

# Positive and negative THMC feedback mechanisms for fracture flow channeling in enhanced geothermal systems

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## ABSTRACT

After over 50 years of exploration and practice, enhanced geothermal systems (EGS) have become a key technology to harness the abundant geothermal energy stored in the shallow crust of the Earth. Despite the significant technical and practical progresses in the past decade, a major operational challenge still remains, i.e., fracture flow channeling, which has been identified as a primary risk in many EGS projects for premature thermal breakthrough and reduced long-term thermal longevity. In this paper, we first analyze major physical and chemical processes that affect fracture flow channeling behavior, especially those alter flow channeling in a feedback manner. A thermo-hydro-mechanical-chemical (THMC) coupled model is then developed to simulate heat extraction from EGS reservoirs and understand the dynamic evolutions of fracture aperture as well as the underlying flow patterns. Thermoelastic effect triggers a positive feedback loop that exacerbate flow channeling, while temperature-dependent viscosity leads to a negative feedback loop that can partially mitigate flow channeling. Water-rock reactions show a complex feedback mechanism, but the overall effect appears to be a strengthened flow channeling. Enhancing negative feedback loops and suppressing positive feedbacks are beneficial to mitigate flow channeling and improve long-term thermal performance.

## 1. INTRODUCTION

Geothermal energy stored in hot dry rocks (HDRs) has been characterized as an essential constituent of the global effort to achieve carbon neutrality and combat climate change (Horne et al., 2025; International Energy Agency report, 2024; Tester et al., 2006). Enhanced geothermal system (EGS) is a promising technology to extract heat energy from HDRs, which generally involves the stimulation of originally low-permeability reservoirs and the continuous water circulation through the stimulated fractures for heat extraction. The breakthroughs in horizontal drilling and multistage fracturing techniques have facilitated remarkable industrial progresses in EGS commercial applications, such as the projects Red and Cape site by Fervo energy. However, several technical challenges still remain, including flow short-circuiting and induced seismicity. From the experience of Project Red and Cape site, Norbeck et al. (2024) indicated that the understanding of thermal longevity remains a primary risk for EGS development. Flow short-circuiting (also called flow channeling) refers to a phenomenon in which most of the injected fluid concentrates in a few major flow channels in the stimulated fracture networks between injection and production wells. A direct consequence of flow channeling is that the effective heat transfer area between circulating fluid and the surrounding rock formations is significantly reduced, and therefore, the thermal longevity is largely compromised. Such a phenomenon has been observed in several EGS field projects, such as the Rosemanowes project in UK (Lu, 2018) and the Soultz EGS project in France (Tester et al., 2006). In the Rosemanowes EGS project, tracer testing results revealed that a dominant flow channel accounted for over half of the 14 L/s total production rate, and only four of the nine possible flow channels carried more than 1 L/s flow rate (Parker, 1999).

A comprehensive understanding of the dynamic evolution of fracture flow channeling behavior under complex thermo-hydro-mechanical-chemical (THMC) coupled processes is essential for the management of fluid sweeping efficiency and optimization of long-term thermal performance. Numerous laboratory and numerical studies have been performed to investigate the underlying physical and chemical effects during heat extraction from EGS reservoirs and their influences on fracture flow patterns (Faoro et al., 2015; Ghassemi and Zhou, 2011; Lima et al., 2019; Pandey et al., 2017; Shu et al., 2020). An important finding from previous studies is that there exist several feedback mechanisms between flow channeling and THMC processes, which may either result in severe flow channeling through a positive feedback loop or suppress flow channeling through a negative feedback loop. The thermoelastic effect accompanied with cold fluid circulation triggers a positive feedback loop between thermal stress and fracture flow channeling, which ultimately leads to significant flow channeling and grievously impairs the thermal recovery performance of EGS reservoirs (Fu et al., 2016; Guo et al., 2016; McLean and Espinoza, 2023; Slatem Vik et al., 2018). On the other hand, temperature-dependent fluid viscosity facilitates a negative feedback loop between fluid viscosity and flow channeling, which could gradually mitigate flow channeling and improve thermal performance (Liu et al., 2024; Okoroafor and Horne, 2022). Other processes, such as water-rock reactions, may also dynamically alter fracture aperture and affect flow channeling behavior in a similar feedback loop manner. Nevertheless, the underlying feedback mechanism remains unclear and requires further investigations.

