

Predicting Mineralogical Changes in EGS Reservoirs: Insights from Geochemical/Reactive Transport Modeling at the FORGE Site

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ABSTRACT

The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) field-scale laboratory was established to advance the development of Enhanced Geothermal System (EGS) resources. This paper aims to predict the mineralogical changes and hydraulic conductivity in the fractured networks using the chemical composition of injected and produced water in wells 16A and 16B during the circulation test conducted between August and September 2024 at the FORGE site. The primary objective is to provide insights into the impact of geochemistry on porosity and flow during the planned long-duration circulation test.

A thermal-hydrological-chemical (THC) model was developed using injections and produced water data to explore water-rock interactions and flow in porous and fractured media, using the FALCON (Fracturing And Liquid CONvection) code and The Geochemist's Workbench. The fracture domain and water chemistry have been updated based on the latest geophysical and geochemical data from the previous circulation tests in August-September 2024.

The model's results predicted the mineralogical changes and the net changes in porosity due to water-rock interaction and temperature variations for 6 months to inform the next long-duration circulation test. The geochemical model, calibrated using produced water data from previous tests, predicted the dissolution of quartz and retrograde precipitation of carbonate minerals. In this simulation, production of CO₂ has been considered based on the characteristics of produced water and gas samples. The mineralogical changes vary in the fractured network, indicating how fluid transport in the wells influences the movement of precipitated or dissolved minerals along the fractured plane.

Model predictions, such as pH, mineral saturations, and concentration of aqueous species were consistent with the produced water chemistry reported during previous circulation tests. The results of this study will aid in planning future long-duration circulation tests and the development of EGS resources for sustainable geothermal production.

1. INTRODUCTION

The Frontier Observatory for Research in Geothermal Energy (FORGE) is a large-scale experimental facility located in a remote area of southwest Utah, approximately 16 km northeast of Milford. Established by the U.S. Department of Energy (DOE), Utah FORGE is dedicated to advancing technologies that enable the commercialization of Enhanced Geothermal Systems (EGS). Unlike conventional geothermal resources that rely on natural permeability, EGS can harness heat from hot, dry rock, significantly expanding the potential for renewable energy production. Research at Utah FORGE focuses on two critical aspects: maintaining fluid circulation between wells and accurately characterizing the reservoir's geology (Moore et al., 2019). Since 2015, multiple wells have been drilled at the site, including two closely spaced, highly deviated wells designed for circulation testing. The injection well, 16A(78)-32, was completed in January 2021, followed by the production well, 16B(78)-32, in June 2023. McLennan et al. (2023) provides a detailed analysis of the reservoir's mineralogical and geological properties based on drill cuttings and cores collected between 2018 and 2022. Figure 1 illustrates a geologic cross-section along the injection-production doublet, showing well trajectories, lithologies, and the reservoir's temperature gradient (Jones et al., 2024). Both wells are deviated approximately 65° from vertical and run parallel, with the production well positioned about 100 meters above the injection well (Jones et al., 2024).

Preexisting fractures play a vital role in developing an EGS reservoir, serving as permeable pathways for fluid circulation. These fractures can be identified in geophysical logs by increased sonic travel time and porosity, coupled with reduced density relative to surrounding rock. Numerous studies have characterized the FORGE reservoir, examining heat and mass transport in both natural and hydraulically induced fractures using geological, geophysical, groundwater, physical, seismic, and geochemical data (Jones et al., 2024; Moore et al., 2023; Podgorney et al., 2019; Podgorney et al., 2021; Simmons et al., 2016; Simmons et al., 2018; Wannamaker et al., 2020; Xing et al., 2024; Kumar et al., 2025). Fracture zones often exhibit high concentrations of secondary minerals formed through precipitation in open spaces, alteration of primary minerals, and fine-grained shearing. Unmineralized conductive fractures typically occur in localized clusters within the reservoir rock and display diverse orientations. These zones also act as sites for alteration and mineralization processes. This study aims to investigate mineralogical changes during a planned six-month circulation test.

