

Multiphase Fluid Flow in Deformable Variable-Aperture Fractures

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Executive Summary

Fractures provide flow paths that can potentially lead to fast migration of fluids or contaminants. A number of energy-related applications involve fluid injections that significantly perturb both the pressures and chemical composition of subsurface fluids. These perturbations can cause both mechanical deformation and chemical alteration of host rocks with potential for significant changes in permeability. In fractured rock subjected to coupled chemical and mechanical stresses, it can be difficult to predict the sign of permeability changes, let alone the magnitude. This project integrated experimental and computational studies to improve mechanistic understanding of these coupled processes and develop and test predictive models and monitoring techniques.

The project involved three major components: (1) study of two-phase flow processes involving mass transfer between phases and dissolution of minerals along fracture surfaces (Detwiler et al., 2009; Detwiler, 2010); (2) study of fracture dissolution in fractures subjected to normal stresses using experimental techniques (Ameli, et al., 2013; Elkhoury et al., 2013; Elkhoury et al., 2014) and newly developed computational models (Ameli, et al., 2014); (3) evaluation of electrical resistivity tomography (ERT) as a method to detect and quantify gas leakage through a fractured caprock (Breen et al., 2012; Lochbuhler et al., 2014). The project provided support for one PhD student (Dr. Pasha Ameli; 2009-2013) and partially supported a post-doctoral scholar (Dr. Jean Elkhoury; 2010-2013). In addition, the project provided supplemental funding to support collaboration with Dr. Charles Carrigan at Lawrence Livermore National Laboratory in connection with (3) and supported one MS student (Stephen Breen; 2011-2013).

Major results from each component of the project include the following: (1) Mineral dissolution in fractures occupied by two fluid phases (e.g., oil-water or water-CO₂) causes changes in local capillary forces and redistribution of fluids. These coupled processes enhance channel formation and the potential for development of fast flow paths through fractures. (2) Dissolution in fractures subjected to normal stress can result in behaviors ranging from development of dissolution channels and rapid permeability increases to fracture healing and significant permeability decreases. The timescales associated with advective transport of dissolved ions in the fracture, mineral dissolution rates, and diffusion within the adjacent porous matrix dictate the sign and magnitude of the resulting permeability changes. Furthermore, a high-resolution mechanistic model that couples elastic deformation of contacts and aperture-dependent dissolution rates predicts the range of observed behaviors reasonably well. (3) ERT has potential as a tool for monitoring gas leakage in deep formations. Using probabilistic inversion methods further enhances the results by providing uncertainty estimates of inverted parameters.

This report describes major results from each component of the project and the corresponding published papers provide additional details.

1 Two-phase flow and mass transfer

This component of the project explored two inter-related issues related to two-phase flow and mass transfer in variable-aperture fractures: (i) interphase mass transfer between a trapped nonwetting phase and a flowing aqueous phase; and (ii) mineral dissolution from the fracture surfaces in the presence of a trapped nonwetting and non-reactive phase.

1.1 *Interphase mass transfer*

Interphase mass transfer in variable aperture fractures occurs in problems where two immiscible fluids are present, such as dissolution of dense nonaqueous-phase liquids into groundwater, dissolution of CO₂ in deep saline aquifers, and evaporation of trapped water by flowing gas during natural gas production. Typically, one fluid is entrapped by capillary forces and resides in immobilized regions whose distribution and geometry are controlled by the relative influence of capillary, gravitational, and viscous forces within the fracture. For the case of fractures bounded by a low porosity/permeability matrix, interphase mass transfer occurs predominantly by diffusive and advective transport from the entrapped phase interface into the phase flowing through the fracture.

This study explored the relative influence of the initial entrapped phase geometry and mean flowing phase velocity on dissolution of the entrapped phase (Detwiler et al., 2009). Systematic simulations used a percolation-based model of nonwetting phase invasion and trapping and depth-averaged models of flow, transport, and mass transfer. The invasion model provides a physically based distribution of entrapped phase within the fracture and the mass transfer model implicitly calculates interphase mass transfer from discrete regions of entrapped phase without the need for empirical mass transfer relationships. We simulated mass transfer for a wide range of initial entrapped phase distributions, with entrapped phase saturations ranging from zero to near the percolation threshold.