The purpose of this study is to comprehensively understand the evolution of fracture flow channeling behavior under coupled THMC processes in EGS reservoirs, with a focus on uncovering the feedback mechanisms between THMC processes and flow channeling behavior. In what follows, we first describe major processes that alter fracture aperture during heat extraction from EGS reservoirs, and demonstrate how these processes facilitate feedback loops and affect fracture flow channeling. We then develop a THMC coupled model

to simulate these coupled processes and quantitatively analyze the dynamic evolution of fracture flow channeling and how the feedback loops affect long-term thermal performance.

## 2. FRACTURE APERTURE AND FLOW EVOLUTION IN EGS RESERVOIRS

### 2.1 THMC effects on fracture aperture

Based on previous studies, fracture aperture and permeability are primarily influenced by four mechanisms: fluid overpressure, poroelastic and thermoelastic effects, and fluid-rock reactions. Fluid overpressure, the excess pressure applied to fracture surfaces, typically causes an immediate increase in aperture (Kang et al., 2022; Zeng et al., 2025). The poroelastic effect is a time-dependent process where fluid leaks into the surrounding rock matrix, raising pore pressure, reducing effective stress, and ultimately leading to matrix relaxation and fracture closure (Fu et al., 2017; Ghassemi et al., 2008). Conversely, the thermoelastic effect involves rock matrix contraction due to cooling-induced thermal stress, which acts to widen fractures (Fu et al., 2016; Guo et al., 2016). Finally, fluid-rock reactions-governed by pressure, temperature, mineralogy, and fluid chemistry-can either reduce aperture through mineral precipitation and fracture clogging or increase it through dissolution (e.g., Ghassemi and Suresh Kumar, 2007; Pandey and Chaudhuri, 2017). A particularly significant reactive process is pressure solution at asperity contacts under high stress, which has been characterized as a key mechanism for fracture sealing (Liu et al., 2006; Murugesu et al., 2024; Yasuhara et al., 2006).

### 2.2 Positive feedback loop between thermal stress and flow channeling

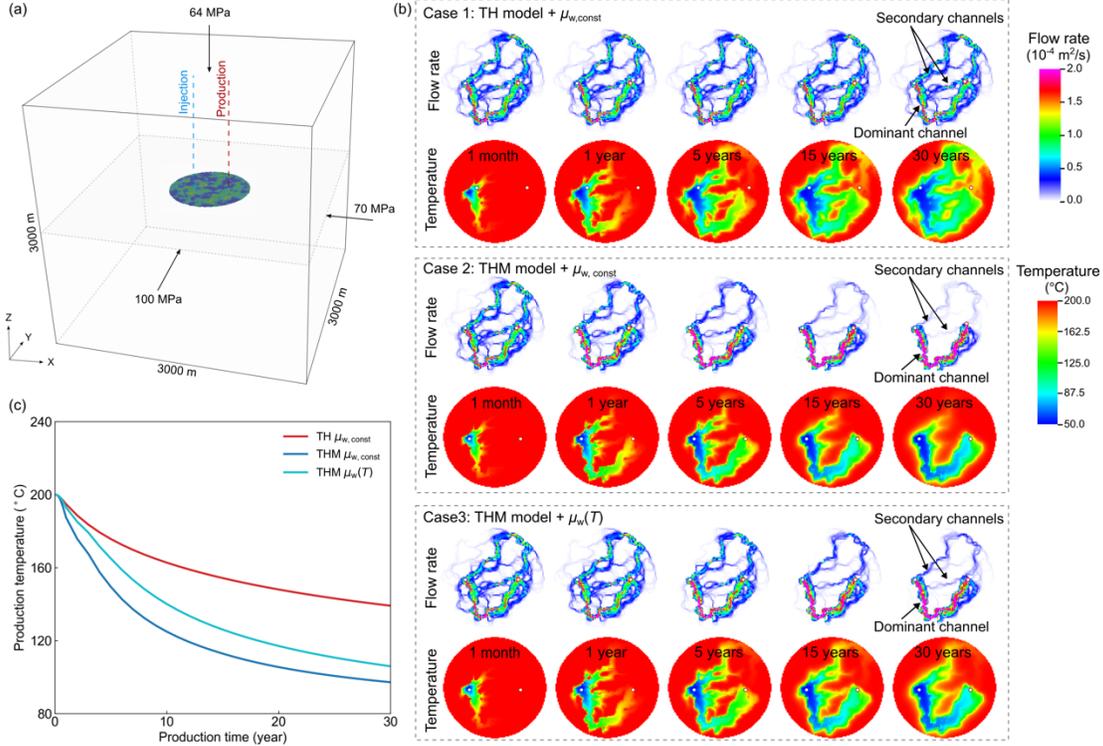
Thermal stress generated during rock cooling has been recognized as a major cause of fracture flow channeling, owing to the reinforcing feedback loop between thermal stress and flow channeling. Initially, fracture flow tends to be channelized owing to the inherent heterogeneity of fracture aperture distribution. During fluid circulation, preferential flow channels experience higher flow rates, leading to faster cooling of the surrounding rock. As noted by Fu et al. (2016), this thermal drawdown induces a tensile thermal stress that counteracts the existing compressive confining stress. This reduction in net compressive stress causes the aperture and permeability of these preferential flow channels to increase more significantly than in less active, secondary flow channels. Consequently, fluid becomes further concentrated into the primary preferential flow channels, accelerating their cooling, amplifying the thermal stress, and leading to even greater permeability enhancement. This self-reinforcing cycle, termed thermal drawdown-induced flow channeling, ultimately promotes severe flow localization in Enhanced Geothermal System (EGS) reservoirs (Fu et al., 2016; Guo et al., 2016; Liu et al., 2024; Rongved et al., 2021).

