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Opening Versus Self-Sealing Behaviour Of Single Fractures In Mudstone Caprocks During CO2 Migration

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Summary

Reactions between CO₂ and CO₂-charged brines and mudrocks may inhibit CO₂ leakage via the precipitation of carbonate minerals or via swelling of clay minerals or enhance leakage via the corrosion of carbonate cements. The timescales for the potential self-sealing behaviour, and/or the magnitudes of the permeability enhancements are uncertain. Laboratory experiments can provide constraints on the intrinsic fracture permeabilities, but the quantification of permeability changes following reaction or under conditions of multiphase flow is challenging in the laboratory. Reactive transport modelling (RTM) provides a numerical laboratory in which the intrinsic permeabilities of rough fractures, and the coupling of the flow and reaction processes, can be investigated. A modified local cubic law (MLCL) is used to model rough fracture permeability, and coupling of permeability-porosity changes to mineralization and clay swelling. The results show that the intrinsic permeability of self-affine fractures is primarily dependent on the roughness and degree of correlation between the two fracture surfaces, and that with increasing roughness the simulated fracture permeabilities are systematically lower than permeabilities predicted from the fracture aperture mean using a cubic law. The dependence of fracture permeabilities on reactions is investigated, and the relationship between mineralization behaviour and fluid residence time is discussed.

Introduction

Fractures are important flow pathways in the subsurface, particularly in low permeability formations such as the caprocks of geological carbon-storage reservoirs. Fractures dominate the transport of fluids and solutes in these systems and the fracture transport properties are strongly influenced by fluid-rock reactions. This is especially true of mudstone caprocks (which include mudstones, claystones and marls) where both the intrinsic permeability of the natural fracture networks, and the coupled reactive-transport processes are uncertain (Kampman *et al.*, 2014). Understanding the dynamic evolution of the fracture flow properties is key to accurate assessment of CO₂ storage conformance in these systems.

The flow of CO₂ and CO₂-saturated brines through fractured mudstone is expected to induce a complex set of reactions including dissolution of the primary matrix, precipitation of secondary minerals and CO₂ degassing, which further promotes carbonate mineral precipitation. Carbonate precipitation driven self-sealing of fractured mudstones has been postulated as a mechanism for healing fracture permeability during CO₂ migration [see review in (Song and Zhang, 2012)]. The reactivity is further complicated by the presence of smectite in some mudstones for which interlayer adsorption of CO₂ can induce volumetric strains sufficient to cause changes in fracture aperture and permeability (Wentinck and Busch, 2017).

At the scale of an individual fracture, the mineral dissolution/precipitation and clay swelling reactions will be strongly coupled to the multiphase flow and solute transport dynamics, and the progress of the reactions will determine the propensity for fracture opening versus self-sealing behaviour. This behaviour will be controlled by the initial mudstone mineralogy, initial fracture hydraulic aperture distribution, fluid residence time, matrix diffusion, migration of the degassing and mineral reaction fronts, and the coupled changes in permeability and subsequent changes in fluid and solute mass transport.

Investigation of these processes via experimentation or field observations is hindered by the complexity and highly coupled nature of the problem. Numerical reactive transport modelling provides a tool for investigating the dynamics of this process. We investigate the controls on fracture opening versus self-sealing for synthetic vertical single rough walled fractures with self-affine fracture surfaces, using 2.5D reactive transport modelling simulations [c.f. (Deng *et al.*, 2016)]. The impact of initial mineralogy (including swelling clays), fracture hydraulic aperture distribution, fluid residence time and poro-elastic effects on the propensity for fracture opening versus self-sealing behaviour is investigated for single and two phases flows. Subsequently, the impacts of fracture geometric properties and roughness on opening versus sealing behaviour are investigated and discussed. Some preliminary validation of the numerical models with core-scale experiments is presented and discussed.

