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Interplay Between Thermoelastic Process and Mineral Reaction: Implications for Flow Channeling within a Fracture with Heterogeneous Apertures in EGS

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INTRODUCTION

Hot dry rocks (HDRs) hold substantial geothermal potential and are expected to play a crucial role in global decarbonization. Enhanced geothermal systems (EGS) extract heat from HDRs by stimulating coupled artificial and natural fracture networks to facilitate fluid circulation and heat exchange. As these fractures serve as the primary flow and heat transfer pathways, their flow patterns critically determine the long-term thermal performance of EGS (Koh et al., 2011; Zeng et al., 2023).

Fluid flow within fractures is primarily governed by spatially heterogeneous aperture distributions, often resulting in flow channeling—where fluid preferentially migrates through a few dominant pathways (Guo et al., 2016; Méheust and Schmittbuhl, 2000; Tsang and Tsang, 1989). Such flow channeling limits the effective heat exchange area and accelerates thermal breakthrough, thereby reducing system efficiency (Guo et al., 2016; Zeng et al., 2026). Characterizing and mitigating this channeling behavior remain major challenges because fracture apertures evolve dynamically under the interaction of multiple thermo-hydro-mechanical-chemical (THMC) processes.

Previous studies have examined individual effects such as fluid pressure, poroelastic process, thermoelastic process, and water–rock reactions (Fu et al., 2016; Pandey et al., 2015; Shu et al., 2023), but few have captured their coupled behavior in three-dimensional heterogeneous fracture systems. Most existing THMC models simplify fracture geometries or assume uniform apertures (Ogata et al., 2018; Salimzadeh and Nick, 2019; Wang et al., 2025), thus failing to capture realistic flow heterogeneity and channeling dynamics.

In this study, we develop a 3D THMC coupled model for a field-scale, single-fracture EGS reservoir and incorporate spatially heterogeneous aperture distributions. The model is used to quantify the competing effects of the thermoelastic process and mineral reaction on fracture flow channeling and long-term thermal performance. By systematically comparing scenarios with and without these processes, we identify the dominant mechanisms controlling flow evolution and propose strategies to mitigate thermal short-circuiting in EGS operations.

1 A FULLY COUPLED THMC FRAMEWORK FOR EGS

This study presents a comprehensive numerical framework that fully couples THMC processes by integrating key physicochemical mechanisms, including fluid overpressure, poroelastic process, thermoelastic process, and mineral reaction. The governing equations of the coupled THM model are described in detail in Zeng et al. (2025) and therefore not repeated here. Building on this fully coupled THM model, the present work introduces a chemical component governed by the following equations for reactive transport in both the rock matrix and fractures:

$$\frac{\partial(\varphi_{\mathrm{r}} c)}{\partial t} + \boldsymbol{u}_{\mathrm{r}} \cdot \nabla c - \nabla \cdot \left(D_{\mathrm{eff,r}} \nabla_{\tau} c\right) = -M \tag{1}$$

$$d_{\mathrm{f}} \frac{\partial(\varphi_{\mathrm{f}} c)}{\partial t} + d_{\mathrm{f}} \boldsymbol{u}_{\mathrm{f}} \cdot \nabla c - \nabla \cdot \left(d_{\mathrm{f}} D_{\mathrm{eff,f}} \nabla c\right) = d_{\mathrm{f}} R + d_{\mathrm{f}} M \tag{2}$$

where c denotes the concentration, φ represents porosity, $\boldsymbol{u}$ is the fluid velocity vector, D_{eff} is the effective diffusion coefficient, M accounts for mass transfer between the fracture and the rock matrix, d_{f} is the fracture aperture and R represents the mineral reaction rate within fracture. The model specifically considers the dissolution and precipitation of amorphous silica ($\mathrm{SiO_2(s)} + 2\mathrm{H_2O} \rightleftharpoons \mathrm{H_4SiO_4(aq)}$), with the reaction rate R given by:

$$R = \frac{2\chi_{\mathrm{SiO2}} k_+}{d_\mathrm{f}} \left(1 - \frac{c}{c_\mathrm{eq}}\right) \tag{3}$$

where, χ_{SiO2} is the amorphous silica content. k_+ and c_eq are the reaction rate constant and equilibrium concentration, respectively, both of which exhibit a dependence on temperature.