In our previous work (Liu et al., 2024), we developed a field-scale, single-fracture THM model to quantitatively investigate the positive feedback loop between thermal stress and flow channeling (Fig. 1(a)). A heterogeneous aperture distribution was assumed in the fracture, and the initial fracture flow exhibited channelized pattern (Fig. 1(b)). A TH simulation that excluded thermal stress effect on fracture aperture and a THM simulation that considered thermal stress were compared to demonstrate how thermal stress effect exacerbated flow channeling and impaired thermal performance (Cases 1 and 2 in Fig. 1(b)). For the TH model, fracture aperture and the corresponding flow pattern remain constant. In the THM model, due to the abovementioned positive feedback from thermal stress, fluid gradually concentrates in a dominant flow channel, while the other secondary channels diminish with time, ultimately leading to severe flow and thermal short-circuiting (Case 2 in Fig. 1(b)). Heat exchange is therefore largely constrained, and the production temperature drops rapidly (Fig. 1(c)).

### 2.3 Negative feedback loop between water viscosity and flow channeling

The reduction of reservoir temperature not only induces thermal stress in rock formations, but also alters fluid physical properties such as density, viscosity, and thermal conductivity. Among these properties, fluid viscosity is of critical importance due to its pronounced sensitivity to the significant temperature contrast between injected fluids and the reservoir rock, exerting considerable influence on fracture flow dynamics and heat transfer processes (Aliyu et al., 2023; Guo et al., 2016; Liu et al., 2024; Okoroafor et al., 2020). For a water-based EGS, fluid viscosity increases with temperature reduction, which tends to facilitate a negative feedback on flow channeling (Liu et al., 2024). Preferential flow channels, which cool more rapidly, experience a greater increase in fluid viscosity, thereby impeding further flow concentration. This suppression redistributes fluid toward hotter, less-swept regions where viscosity remains comparatively lower. Consequently, this viscosity-mediated feedback counteracts the flow channeling exacerbated by thermal-stress effects, ultimately improving the overall heat sweep efficiency of the system.

Our previous work also examined the effect of such a negative feedback loop on fracture flow behavior and EGS thermal performance (Liu et al., 2024). For Cases 1 and 2 in Fig. 1(b), water viscosity is assumed constant. An additional THM modeling with temperature-dependent water viscosity was also performed to analyze the negative feedback loop (Case 3 in Fig. 1(b)). The evolution of fracture flow pattern clearly demonstrates that the major flow channel is not as dominant as it is in THM model with constant water viscosity. The secondary flow channels still play considerable roles in fluid circulation after 30 years. Nevertheless, compared with the TH model, the flow pattern from Case 3 is more concentrated, meaning that the negative feedback loop can only partially mitigate the flow channeling caused by thermal stress. The comparison of production temperature curves further corroborated such a result (Fig. 1(c)).



