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Mineral Reactions in Deep Fractured Upper Rhine Graben Formations: A Numerical Study for Uncertainty-Driven Reservoir Management

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Introduction

Thermo-hydro-chemical (THC) reactive transport in fractured geothermal reservoirs plays a critical role in optimizing thermal energy extraction and ensuring sustainable management. It governs how heat, fluids, and minerals interact in fractured geothermal reservoirs. Temperature and pressure changes during production drive brine flow, solute transport, and reactions such as calcite dissolution or precipitation (Fig. 1); these feedbacks can either enhance permeability or clog flow paths, directly affecting long-term performance. This becomes important in complex cases where multiple brines coexist in different saturation states, which further influences reactive transport behavior and reservoir evolution. The current case study targets the Middle Buntsandstein sandstone beneath Wörth am Rhein in the Upper Rhine Graben, where the DEKAPALATIN geothermal project is now being implemented (Fig. 2).

Interplay of Flow Rate, Temperature, and Concentration

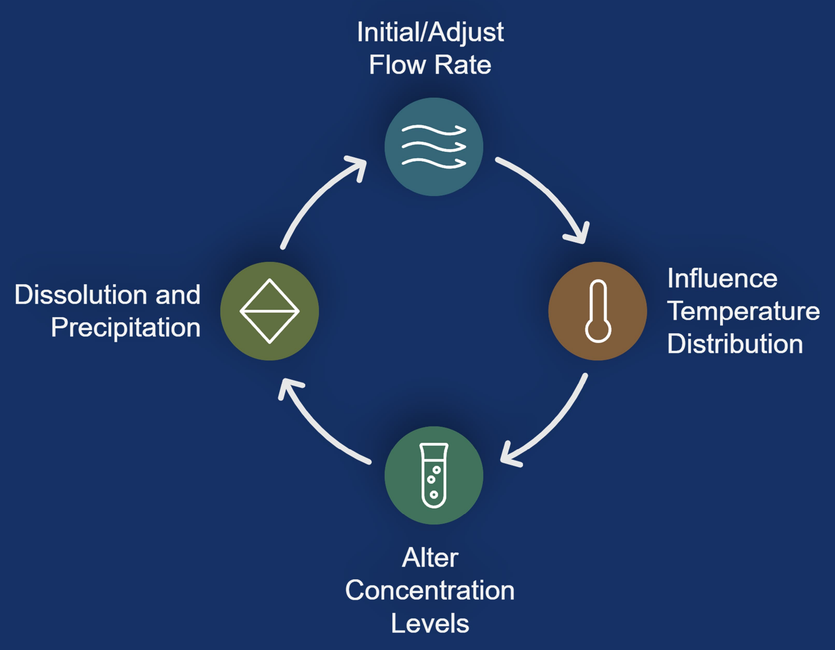


Fig. 1. Conceptual THC feedback loop

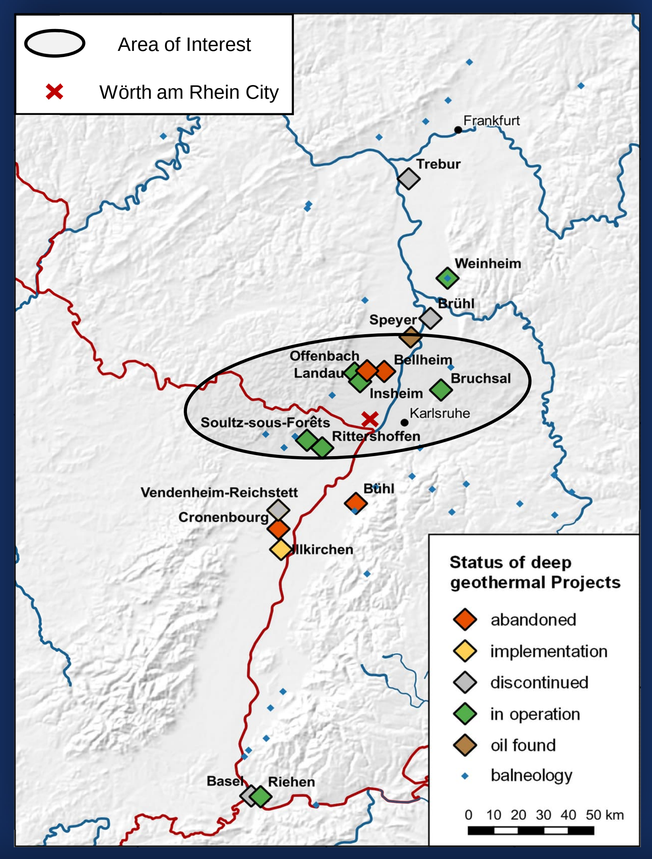


Fig. 2. Map of deep geothermal projects in the Upper Rhine Graben (adapted from [1]); the area of interest and the location of Wörth am Rhein have been highlighted for clarity

Methodology

- Model Geometry and Setup:
  - The domain is a 100-meter single horizontal fracture (Fig. 3), that carries approximately 100% of the flow. The initial composition of the fracture is about 24 vol% calcite
  - The initial temperature is 160 °C, while a 60 °C brine is injected from the left side
  - Injection and production mass fluxes (1e-4 kg/sec) are matched (1:1), maintaining the pressure near its initial value of approximately 400 bar
  - Total simulation time: 3 years