In this study, fluid overpressure, poroelastic process, and thermoelastic process affect the fracture aperture by modifying the effective normal stress (σ_n') acting on fracture surfaces, while mineral reaction directly changes the aperture through the rates of dissolution and precipitation (R).

$$d_\mathrm{f} = d_\mathrm{f,ini} + d_\mathrm{f,S} + d_\mathrm{f,R} = d_\mathrm{f,ini} + \sigma_n'/K_n + \int V_\mathrm{m} d_\mathrm{f} R \, dt \tag{4}$$

Where, $d_\mathrm{f,ini}$ is the initial aperture, $d_\mathrm{f,S}$ and $d_\mathrm{f,R}$ represent stress-induced and reaction-induced aperture changes, respectively, K_n is the fracture stiffness, and V_m is the molar volume of amorphous silica.

2 MODEL & RESULTS

2.1 A field-scale single fracture EGS model

We construct a three-dimensional model (3 km × 3 km × 3 km) representing an EGS reservoir located at depths of 1.5–4.5 km, containing a central horizontal, disk-shaped fracture with a diameter of 1 km (Figure 1a). The fracture aperture follows a spatially heterogeneous lognormal distribution (mean 0.24 mm, standard deviation 0.17 mm, correlation length 100 m). At the fracture depth, hydrostatic pressure is 34 MPa, temperature reaches 200 °C, vertical stress is 64 MPa, and horizontal stress is 46.8 MPa. The initial concentration of amorphous silica in the model is set to 15.5 mol/m^3, corresponding the saturation status at 200 °C. Boundary conditions are specified as impermeable and adiabatic on lateral faces, with fixed temperature at the top and bottom and roller constraints applied to lateral and basal mechanical boundaries.

The simulation involves injecting fluid at 50 °C into the fracture at a constant rate of 20 kg/s for 30 years, while maintaining the production well pressure at 34 MPa. Two injection chemistries are considered: undersaturated fluid (0 mol/m^3 amorphous silica) and supersaturated fluid (20 mol/m^3 amorphous silica). Fracture and rock matrix properties are summarized in Table 1. Water viscosity, density, specific heat capacity, and thermal conductivity are treated as temperature-dependent parameters according to the literature.

Table 1. Physical and mechanical parameters used in numerical models.

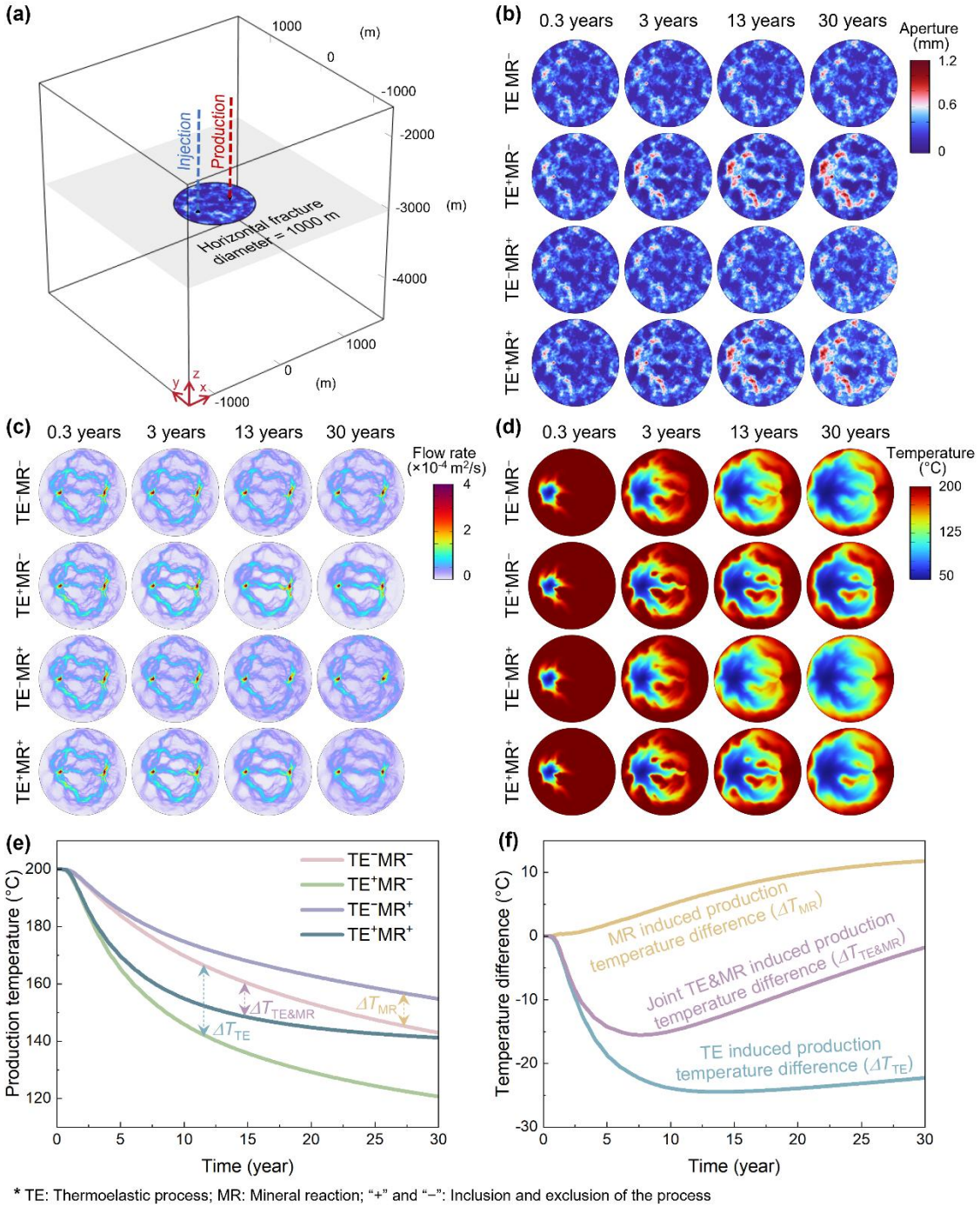
Parameters	Values	Parameters	Values
Rock density	2500 kg/m^3	Rock specific heat capacity	915 J/kg/K
Rock porosity	0.01	Rock thermal conductivity	3.5 W/m/K
Rock elastic modulus	33.3 GPa	Fracture normal stiffness	50 GPa/m
Rock Poisson's ratio	0.3	Solute diffusion coefficient	1E-9 m^2/s
Rock permeability	1E-17 m^2	Amorphous silica content	50%
Rock thermal expansion coefficient	8E-6 1/K	Fluid compressibility	5.11E-10 Pa^{-1}