**Figure 1: Fracture flow pattern and temperature distribution in a single fracture EGS model (Liu et al., 2024). (a) A 3D EGS model with a horizontal fracture connecting an injection well and a production well for fluid circulation. (b) Evolution of fracture flow field and temperature during cold water circulation. Three cases with different model settings are compared, including a TH model with constant fluid viscosity, a THM model with constant fluid viscosity, and a THM model with temperature-dependent fluid viscosity. (c) Production temperature curves corresponding to the three cases.**

### 3. FRACTURE FLOW AND THERMAL PERFORMANCE UNDER THMC COUPLED EFFECTS

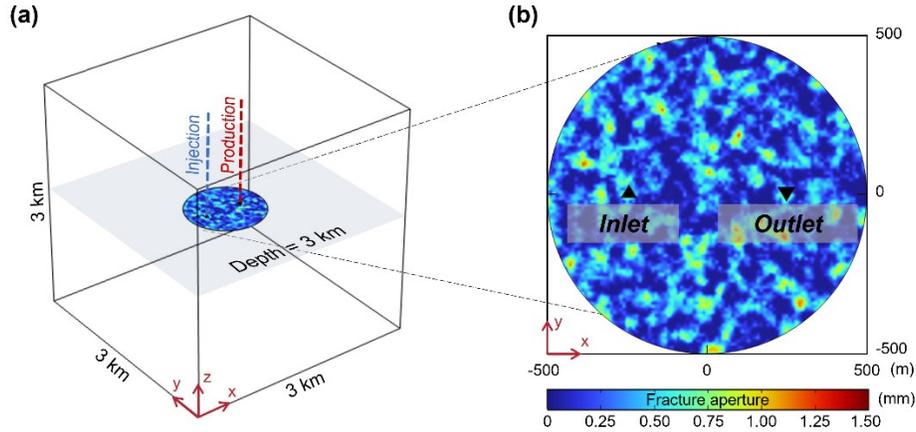
Besides the thermal stress-induced positive feedback and the temperature-dependent viscosity-induced negative feedback, water-rock reactions, as mentioned before, may also significantly alter fracture aperture and affect flow pattern, especially during the long-term thermal production period. Based on the THM model from our previous work, we further develop a THMC coupled model to systematically investigate the dynamic evolution of fracture flow channeling behavior under the joint effect of thermal stress, temperature-dependent viscosity and water-rock reactions.

#### 3.1 A THMC coupled EGS model

Since the THM and THMC coupling frameworks have been widely reported in the literature (Ghassemi et al., 2008; Guo et al., 2016; Taron and Elsworth, 2009; Yasuhara and Elsworth, 2004; Zeng et al., 2025), here we only introduce how water-rock reactions are considered in our THMC framework and coupled to the THM processes. Water-rock reactions in EGS primarily involve mineral dissolution and precipitation triggered by the disruption of thermal and chemical equilibrium due to the injection of relatively cold water into hot rock formations. When fracture fluid is oversaturated under the subsurface pressure and temperature conditions, mineral precipitation occurs along fracture surfaces and reduces fracture aperture, and if fracture fluid is undersaturated, mineral dissolution occurs at fracture free-face and fracture aperture increases. Pressure solution refers to a particular mineral dissolution reaction at fracture contact asperities where elevated compressive normal stress enhances reaction rates (Rutter, 1983). Contrary to free-face dissolution, pressure solution generally causes aperture decrease and fracture sealing (Murugesu et al., 2024; Yasuhara and Elsworth, 2004). As granite has been characterized as the dominant mineral type in many EGS reservoirs, we consider the dissolution and precipitation of amorphous silica as the primary water-rock reactions in our model. To bridge reaction kinetics and fracture evolution, we integrate the reaction rate laws for both free-face reactions and pressure solution directly as source-sink terms into the fracture solute transport equation. Solving this equation yields the net mass transfer rates, which are then translated into dynamic updates of the fracture aperture, thereby closing the feedback loop between chemical evolution and the THM system.