Results from these simulations show that interfacial area evolves with a near-linear dependence on entrapped phase saturation during dissolution, and fracture-scale intrinsic mass-transfer-rate coefficients exhibit a nonlinear dependence on Peclet number and a negligible dependence on entrapped phase saturation. These observations provided a basis for the development of constitutive relationships that quantify interphase mass transfer in variable aperture-fractures as a function of entrapped phase saturation and flow rate; coarse-grid dissolution simulations using these constitutive relationships demonstrated good agreement with results from the high-resolution mechanistic simulations. These results are significant because it supports the use of more efficient computational models to simulate the complex coupled processes of two-phase flow and mass transfer, which makes the application of these models possible at much larger scales.

1.2 Mineral dissolution

During reactive fluid flow in saturated fractures, the relative rates of dissolved mineral transport and local reactions strongly influence local aperture alterations and the resulting changes in fracture permeability (or transmissivity). In the presence of an entrapped residual nonaqueous phase (e.g., CO₂ or oil), the spatial distribution of the entrapped phase will influence flow and transport and thus, local aperture alterations. These aperture alterations will in turn alter the balance of forces acting on immobile regions of the trapped phase. The resulting mobilization of the entrapped phase may subsequently alter flow pathways and fracture transmissivity in a manner that defies quantification with currently used constitutive relationships.

This experimental study involved quantitative visualization experiments in which fracture aperture and entrapped phase distribution were directly measured at high spatial resolution (75 × 75 μm) during reactive fluid flow and dissolution in 9.4 × 14.5-cm fractures (Detwiler, 2010). The experiments differed only in the orientation of the fracture with respect to gravity, which influenced both the initial entrapped phase geometry and the evolution of the entrapped phase as dissolution altered fracture apertures. The presence of the entrapped phase leads to a much earlier formation of distinct dissolution channels than has been observed in saturated fractures. Compared to a similar experiment in a fully saturated fracture, dissolution in the partially saturated fractures leads to as much as a 6-fold increase in transmissivity after an equal amount of dissolution from the fracture surface (doubling of the mean fracture aperture). Furthermore, the relative influence of gravity determines whether trapped bubbles mobilize because of capillary forces (against prevailing viscous forces) or gravitational forces, which is in the direction of prevailing viscous forces for the experiments presented here. Because the presence of an entrapped phase enhanced channeling, which we expected to reduce dissolution-induced deformation, the next component of the project emphasized single-phase flows in fractures subjected to normal stress.

2 Coupled reactive flow and mechanical deformation

Mineral reactions occurring along fracture surfaces and in the porous matrix adjacent to the fractures combined with mechanical stresses acting on fractures can lead to changes in fracture aperture (transmissivity) over time. When the residence time of reactive fluid within a fracture is long, relative to reaction rates, aperture growth occurs predominantly along preferential flow paths leading to reactive instabilities. At higher flow rates, dissolution occurs more uniformly throughout the fracture and reaction instabilities occur only at larger length scales. In the absence of mechanical stresses, the relative timescales of chemical reactions at mineral interfaces (τ_r) and advective transport of dissolved ions within the fracture (τ_a) control fracture dissolution. Dissolution limited to fracture surfaces prevails when τ_r is short relative to the diffusive time scale within the porous rock matrix adjacent to

the fracture (τ_d) – a condition that is often met during laboratory-scale experiments. However, for relatively slow reaction kinetics, significant reactions may also occur within the porous matrix.

The addition of normal stresses, in conjunction with dissolution, can cause either a permeability increase or decrease depending upon experimental conditions, sometimes during the same experiment. Pressure solution and brittle failure at contacts between fracture surfaces have been invoked as possible mechanisms to explain these observations when negligible degradation of the rock matrix is observed. We hypothesized that dissolution-induced permeability reductions are possible due to the preferential dissolution of small-aperture regions

This study leveraged a set of experiments carried out in support of the IEAGHG Weyburn-Midale CO₂ Monitoring and Storage Project to explore in detail the combined influence of mineral dissolution and mechanical deformation on fracture permeability under a range of different flow conditions and two different mineralogies.