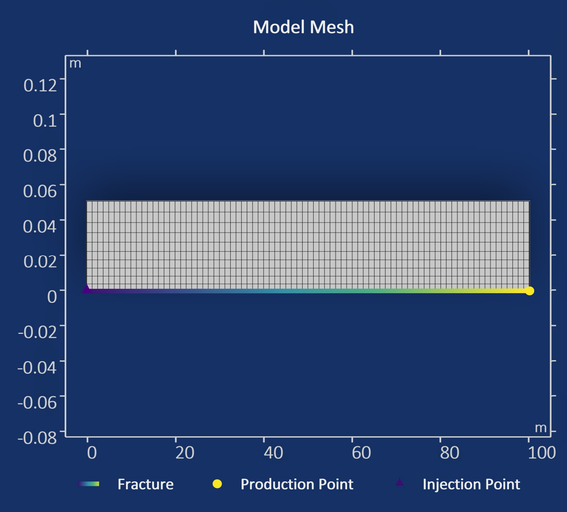
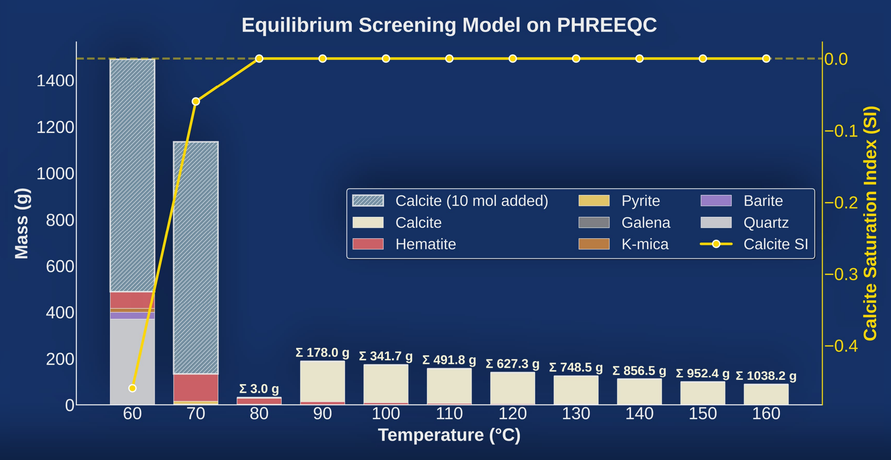


Fig. 3. Model setup

  - Two brine compositions (B1–B3) represent the east-to-west geochemical gradient of the study area [2], where B1 corresponds to the easternmost mixture and B3 to the westernmost. These brines were used to initialize the model under various scenarios, to investigate the impact of brine composition, porous matrix porosity, and flow rate on the dissolution and precipitation behavior of calcite. THC coupling is implemented via iCP [3] (Fig. 4)