2.2 Effects of thermoelastic process and mineral reaction on flow channeling behavior

To isolate and quantify the individual and combined effects of the thermoelastic process and mineral reaction on flow channeling, we compare a baseline scenario without either mechanism (marked as TE$^-$MR$^-$) with simulations that include only the thermoelastic process (TE$^+$MR$^-$), only the mineral reaction (TE$^-$MR$^+$), and both mechanisms (TE$^+$MR$^+$). The thermoelastic process is deactivated by setting the rock's thermal expansion coefficient to zero, whereas the mineral reaction is suppressed by assigning a zero kinetic rate for amorphous silica dissolution–precipitation.

The simulations indicate that the thermoelastic process is primarily confined to the cooled regions of the reservoir (Figure 1b–d, first and second rows). Thermal contraction of the rock matrix generates tensile stresses that markedly increase fracture apertures within the cooled zones, whereas apertures in the distal, hotter regions remain nearly unchanged (Figure 1b, first and second rows). This spatially heterogeneous aperture

evolution amplifies pre-existing preferential flow paths, thereby intensifying flow channeling (Figure 1c, first and second rows). Consequently, the thermoelastic process reduces the effective heat exchange area between the fluid and the rock formation (Figure 1d, first and second rows) and accelerates thermal breakthrough between injection and production wells (Figure 1e). The thermoelastic process exerts its strongest influence during the first 12.5 years, causing a rapid decline in the production temperature difference (Figure 1f). After this period, the effect weakens, and the decline rate of production temperature difference slows, with even a slight rebound (Figure 1f). This transition is attributed to the temperature-dependent viscosity of water: as the cooled zone expands, the increased viscosity within it gradually offsets the thermoelastic process–induced flow channeling, thereby reducing the rate of thermal drawdown.



* TE: Thermoelastic process; MR: Mineral reaction; "+" and "–": Inclusion and exclusion of the process

Figure 1. Coupled THMC processes govern fluid flow pathways and heat extraction efficiency in a single-fracture EGS. (a) Conceptual model incorporating spatially heterogeneous fracture aperture. (b-d) Spatiotemporal evolution of fracture aperture, flow rate, and temperature under different process combinations. (e) Production temperature over time for different scenarios, including $TE^{-}MR^{-}$, $TE^{+}MR^{-}$, $TE^{-}MR^{+}$ and $TE^{+}MR^{+}$. (f) Relative contributions of thermoelastic process and mineral reaction to production

temperature. Temperature differences in (f) are quantified relative to the baseline case (TE^-MR^-) by comparing with scenarios that include only thermoelastic process (TE^+MR^-), only mineral reaction (TE^-MR^+), or both (TE^+MR^+). Notably, all scenarios involving mineral reaction assume undersaturated fluid injection.