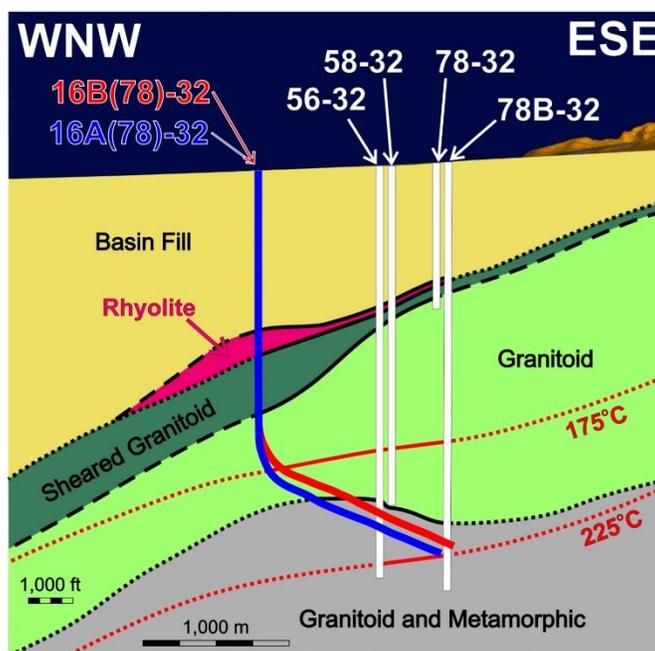


Figure 1: Geologic cross-section showing injection (16A) and production well (16B) doublet showing well tracks, lithologies, and the temperature gradient in the reservoir (Jones et al., 2024)

2. GEOLOGIC SETTING

The basement rocks at Utah FORGE consist predominantly of plutonic formations, with deeper sections containing alternating layers of plutonic and metamorphic units. Overlying these basement rocks is a basin fill that reaches thicknesses of up to about 3,000 meters, comprising a stratified sequence of Tertiary, Quaternary, and Recent deposits. With increasing depth, this sequence transitions from alluvial fan deposits to lacustrine sediments with minor evaporite layers, and further includes interbedded volcanic and volcanoclastic units ranging from felsic to intermediate composition (Jones et al., 2024).

2.1 Mineralogy

Core samples from well 16A(78)-32 reveal weakly to moderately foliated granitoid at depth, with thin plagioclase and quartz dikes near the bottom (Jones et al., 2021). Certain intervals contain strongly foliated, biotite-rich rock featuring quartz and plagioclase lenses, along with folded dikes. Fractured zones exhibit distinctive mineralization, beginning with early inclusion-rich albite ± quartz, followed by Mg- and Fe-bearing carbonates within a fine-grained quartz ± illite matrix (Jones et al., 2021; Jones et al., 2024). This mineralization occurs sporadically throughout the well and other Utah FORGE wells.

XRD analyses indicate that secondary minerals—such as quartz, albite, carbonates, and clays—range from less than 1% to over 90% by weight, with the highest concentrations observed at the granitoid-orthogneiss contact. The mineralogical composition considered in this study is based on bulk XRD results from well 16A(78)-32. Mineral abundances for depths between 9,000 and 10,000 feet are summarized in Table 1 as weight percentages, rounded to the nearest whole number. Fields marked “tr” (trace) denote minerals present at less than 1% by weight, as determined by Rietveld refinement. Additionally, “tr” may indicate minerals detected in the clay-sized fraction but absent in the bulk sample, and/or observed in low abundance during petrographic analysis.

Table 1: Mineralogical composition of well 16A(78)-32 at the FORGE site determined by bulk XRD analysis

Measured Depth (ft)	Quartz	Plagioclase	K-Feldspar	Biotite	Hornblende	Clinopyroxene	Titanite	Magnetite	Muscovite	Sillimanite	Epidote	Actinolite	Anhydrite	Calcite	Siderite	Illite	Chlorite
9000-9010	27	62	4	3	tr		1	tr								tr	tr
9100-9110	7	51	7	11	18	1	3		tr				1	tr	1		
9200-9210	40	33	17	4	1		2	tr	tr	tr						tr	1
9300-9310	11	52	27	5	1	1	tr	tr				tr	tr			1	tr
9400-9410	6	59	11	8	10	1	2	tr	tr				tr				tr

9500-9510	6	69	10	2	3		2	tr			4	tr		tr		2	tr
9600-9610	8	55	28	3	1		1	tr			tr			1		2	tr
9700-9710	36	42	8	3	1		tr	tr	tr		tr			tr		4	2
9800-9810	38	47	5	5	tr		tr	tr						tr		1	tr
9900-9910	14	50	5	8	10	1	3	tr	tr	tr	2	tr		1	tr	3	2
10000-10010	17	43	16	8	tr	3	1			1	1			tr		4	2

2.2 Water chemistry

Table 2 shows sample data collected from well 16A(78)-32, 16(B)78-32, and monitoring well 58-32 during the August-September 2024 circulation test. This speciation has been used to set up and calibrate geochemical simulations.