Similar to previous work in Guo et al. (2016) and Liu et al. (2024), we develop a single-fracture model with a size of  $3 \text{ km} \times 3 \text{ km} \times 3 \text{ km}$  (Fig. 2). A single circular fracture 1 km in diameter is assumed in the center of the model, connecting an injection well and a production well 500 m apart. Note that the top of the model is not ground surface, but 1.5 km below ground surface, meaning that the fracture is 3 km below ground surface. We assume a heterogeneous aperture distribution following a log-normal distribution in the fracture, with a mean aperture of 0.24 mm, a standard deviation of 0.17 mm, and a correlation length of 100 m (Fig. 2). A hydrostatic pressure and a local

thermal gradient of 40 °C/km are assumed in the model, and the initial pressure and temperature at the fracture depth are 34 MPa and 200 °C respectively. We set impermeable boundaries in the model, and the lateral boundaries are set as adiabatic, while the temperatures at the model top and bottom are fixed at their initial values. The in-situ stresses are 64 MPa and 46.86 MPa at the fracture depth in the vertical and horizontal directions respectively. Roller constraints are applied to the lateral and bottom boundaries. We consider amorphous silica as a representative reactive mineral, with an initial concentration of 15.5 mol/m<sup>3</sup> in the model. An undersaturated injection condition with a zero-injection concentration is used, meaning that mineral dissolution will be triggered in the model. The injection rate and temperature are 20 kg/s and 50 °C respectively. Major rock and fracture parameters are provided in Table 1. We perform four simulations to demonstrate the effect of water-rock reactions on fracture flow and thermal performance, including a TH model, a THM model, a THMC model that only considers free face dissolution, and a THMC model considering both free face dissolution and pressure solution.



**Figure 2: A field-scale, single-fracture EGS model. (a) Diagram of the 3D EGS model. (b) Fracture aperture distribution in the fracture.**

**Table 1: Rock and fracture parameters for the THMC coupled EGS model.**

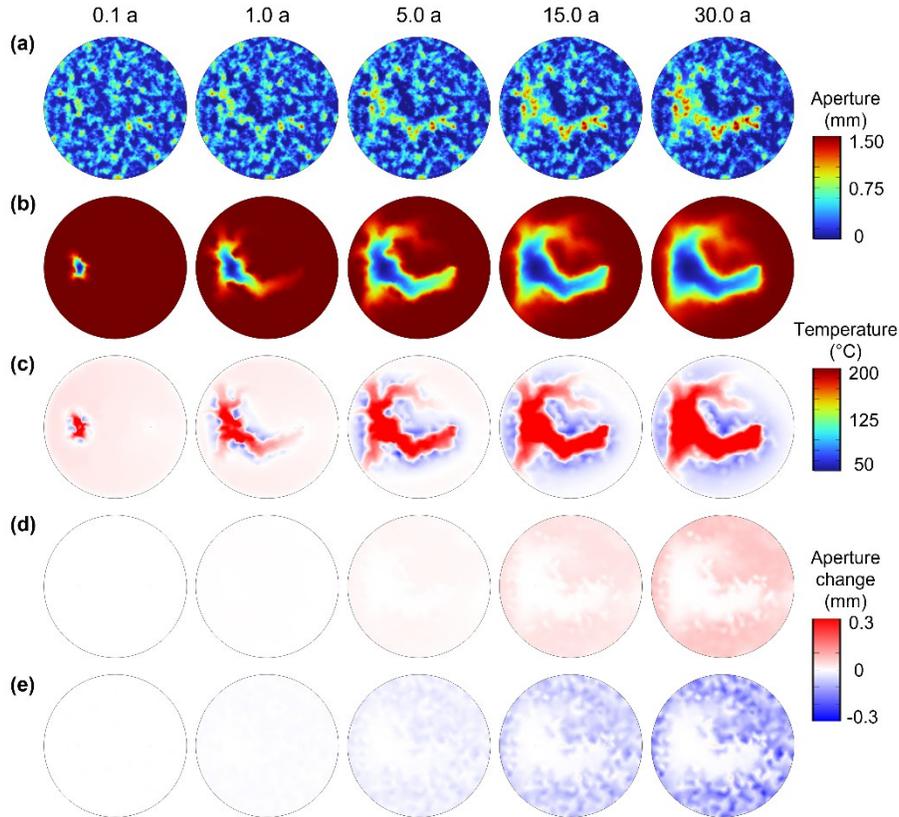
Parameter	Value	Parameter	Value
Rock density	2500 kg/m <sup>3</sup>	Rock thermal conductivity	3.5 W/m/K
Rock porosity	0.01	Amorphous silica content	50%
Rock elastic modulus	33.3 GPa	Fracture normal stiffness	50 GPa/m
Rock Poisson's ratio	0.3	Residual aperture	0.01 mm
Rock permeability	1×10 <sup>-17</sup> m <sup>2</sup>	Critical stress	70 MPa
Rock thermal expansion coefficient	8×10 <sup>-6</sup> 1/K	Initial fracture contact area ratio	5%
Rock specific heat capacity	915 J/kg/K	Fluid compressibility	5.11×10 <sup>-10</sup> Pa <sup>-1</sup>
Solute diffusion coefficient	1×10 <sup>-9</sup> m <sup>2</sup> /s		