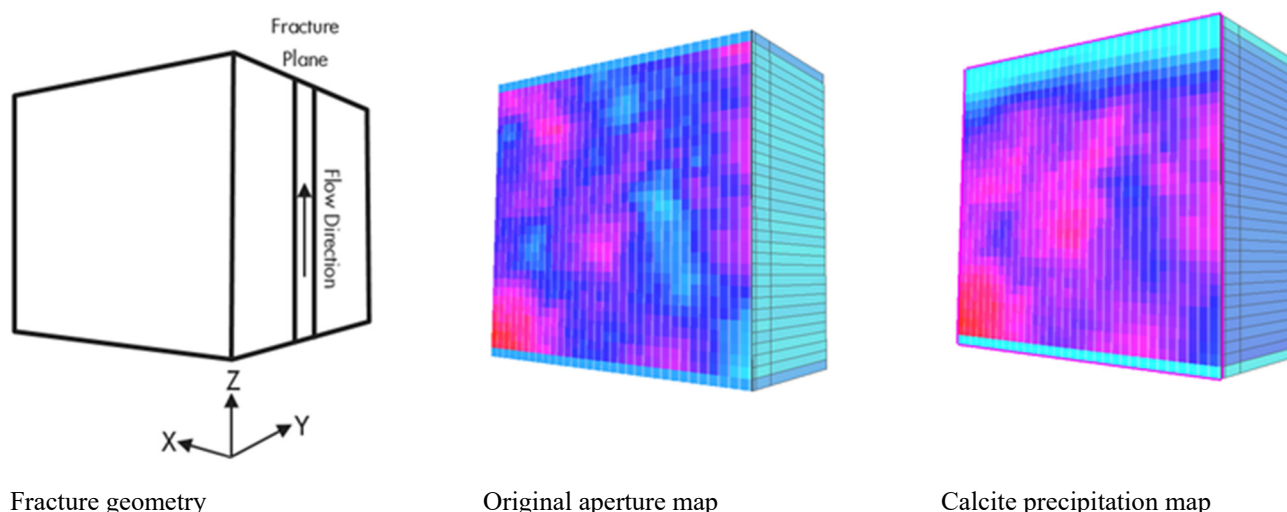


Figure 1 Fine-scale fracture + matrix Reactive Transport model, incorporating fracture microstructure through aperture map based on methodology in ref. [3].

Reactive Transport Simulations

During CO₂ leakage the progress of fracture mineralization depends on a balance of processes:

- i) Mixing of the host brine with invading (CO₂-charged) brine;
- ii) Dissolution of wall-rock minerals;
- iii) Diffusion of solutes from the wall rock into the fracture;
- iv) Degassing of CO₂ from the brine, driving mineral super-saturation.

In these single-fracture models using MoReS-PHREEQC all these processes are implemented and solved in a fully coupled way (using a loose-coupling approach). The transport code (MoReS) solves the mixing, diffusion and water-gas phase behaviour and component partitioning (including degassing). The geochemical code (PHREEQC) solves the chemical equilibrium and/or kinetics equations for mineral dissolutions and/or precipitation.

The main objects of the single fracture mineralization modelling in MoReS-PHREEQC are to:

- i) Establish constitutive relationships between the geometric properties of the fracture surfaces (e.g. roughness) and single fracture permeability, and validate these with laboratory experiments;
- ii) Investigate the relative controls of different reaction mechanisms on the magnitude and rates of carbonate mineralization and the self-sealing behaviour of fractures, in one phase (brine) and two phase (brine-CO₂) systems, and where possible validate these with laboratory experiments;
- iii) Establish constitutive relationships between the progress of fracture mineralization and fracture permeability for different rough fracture geometries (i.e. variable roughness), and validate these with laboratory experiments;
- iv) Establish constitutive relationships for closure/self-sealing time-scales, as a function of fluid residence time and/or Damköhler and/or Péclet number, and validate these with laboratory experiments;
- v) Investigate the use of these various constitutive relationships in up-scaling schemes for meso- and large-scale CO₂ migration models, and whether fracture mineralization at the meso- and large-scales can be modelled using these constitutive relationships, and to what extent a simplified geochemical model must be employed, including a set of geochemical pseudo components (e.g. Ca²⁺, CO₂, H₂O, salt).

Initial results have already been obtained (Figure 1), including microstructural effects, and will be presented and discussed.

References

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