Table 2: Aqueous species composition (mg/kg) of well 16A(78)-32 and 16B(78)-32 at the FORGE site determined by chemical analysis measured on August 22, 2024.

Species (mg/kg)	16A(78)-32	16B(78)-32	58-32
Na ⁺	2260	2540	3550
K ⁺	250	269	339
Ca ²⁺	190	108	94.6
Mg ²⁺	12.6	1.24	6.26
B	30.6	30.3	36.5
SiO ₂	151	298	205
Cl ⁻	3920	4210	5460
SO ₄ ²⁻	132	179	4.57
HCO ₃ ⁻	297	163	1200
CO ₂ (aq)	--	1187	--
As	1.10	1.27	0.04
pH	6.99	6.05	6.38

2.3 Numerical modeling

FALCON (Fracturing And Liquid CONvection) is a versatile subsurface simulator designed for addressing coupled thermal-hydraulic-mechanical-chemical (THMC) problems (Podgorney et al., 2019; Xia et al., 2017). It has been utilized in the study of geothermal reservoir dynamics, groundwater flow and transport, carbon sequestration, and more. Developed using Idaho National Laboratory's (INL) Multiphysics Object-Oriented Simulation Environment (MOOSE) framework (Gaston et al., 2012; Wilkins et al., 2021), FALCON features a modular, plug-and-play design. This architecture represents governing partial differential equations (PDEs) in a weak form, with the residual term described as a "kernel." These kernels are solved using a finite element scheme and can be coupled together for various applications. MOOSE's architecture allows for the convenient coupling of different processes. FALCON has been validated through several benchmark problems, and its source code is open source, with governing equations available in the MOOSE documentation. The discrete fractured network (Figure 2) for this model is plotted in figure 2. For the geochemical simulations in this study, we used mineral kinetics data from Palandri and Kharaka (2004) and thermodynamic data from Wolery and Jove-Colon (2007).

3. RESULTS & DISCUSSION

3.1. pH Evolution (Figure 3):

The pH profile over 180 days shows a gradual decrease in pH due to CO₂ dissolution, indicating acidification of the circulating fluid. This change in acidity strongly influences mineral stability and reaction kinetics within the fractured network.

3.2. Mineral Saturation Trends (Figures 4 & 5):

Calcite: Initially undersaturated, resulting in early dissolution, followed by retrograde precipitation as reservoir temperature increases during circulation.

Anhydrite: Shows progressive precipitation under evolving thermal conditions, indicating sulfate incorporation into secondary mineral phases.

Albite and Quartz: Albite remains near equilibrium, while quartz exhibits dissolution, consistent with elevated SiO₂ concentrations in produced water.

Carbonates (Siderite, Aragonite): Saturation indices suggest precipitation during later stages of the simulation.

Clays (Illite, Kaolinite): Minor changes observed, indicating limited clay alteration during the simulation period.

3.3. Porosity Changes (Figure 6):

Porosity evolution is spatially variable, with localized increases due to calcite dissolution and minor decreases where carbonate and anhydrite precipitation occurs. Overall, net porosity change is modest but significant for flow pathways.

3.4. Permeability Alterations (Figure 7):

Permeability trends mirror porosity changes, with slight enhancements in zones of dissolution and reductions where secondary mineral precipitation (including anhydrite) occurs. These changes could impact long-term fluid circulation efficiency.