In contrast to the thermoelastic process, the mineral reaction primarily affects the hotter regions of the reservoir (Figure 1b–d, first and third rows). The injection of undersaturated fluid drives the dissolution of amorphous silica across the entire fracture surface. The dissolution rate, however, is highly temperature dependent: aperture change remains minimal (~0.001 mm over 30 years) in the cooled zone near the injector but becomes substantial (~0.2 mm over 30 years) in the hotter regions (Figure 1b, first and third rows). Significant dissolution-induced aperture enlargement in the hotter regions alleviates flow channeling by enhancing the permeability of previously underutilized flow paths, thereby promoting a more uniform flow distribution (Figure 1c, first and third rows). Consequently, mineral dissolution enlarges the effective heat exchange interface between the fluid and the rock formation (Figure 1d, first and third rows) and delays thermal breakthrough at the production well (Figure 1e). The contribution of mineral reaction is cumulative: prolonged injection produces progressively greater thermal benefits, as evidenced by a steadily increasing production temperature difference over time (Figure 1f).

When the thermoelastic process and mineral reactions occur simultaneously, they exert opposite effects on fracture flow patterns. The thermoelastic process–induced aperture increase in cooled regions promotes flow channeling, whereas the mineral reaction–induced aperture increase in hotter zones enhances flow dispersion, thereby mitigating channelization (Figure 1b–d, first and fourth rows). This interaction yields a distinct thermal production profile in the fully coupled scenario (TE^+MR^+): the production temperature decreases more rapidly than that in the baseline scenario (TE^-MR^-) during the early stage, but the decline rate slows during the mid-to-late stages, with temperature gradually converging toward baseline scenario (Figure 1e). Quantitatively, the temperature difference between the two scenarios reaches -15.5 °C within the first 7.5 years and then decreases steadily to -1.8 °C by year 30 (Figure 1f). These dynamics indicate that the thermoelastic process dominates initially, intensifying fracture flow channeling. Over time, however, the cumulative effects of mineral dissolution become dominant, counteracting flow channeling and stabilizing long-term thermal performance.

2.3 Effect of injectate chemistry on flow channeling behavior

Our previous results show that injecting undersaturated fluid mitigates thermoelastic process–induced flow channeling by promoting mineral dissolution. However, prolonged use of undersaturated fluid substantially increases operational costs. In practice, most enhanced geothermal systems reinject cooled production fluid to maintain economic viability. This closed-loop circulation gradually increases the dissolved silica concentration, which can exceed saturation and trigger precipitation.

To evaluate the effect of injectate chemistry, we simulate an oversaturated injection scenario. Results indicate that oversaturated injection induces amorphous silica precipitation, particularly in high-temperature regions, which decreases fracture apertures and intensifies flow channeling (Figure 2a). After 30 years, the effective heat-swept volume becomes more restricted than in the thermoelastic-only case (Figure 2a), leading to the fastest thermal decline among all scenarios (Figure 2b). These results quantitatively confirm that silica precipitation aggravates thermoelastic process–induced flow channeling. Therefore, to sustain EGS performance, injection strategies should either prioritize fluids with the lowest economically feasible silica concentration or employ innovative descaling technologies to maintain undersaturation.

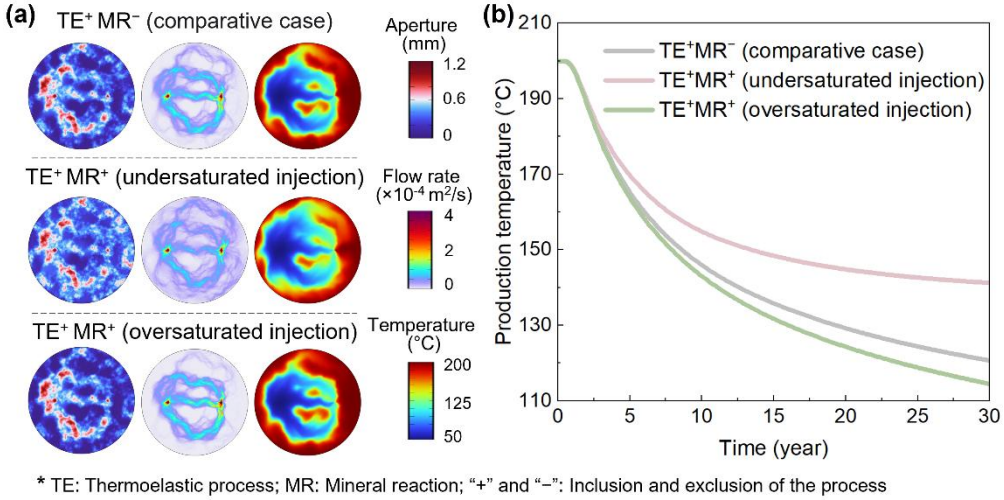


Figure 2. Effect of injectate chemistry on heat extraction pathways and efficiency. (a) Snapshots of fracture aperture, flow rate, and temperature fields at the 30-year mark. (b) Comparison of production temperature profiles resulting from undersaturated and oversaturated injection fluids.