2.1 Experimental studies

Developing a mechanistic understanding of fracture alteration processes requires quantifying the roughness of fracture surfaces and the contacts and void spaces between fracture surfaces at high spatial resolution (10s of microns) over a broad range of scales (centimeters to meters). Prior to carrying out flow experiments in fractured cores, we developed a scalable method for measuring fracture surfaces and reconstructing fracture aperture fields using an optical profilometer (Ameli et al, 2013). We evaluated the method by measuring two fractured limestone cores; one was a tensile fracture with strong cross correlation between the surfaces and the other was a saw-cut, sand-blasted fracture with negligible cross correlation between the surfaces. Results of repeated measurements of these two fractures demonstrated that well-correlated surfaces, where the correlation between the surfaces can aid reconstruction, can be mated to yield aperture measurements with local uncertainties of $\pm 8 \mu\text{m}$. Poorly correlated surfaces, where reconstruction relies solely upon the precision of the placement of the halves of the core on the profilometer stage, can be reproduced with local uncertainties of $\pm 20 \mu\text{m}$. Additionally, we quantified the accuracy of the technique by comparing calculated aperture profiles of a fractured concrete core to thin sections cut from the core after impregnating it with epoxy. The median deviation between the two measurements, which includes errors due to residual misalignment of the profiles, was $29 \mu\text{m}$ supporting the accuracy of the method. Our results emphasize the potential for using noncontact surface measurements to accurately and precisely reconstruct fracture apertures over a wide range of length scales.

Geometrical alteration in fractures caused by mineral dissolution changes the contact area between fracture surfaces and affects the mechanical strength of fractures. It is difficult to determine the influence of dissolution on fracture porosity

and permeability given the competition between fracture opening due to dissolution and fracture closure caused by mechanical deformation and simulating flow in fractured reservoirs during enhanced oil recovery or CO₂ sequestration, where local porosity changes may significantly alter permeability, remains a fundamental challenge. This study involved experiments and numerical simulations to explore the influence of coupled geochemical alteration and mechanical deformation on calcium carbonate fracture geometry (Elkhoury et al., 2013). We scanned fracture surfaces, before and after the flow experiments, using the high-resolution optical profilometry technique described above. Flow of brine equilibrated with CO₂ at 60°C and pore pressure of 14 MPa led to significant dissolution of the fractured calcium carbonate cores.

The evolution of the dissolution process during the reactive flow experiments depended, to first order, on the dimensionless Damkohler number D_a . We varied D_a in experiments by changing the flow rate and observed a transition in dissolution behavior over the range of flow rates from 0.1 ml/min to 20 ml/min. At large D_a (small flow rate), dissolution caused the formation of large-scale channels aligned with the fractures. At small D_a (large flow rate), dissolution occurred more uniformly over the fracture surfaces. However, the area of contacting asperities, controlled by the significant mechanical stresses (28 MPa) and fracture surface roughness, constrained the spatial extent of the dissolution. We used the measured aperture fields as input to a single-species, reactive-transport model. Simulated Ca²⁺ dissolution agreed well with temporal evolution of measured Ca²⁺ concentrations in collected effluent samples. Comparison of the simulated dissolved aperture fields with measured aperture fields after flow-through shows qualitative agreement. We also used our reactive-transport model to explore the role of changing fluid properties and flow rates on dissolution and the resulting alteration of porosity and permeability beyond our experimental conditions. These simulations demonstrate the importance of length scale on interpreting dissolution processes observed in laboratory experiments. Most notably, because D_a depends linearly upon fracture length, laboratory observations at small D_a (i.e., prominent dissolution channels), are likely to be more common at the field scale.

We also carried out a set of dissolution experiments in fractured caprock cores of dolomitic anhydrite. In these experiments, reaction kinetics were sufficiently slow that diffusion into the porous matrix allowed for measurable dissolution to occur within the porous matrix (Elkhoury et al., 2014). Furthermore, preferential dissolution of anhydrite left a compacted layer of dolomite in the fractures. At low flow rate (high D_a), preferential flow paths persisted within the dolomite layer. However, at high flow rate (low D_a), permeability decreased by a dramatic two orders of magnitude. This observed self-healing process suggests that in such caprocks, the likelihood of runaway permeability growth, such as that observed in predominantly carbonate cores, is reduced due to the significant difference in solubilities and reaction rates for the two dominant minerals (anhydrite and dolomite). These results highlight the importance of developing detailed

mechanistic models that reflect the important processes leading to dissolution-induced permeability changes.