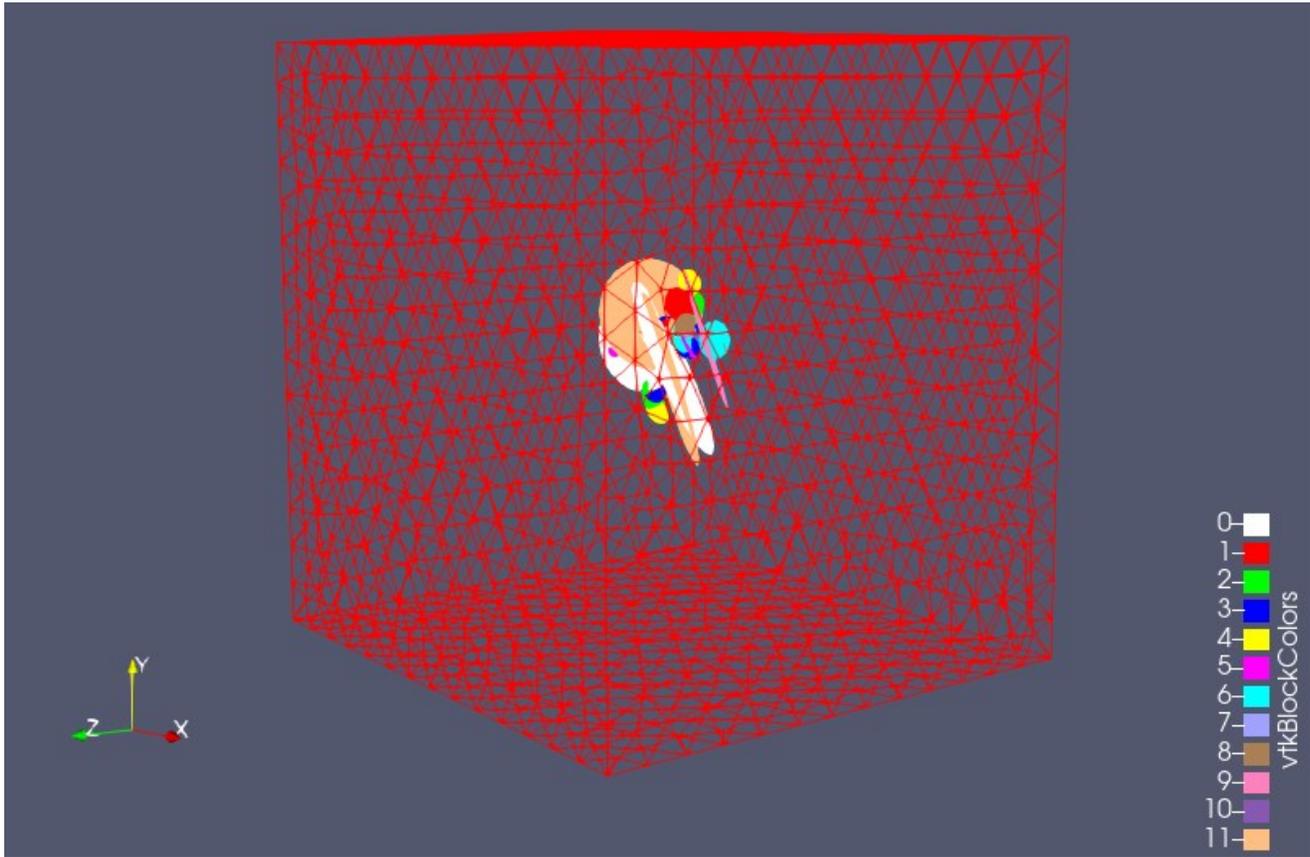


Figure 2: Updated Discrete Fracture Network (DFN) model used for reactive transport simulations, illustrating fracture geometry and connectivity within the reservoir domain.