### 3.2 Evolution of fracture aperture, flow field, and temperature

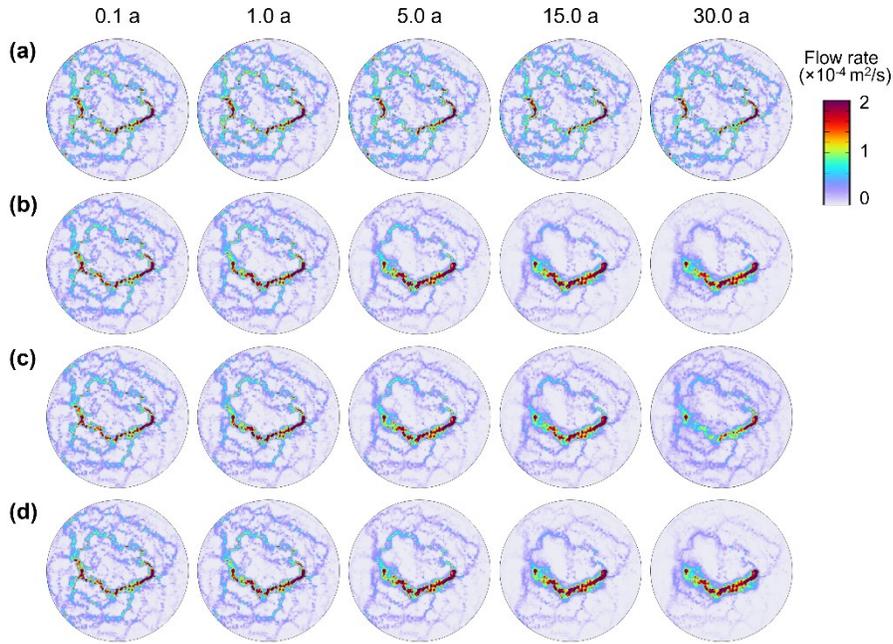
Under the joint influence of stress and water-rock reactions, fracture aperture gradually increases in the center of the fracture (between the injection and production wells) and decreases at the periphery of the fracture (Fig. 3(a)). We further analyze aperture change caused by stress, free face dissolution (mineral dissolution at fracture free surface) and pressure solution individually (Fig. 3(c), (d) and (e)). Specifically, stress-induced aperture change is obtained by subtracting aperture distribution in the TH model from that in the THM model, free face dissolution-induced aperture change is obtained by subtracting aperture distribution in the THM model from that in the THMC model that only considered free face dissolution, and pressure solution-induced aperture change is represented by the difference between the two THMC models. Note that the obtained stress-induced aperture change includes not only thermal stress effect, but also the effects of overpressure and poroelastic effect. Nevertheless, as the overpressure and poroelastic effects are relatively weak compared with the thermoelastic effect, the stress-induced aperture change is mainly from thermal stress. It is obvious that the stress-induced aperture change is positive (aperture increase) in the cooled region (Fig. 3(b)), which is mainly attributed to thermal stress effect. An interesting

phenomenon is that aperture on the edge of the cooled region actually decreases slightly due to stress redistribution effect. On the periphery of the fracture, stress-induced aperture change is nearly zero. On the contrary, water-rock reaction-induced aperture change, including free face dissolution- and pressure solution-induced, mainly occurs on the periphery of the fracture, and is almost zero in the cooled region (Fig. 3(d) and (e)). This is mainly because water-rock reaction is highly temperature sensitive. The low temperature largely suppresses water-rock reaction rate. As expected, free face dissolution leads to aperture increase, while pressure solution results in aperture decrease, thus the two reactions compete to alter fracture aperture distribution.