2.2 Model development and evaluation

Reactive fluid-flow experiments in fractures subjected to normal stress suggest the potential for either increased or decreased permeability resulting from fracture-surface dissolution. We developed a computational model that couples mechanical deformation and chemical alteration of fractures subjected to constant normal stress and reactive fluid flow (Ameli et al., 2014). The model explicitly represents micro-scale roughness of the fracture surfaces and calculates elastic deformation of the rough surfaces using a semi-analytical approach that ensures the surfaces remain in static equilibrium. A depth-averaged reactive transport model calculates chemical alteration of the surfaces, which leads to alteration of the contacting fracture surfaces. The mechanical deformation and chemical alteration calculations are explicitly coupled, which is justified by the disparate timescales required for equilibration of mechanical stresses and reactive transport processes. An idealized analytical representation of dissolution from a single contacting asperity shows that under reaction-limited conditions, contacting asperities can dissolve faster than the open regions of the fracture. Computational simulations in fractures with hundreds of contacting asperities show that the transition from transport-limited conditions (low flow rates) to reaction-rate-limited conditions (high flow rates) causes a shift from monotonically increasing permeability to a more complicated process in which permeability initially decreases and then increases as contacting asperities begin to dissolve. These results are qualitatively consistent with the experimental observations described above and others reported in the literature. Our results suggest the potential importance of the relative magnitude of mass transport and reaction kinetics on the evolution of fracture permeability. For reaction-rate limited dissolution, dissolution rates are faster in small aperture regions resulting in the potential for fracture aperture to decrease due to mineral dissolution. This is an important observation, because to our knowledge this mechanism has not been previously demonstrated as a potential explanation for anomalous permeability alteration.

3 Evaluation of ERT as a leakage monitoring technique

Field-scale studies have shown electrical resistivity tomography (ERT) to be an effective tool for imaging resistivity anomalies and monitoring infiltration events in the near subsurface. ERT also shows potential for monitoring supercritical-CO₂ injections, despite deployment challenges in the deep subsurface.

3.1 Experimental studies

We carried out analog bench-scale experiments aimed at evaluating the ability of ERT to quantify the volume and spatial distribution of a resistive fluid injected into a brine-saturated porous medium (Breen et al., 2012). Our experiments provided a well-controlled analog for supercritical-CO₂ injection into a simplified brine-saturated anticlinal reservoir. We injected measured volumes of air into translucent chambers filled with quartz sand, lined with electrodes, and saturated with a low resistivity salt solution. Between injections, a CCD camera captured high-resolution images, and an ERT data acquisition system scanned the chamber. Processing of the CCD images using quantitative visualization techniques resulted in high-resolution measurements of the spatial distribution and saturation of the injected gas. Direct comparison to inverted resistivity fields then provided a quantitative measure of the ability of ERT to estimate the total volume of injected gas and its spatial distribution within the chamber.

We carried out two experiments designed to represent different injection scenarios: (A) low injection rate and strong capillary barrier and (B) high injection rate and weaker capillary barrier. Results showed that ERT provides good estimates of the shape, size and location of the primary plume, but overestimated brine saturation within the plume and did not detect thin pathways of gas from the injection port or within the overlying capillary barrier. ERT measurements also indicated a change in saturation within the primary plume that corresponded with observed leakage through the capillary barrier in (B), demonstrating the potential utility of ERT as a leakage-monitoring tool. Repeated ERT scans during our experiments led to degradation in data quality that corresponded with an increase in measured contact resistance. Decreased data quality over time is clearly a concern for ERT implementation as a long-term monitoring strategy and deserves further study to quantify the responsible mechanisms.

3.2 Model development and evaluation

Application of ERT as a tool for monitoring leakage requires robust estimates of parameter uncertainty if we are to successfully distinguish inversion artifacts from potentially small changes due to leakage. Unlike the deterministic inversion process used to invert data from our initial experimental results, probabilistic inversion techniques provide the full posterior probability density function of the saturation field and accounts for the uncertainties inherent in the petrophysical parameters relating the resistivity to saturation. This component of our ERT study involved collaboration with Dr. Niklas Linde and his PhD student, Tobias Lochbühler from the University of Lausanne.

We estimated saturation fields using Markov chain Monte Carlo inversion of the measured data and directly compared inversion results to saturation measurements from light transmission measurement (Lochbühler et al., 2014). Different model parameterizations are evaluated in terms of the recovered saturation and

petrophysical parameter values. We parameterized the system using several configurations with decreasing complexity and number of parameters: (1) cartesian coordinates, (2) coefficients representing the large wavelength components of the discrete cosine transform of the domain, and (3) by fixed saturation values in structural elements whose shape and location is assumed known or represented by an arbitrary Gaussian bell structure. Our results demonstrated that estimated saturation fields are in overall agreement with saturations measured by light transmission, but differ strongly in terms of parameter estimates, parameter uncertainties and computational intensity. Discretization in the frequency domain (as in the discrete cosine transform parameterization) provides more accurate models at a lower computational cost compared to spatially discretized (cartesian) models. A priori knowledge about the expected geologic structures allows for non-discretized model descriptions with markedly reduced degrees of freedom. Constraining the solutions to the known injected gas volume improved estimates of saturation and parameter values of the petrophysical relationship.

Peer-reviewed publications citing support from this grant

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