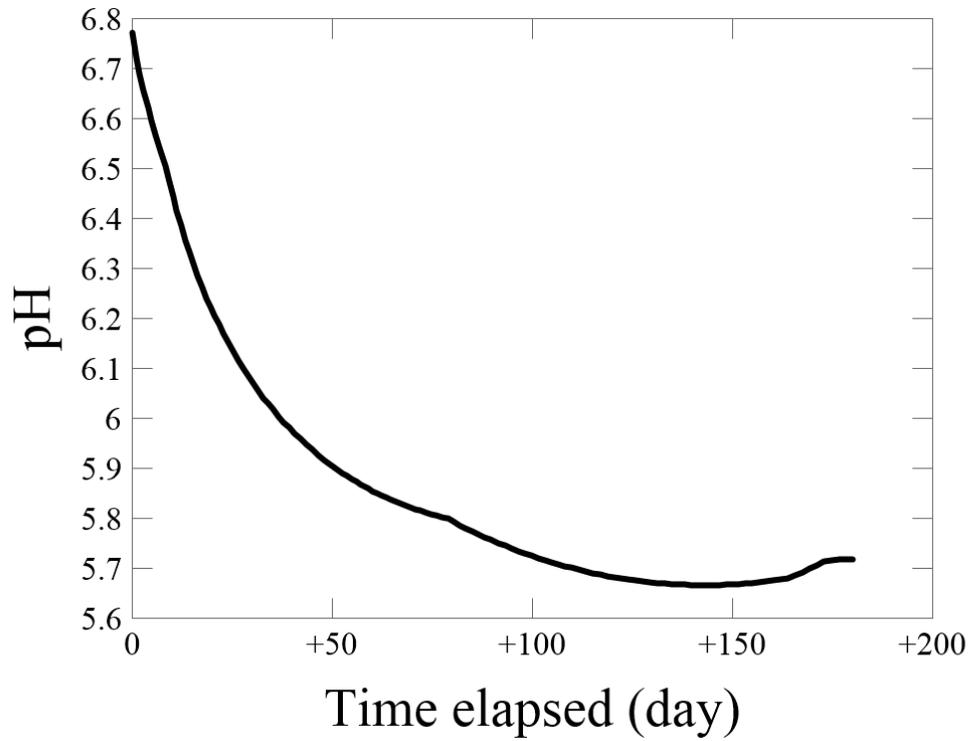


Figure 3: Simulated pH evolution over 180 days of mineral-water interaction, highlighting acidification due to CO₂ dissolution and its impact on geochemical reactions.

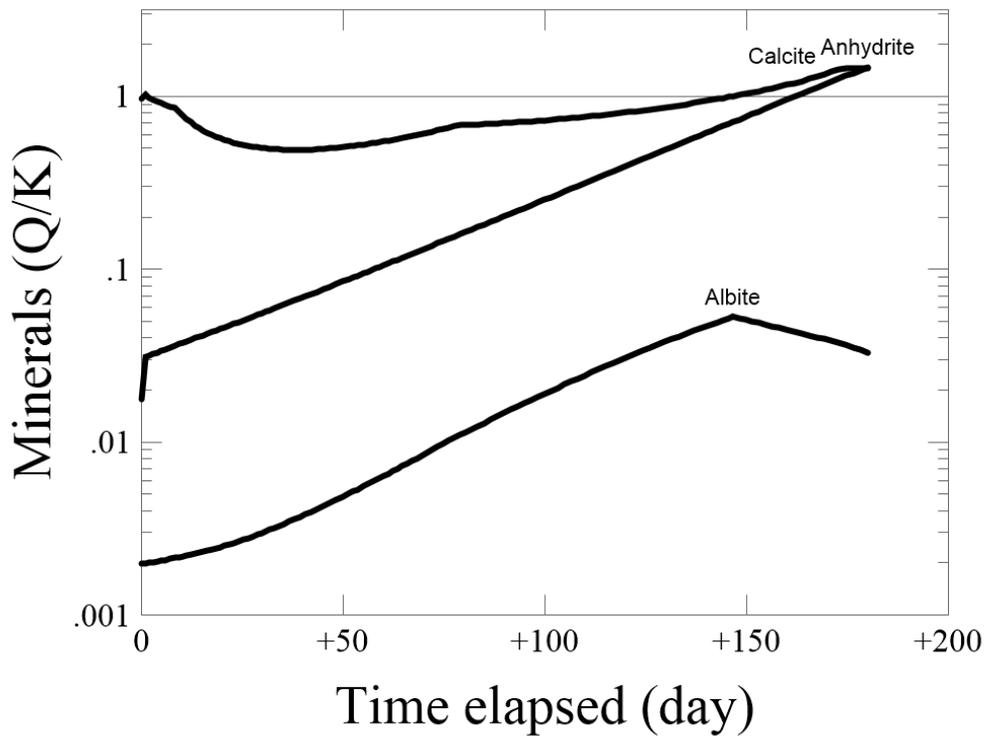


Figure 4: Mineral saturation indices for calcite, anhydrite, and albite during the simulation period, showing early calcite dissolution followed by retrograde precipitation and progressive anhydrite precipitation.