Similar to previous studies, the comparison of flow field between the TH and THM models in this study also demonstrates a concentrated flow pattern, indicating the thermal stress-induced flow channeling behavior (Fig. 4(b)). As free face dissolution enlarges peripheral aperture, a relatively dispersed flow field is observed in the THMC model (Fig. 4(c)). On the other hand, pressure solution tends to seal peripheral aperture and therefore exacerbates flow channeling (Fig. 4(d)). The comparison of flow field between Fig. 4(b) and (d) indicates that the combined effect of free face dissolution and pressure solution causes a slightly more concentrated flow pattern, meaning that the flow channeling effect due to pressure solution is stronger than the flow dispersion effect from free face dissolution for the model in this study.

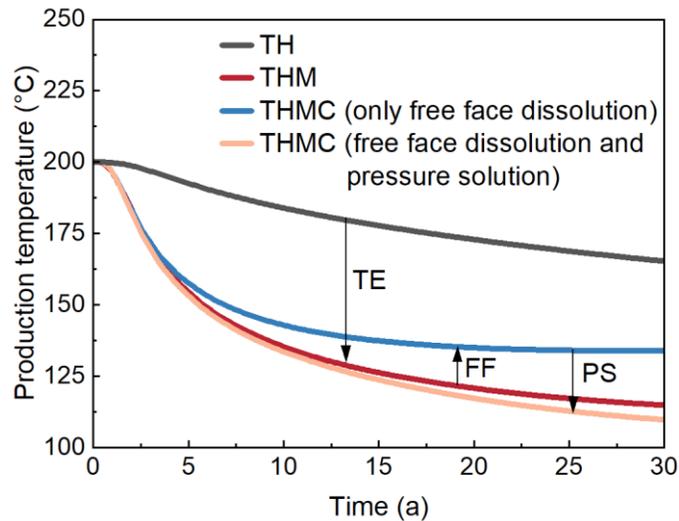


**Figure 3: Evolution of fracture aperture and temperature during 30 years of water circulation. (a) Aperture distribution. (b) Temperature distribution. (c) Aperture change due to stress, including the effects of overpressure, poro-elastic, and thermo-elastic effects. (d) Aperture change due to free face dissolution on fracture surfaces. (e) Aperture change due to pressure solution at fracture asperities.**



**Figure 4: Evolution of fracture flow field during 30 years of water circulation. (a) Results from the TH model. (b) Results from the THM model. (c) Results from the THMC model that considers free face dissolution. (d) Results from the THMC model that considers both free face dissolution and pressure solution.**

The comparison of production temperatures between the four simulations further corroborates the competitive effects of thermoelastic, free face dissolution and pressure solution on thermal performance. While thermoelastic effect causes significant decrease in production temperature due to strengthened flow channeling, free face dissolution could reduce the slowdown of production temperature because flow is dispersed. However, as pressure solution deteriorates flow channeling, production temperature is much smaller in the THMC model with pressure solution than that without.



**Figure 5: Comparison of production temperatures from the four simulations. TE means thermoelastic effect, FF means free face dissolution effect, and PS represents pressure solution effect.**

#### 4. CONCLUSIONS

In this study, we develop a THMC coupled model to investigate the dynamic evolution of fracture flow pattern during heat extraction from EGS reservoirs. While previous studies have revealed the positive feedback loop between thermal stress and flow channeling as well as the negative feedback loop between fluid viscosity and flow channeling, this study preliminarily examines the effects of water-rock reactions on fracture flow pattern. Through a series of numerical simulations, we found that under an undersaturated injection condition, mineral dissolution on fracture free surface appears to trigger a negative feedback loop which gradually drives a relatively dispersed flow pattern, enhancing long-term thermal performance. On the other hand, pressure solution at fracture asperities seems to induce a positive

feedback loop that exacerbates flow channeling and impairs thermal performance. The two water-rock reactions thus compete to alter fracture aperture distribution. For the case in the current study, pressure solution appears to exert a more significant effect, and the combined effect of pressure solution and free face dissolution is a slightly more severe flow channeling behavior.

A main limitation of the current study is that a simple fracture geometry, i.e., single fracture, is assumed in the THMC model. Future studies should further incorporate relatively complex but realistic fracture networks to comprehensively understand the various feedback mechanisms, as well as their influences on fracture flow channeling behavior and thermal performance.

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