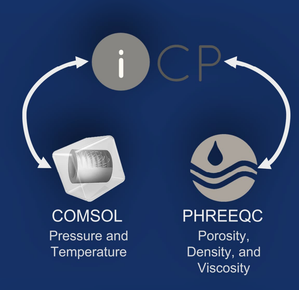


Fig. 4. Simulation framework & Calcite Behavior

What the plots show and what it means

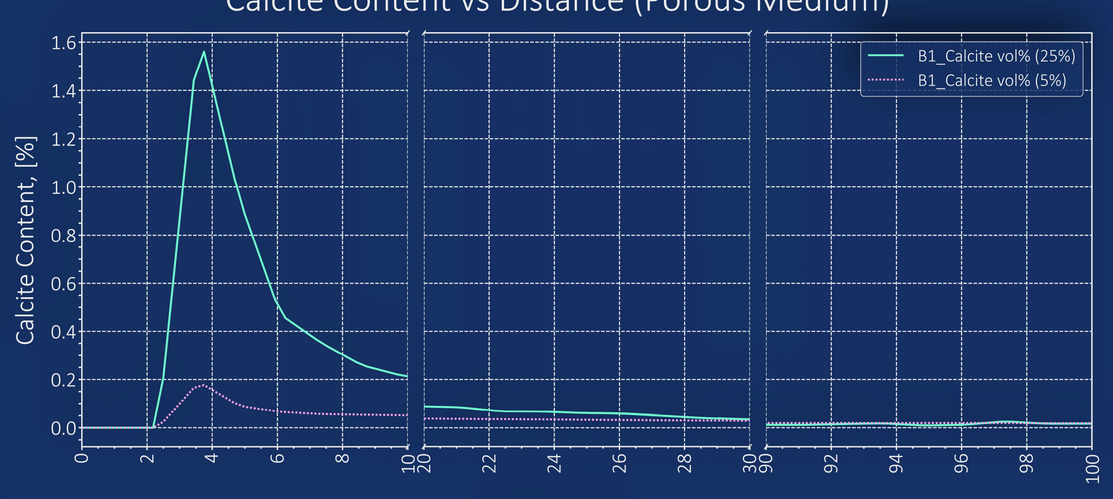


Fig. 5. Calcite content changes in the nearby porous matrix

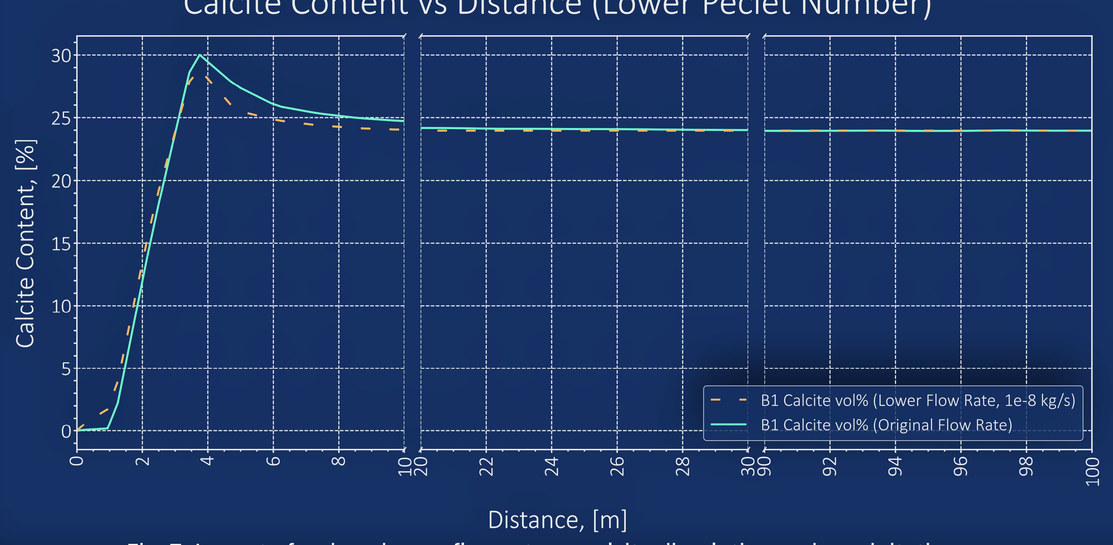


Fig. 7. Impact of reduced mass flow rate on calcite dissolution and precipitation

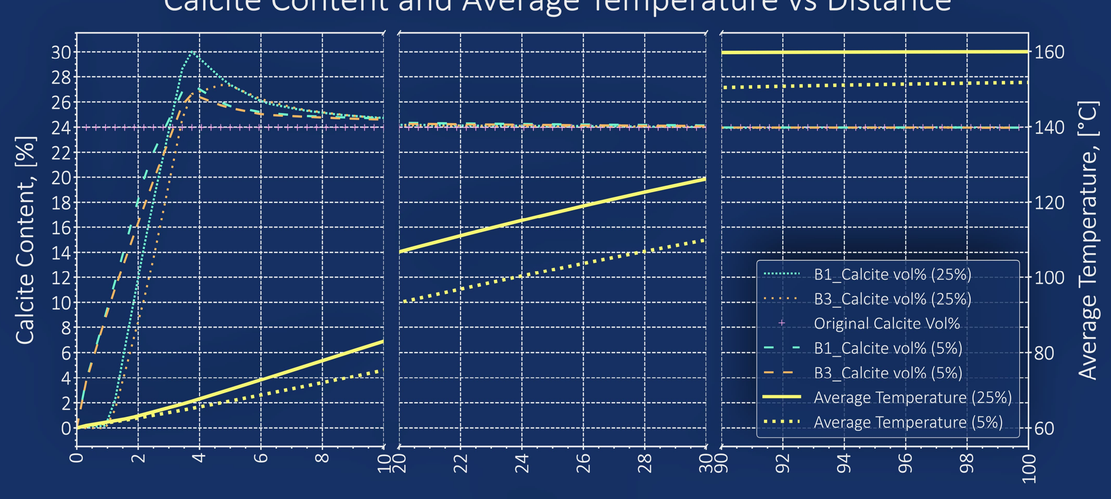


Fig. 6. East-to-west brine gradient shows the same sequence, with different strengths

- Discussion:
  - Calcite dissolution upstream loads the brine with $CaCO_3$, driving supersaturation and triggering precipitation — first apparent in the 0–10 m section, continuing through 20–30 m, and reaching equilibrium by 90–100 m. The east-to-west brine gradient (B1 → B3) follows the same sequence but with varying intensity, where B3 shows faster dissolution and less precipitation (Fig. 5 and 6)
- Conclusions:
  - Calcite is the most reactive mineral in the area of interest and the primary driver of permeability change
  - Fracture–matrix interactions may substantially influence dissolution–precipitation reactions and should be considered in permeability predictions
  - Reducing the mass flow rate affects the reaction front but does not significantly alter the overall dissolution–precipitation pattern (Fig. 7)

References

[1]: *Frey et al., Geotherm. Energy 10, 18 (2022)*
[2]: *Sanjuan et al., Chem. Geol. 428, (2016)*
[3]: *Nardi et al., Comput. Geosci. 69 (2014)*

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