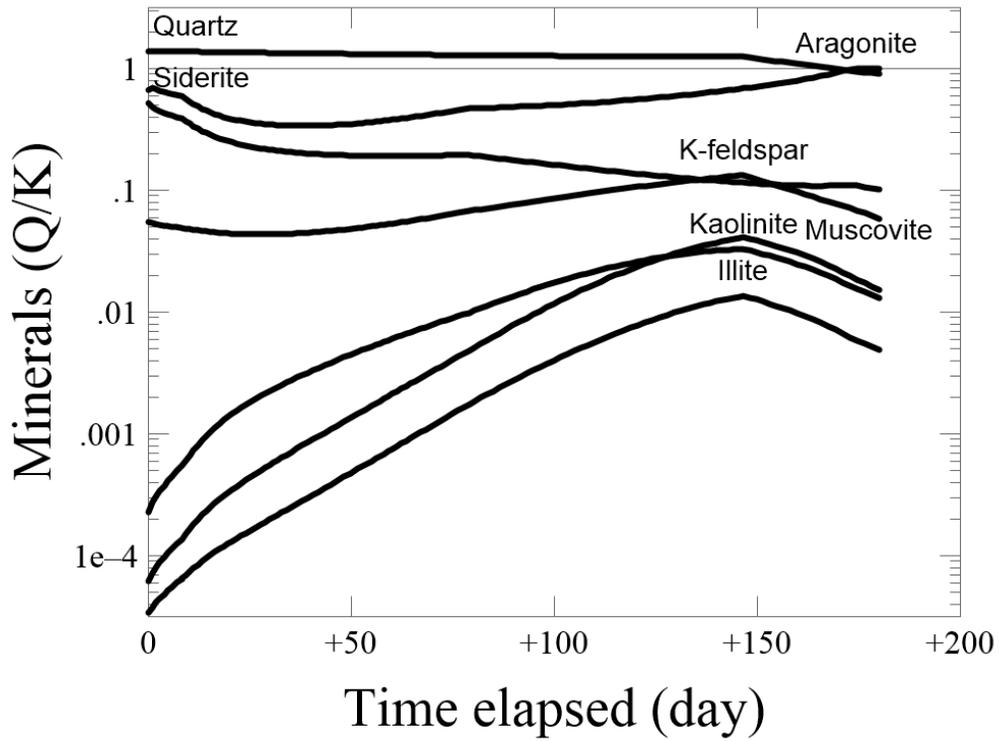


Figure 5: Saturation trends for key minerals including quartz, aragonite, siderite, K-feldspar, kaolinite, muscovite, and illite, indicating heterogeneous alteration across the fracture network.

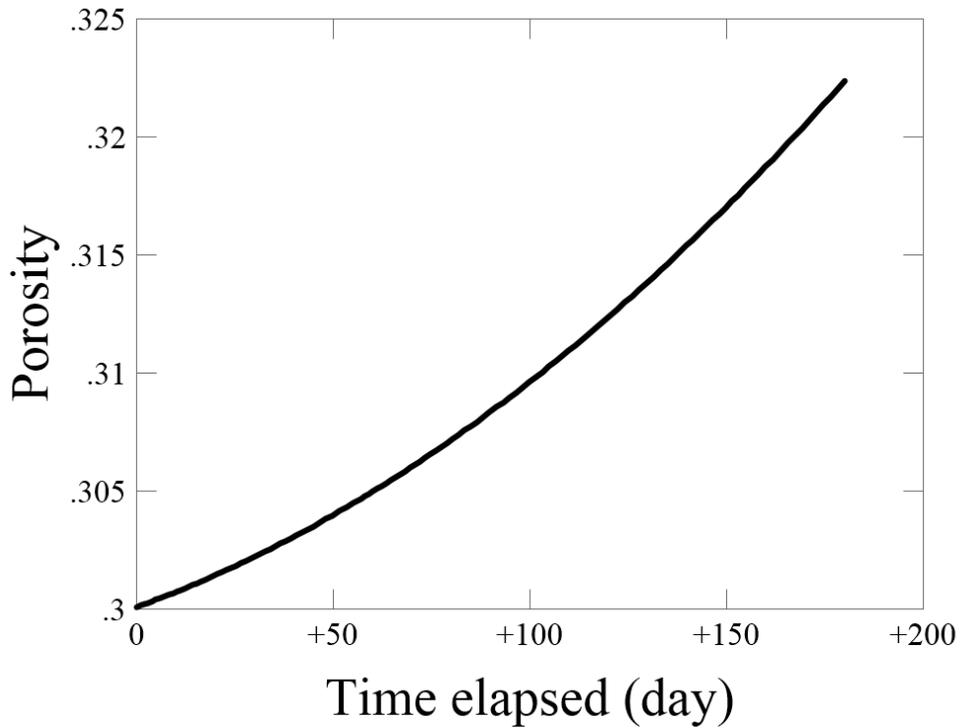


Figure 6: Porosity evolution over time due to mineral dissolution and precipitation, with localized increases from calcite dissolution and decreases from carbonate and anhydrite precipitation.