3 CONCLUSION

In this study, we investigate the individual and combined effects of the thermoelastic process and mineral reaction on fracture flow channeling and the long-term thermal performance of EGS. Our results show that the thermoelastic process during cold-fluid injection enhances fracture flow channeling, thereby accelerating thermal breakthrough. Conversely, mineral dissolution under undersaturated conditions mitigates flow channeling by increasing apertures outside dominant pathways, thereby enlarging the effective heat-exchange area between the fluid and the rock matrix. In contrast, mineral precipitation under supersaturated conditions intensifies flow channeling and leads to a faster decline in production temperature. These findings underscore the critical role of injectate chemistry in controlling THMC-coupled processes and the long-term performance of EGS.

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REFERENCES

Fu, P., Hao, Y., Walsh, S.D.C., and Carrigan, C.R.: Thermal drawdown-induced flow channeling in fractured geothermal reservoirs, *Rock Mechanics and Rock Engineering*, **49**, 3, (2016), 1001-1024.

Guo, B., Fu, P., Hao, Y., Peters, C.A., and Carrigan, C.R.: Thermal drawdown-induced flow channeling in a single fracture in EGS, *Geothermics*, **61**, (2016), 46-62.

Koh, J., Roshan, H., and Rahman, S.S.: A numerical study on the long term thermo-poroelastic effects of cold water injection into naturally fractured geothermal reservoirs, *Computers and Geotechnics*, **38**, 5, (2011), 669-682.

Méheust, Y., and Schmittbuhl, J.: Flow enhancement of a rough fracture, *Geophysical Research Letters*, **27**, 18, (2000), 2989-2992.

Ogata, S., Yasuhara, H., Kinoshita, N., Cheon, D.S., and Kishida, K.: Modeling of coupled thermal-hydraulic-mechanical-chemical processes for predicting the evolution in permeability and reactive transport behavior within single rock fractures, *International Journal of Rock Mechanics and Mining Sciences*, **107**, (2018), 271-281.

Pandey, S.N., Chaudhuri, A., Rajaram, H., and Kelkar, S.: Fracture transmissivity evolution due to silica dissolution/precipitation during geothermal heat extraction, *Geothermics*, **57**, (2015), 111-126.

Salimzadeh, S., and Nick, H.M.: A coupled model for reactive flow through deformable fractures in Enhanced Geothermal Systems, *Geothermics*, **81**, (2019), 88-100.

Shu, B., Zeng, F., Kemeny, J., Zhu, R., Chen, K., and Tan, J.: Analysis of the hydraulic and heat transfer evolution mechanism of a single rock fracture, *Journal of Earth Science*, **34**, 1, (2023), 205-213.

Tsang, Y.W., and Tsang, C.F.: Flow channeling in a single fracture as a two-dimensional strongly heterogeneous permeable medium, *Water Resources Research*, **25**, 9, (1989), 2076-2080.

Wang, J., Ahmed, B., Huang, J., Nong, X., Xiao, R., Abbasi, N.S., Alidekyi, S.N., and Li, H.: Physical and Mechanical Properties and Constitutive Model of Rock Mass Under THMC Coupling: A Comprehensive Review, *Applied Sciences*, **15**, 4, (2025), 1-30.

Zeng, F., Shu, B., and Shen, Q.: A combination of Light Detection and Ranging with Digital Panoramic Borehole Camera System in fracture mapping to characterize discrete fracture networks, *Bulletin of Engineering Geology and the Environment*, **82**, 7, (2023), 249.

Zeng, F., Wu, H., Zhang, K., and Liu, Y.: Fracture aperture evolution in subsurface fractured reservoirs: Insights from thermo-hydro-mechanical simulations and implications for field-scale applications, *International Journal of Rock Mechanics and Mining Sciences*, **195**, (2025), 106254.

Zeng, F., Wu, H., Song, G., Wang, Y., and Ji, J.: Competition between thermoelastic process and mineral reaction on fracture flow channeling: Implications for long-term thermal performance of EGS reservoirs, *Engineering Geology*, **364**, (2026), 108610.