are crucial for modeling fluid flow within the system. These properties determine the pathways and rates of water movement through the geological layers. Besides these, different boundary conditions need to be implemented accordingly. The initial condition is set as 20°C and constant saturated water head for the whole domain. Table 1 lists the detailed input properties. We assume these properties are accurate and given by priors because it is hard for us to calibrate many parameters simultaneously.

The output data include temperature distribution and water flow patterns across the model domain. These outputs help evaluate how the permeability structure influences the vent temperature and overall system behavior.

Calibration

This study focuses on the calibration of the permeability of the granite, which acts as the host rock in the model. Before calibration, we set the calibration range from 10^{-18}~10^{-15} m^2 based on the priors. Therefore, our goal of the simulation is to run a set of models with different permeability values of the granite and output its corresponding responses. By comparing the responses with the vent temperature in the real world, we can pick the most matched permeability value as the optimal guess for the permeability of the granite.

Assuming we can easily measure the temperature around the vent near the surface, we can set several observation points in our model and calculate their temperature. Then, we can pick one typical hydrothermal system in Boise and use the thermal log to know its real temperature. Another alternative way is looking up the historical data from papers, and understanding where and how these data are collected. Then, we can use these historical data to reasonably infer the current temperature. Finally, we can use the Root Mean Squared Error (RMSE) for data match qualification.

The RMSE can be represented as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum(y_i^{obs} - y_i^{sim})^2} \tag{2}$$

Where y_i^{obs} is the observed data, y_i^{sim} is the simulated values, and n is the number of data points. The optimal permeability will be the model having the least RMSE value.

Numerical Experiment Design

The MODFLOW couples the heat and water flow using the governing equations as shown below:

$$(1+\frac{1-\theta}{\theta}\frac{\rho_s c_s}{\rho_{wc_w}})\left(\frac{\partial(\theta T)}{\partial t}\right) = \frac{\partial}{\partial x}(\theta[\frac{k_{T0}}{\theta\rho_w c_w} + D_{ij}]\frac{\partial T}{\partial x_j}) - \frac{\partial}{\partial x_i}(\theta v_i T) + q_s T_s \tag{3}$$

$$k_{T0} = [\theta k_{Tw} + (1-\theta)k_{Ts}] \tag{4}$$

Table 2 Unit and physical meaning of parameters

Symbol	Physical meaning	Unit
θ	Water content	unitless
ρ_s, ρ_w	Solid and water density	kg/m^3
T	Temperature	K
k_{T0}	Effective thermal conductivity of the porous medium	W/(m K)
k_{Tw}, k_{Ts}	Thermal conductivity of solid phase and liquid phase	W/(m K)
D_{ij}	Diffusion-dispersion tensor	m^2/s
T_s	Temperature of the source	K
q_s	volumetric flow rate per unit volume of aquifer representing sources and sinks	(m^3/s)/m^2
v_i	volumetric flow rate per unit surface	(m^3/s)/m^2
c_s, c_w	Heat capacity of solid phase and liquid phase	J/kg/K

Governed by equation (3), MODFLOW calculates the temperature distribution considering conduction, convection, and heat source. On the right side, the first item represents the conduction, the second item represents the conduction and the last item represents the heat source. For each stress period, MODFLOW first calculates the water flow field and then incorporates it as the convection term for the follow-up calculations.

For the calibration process, we will set an empirical permeability range from 10^{-18}~10^{-15} m^2 for the granite, the host rock. Within one order, four permeability values will be assigned with a certain spacing for testing. We will set a vertical observation line along the fault conduit in Figure 1 so that we can know the model responses in terms of the temperature distribution along the fault, which corresponds to the most accessible data in the fieldwork. Usually, due to the mixed effects caused by conduction and convection, the vent temperature varies with the change in permeability. Also, host rock with a narrow range of permeability can promote heat transfer in the system, which brings thermal water to the ground surface via fault. For example, Figure 3 shows the different temperature distribution patterns along the depth in the fault under different permeability effects. If we zoom in on the temperature around the vent area, we can clearly notice that the different vent temperature corresponds to different permeability structures shown in Figure 4. However, to ensure the calibrated permeability is correct, it will be better if we can compare as many points as possible to eliminate any possible bias and use RSME to calculate the overall misfit between the responses and observations.

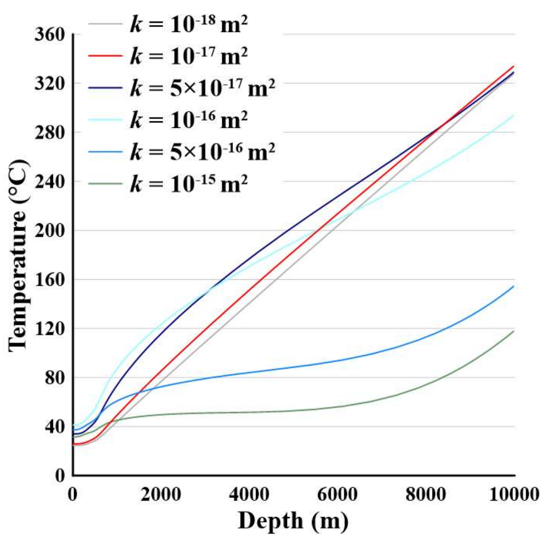

Figure 3: Simulated temperature along depth in the fault

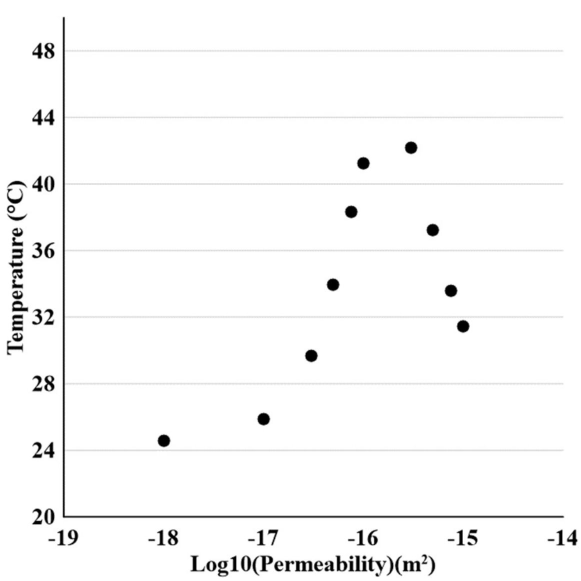

Figure 4 Simulated water temperature of the warm spring at the fault location on the ground surface.

Reference

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