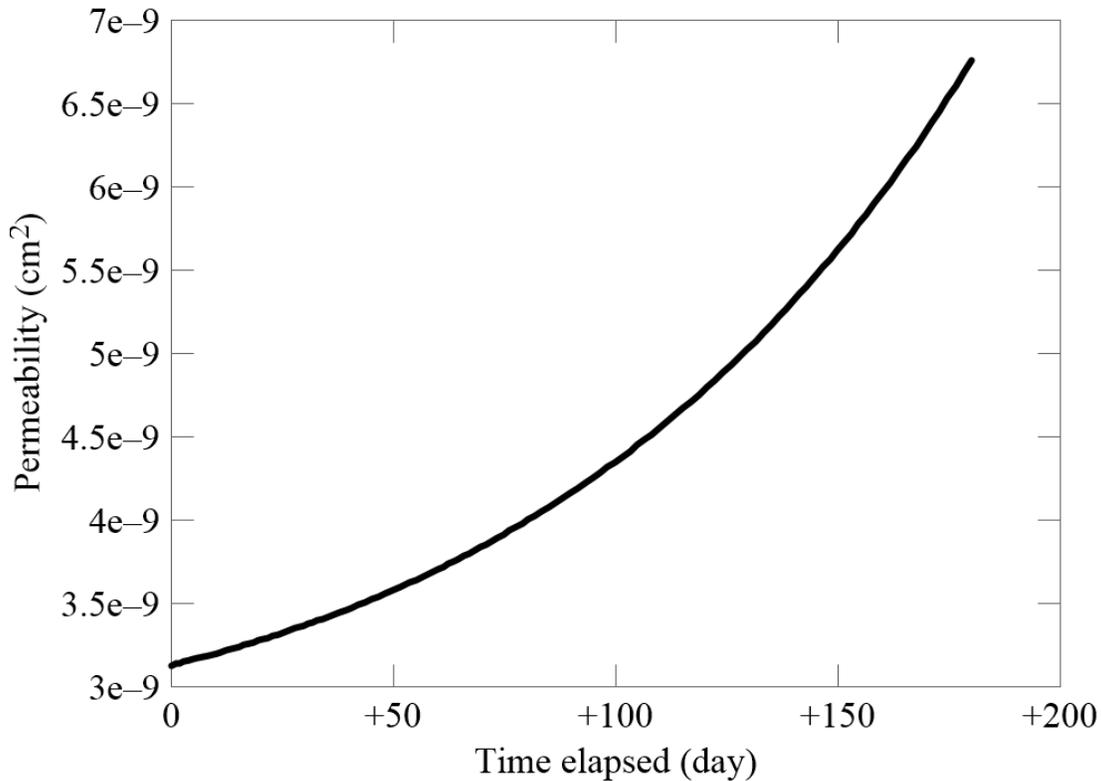


Figure 7: Permeability changes associated with mineralogical alterations, showing slight enhancements in dissolution zones and reductions where secondary minerals (including anhydrite) precipitate.

4. CONCLUSIONS

- Reactive transport modeling predicts **dynamic mineralogical changes** during the six-month circulation test, primarily driven by CO₂-induced pH shifts and temperature variations.
- **Calcite dissolution followed by retrograde precipitation**, along with **anhydrite precipitation**, are dominant processes influencing porosity and permeability evolution.
- Quartz and albite exhibit minor dissolution, while carbonate and sulfate minerals show localized precipitation, suggesting heterogeneous alteration across the fracture network.
- Changes in porosity and permeability, although modest, highlight the importance of **continuous monitoring and model refinement** for accurate prediction of reservoir performance.
- Future work should incorporate **3D fracture network modeling**, improved reaction kinetics, and heterogeneity considerations to enhance predictive capability and optimize EGS operations.

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