

Numerical investigation of microbially induced calcite precipitation as leakage mitigation technology

Motivation

Preventing leakage of carbon dioxide (CO₂) from storage reservoirs is important for both efficiency and security of carbon capture and storage (CCS) as mean to mitigate global climate change. Possible leakage paths are:

- improperly abandoned wells,
- the vicinity of the injection well,
- weak spots in the cap rock.

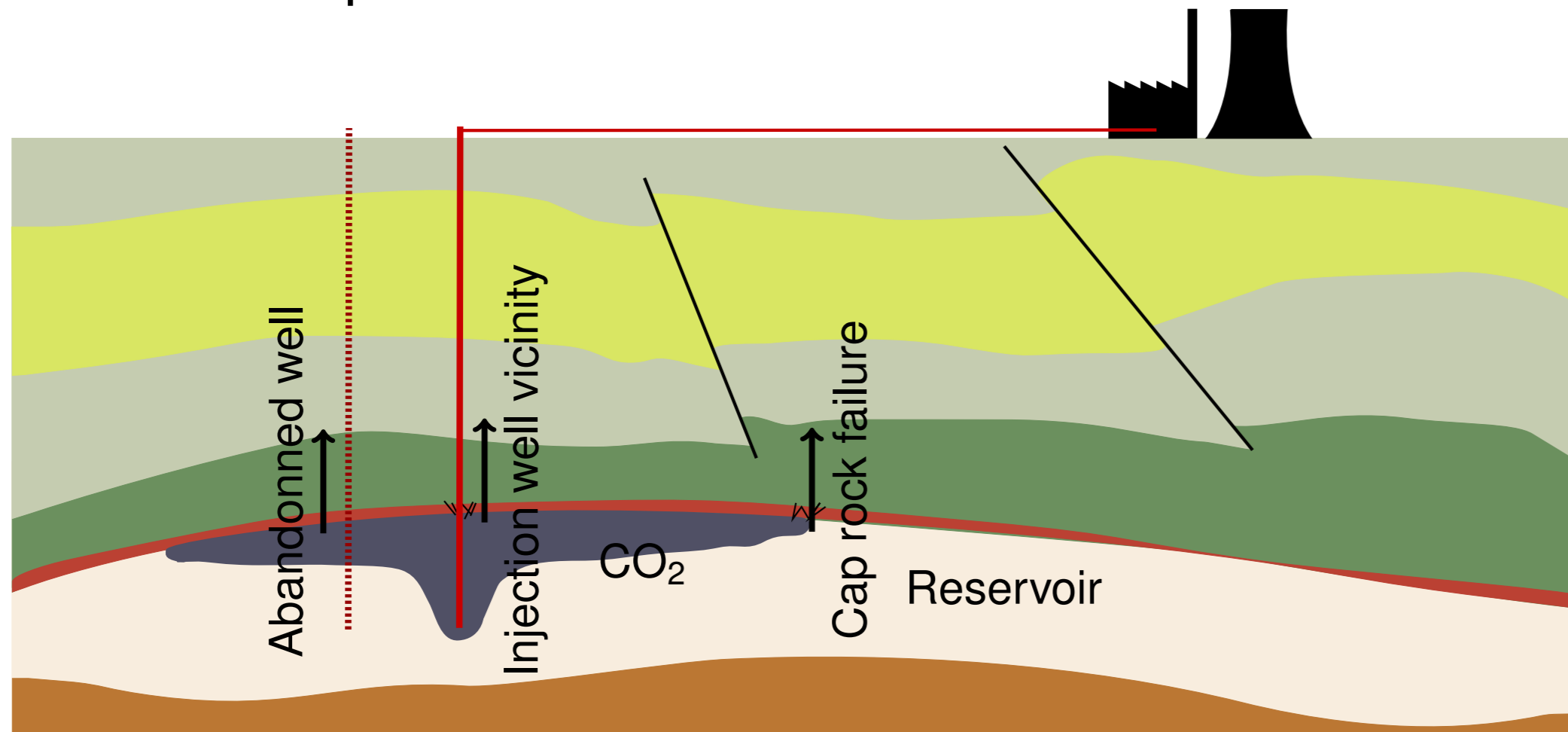


Figure 1: Possible leakage pathways of sequestered CO₂.

At the present, the standard sealing technology is injection of cement. Microbially induced calcite precipitation (MICP) has several advantages compared to the injection of cement [2]:

- **reduced injection pressure** and **increased radius of influence** due to low viscosity of injected fluids,
- more homogeneous plugging due to catalyzed reactions in the medium, no clogging of the injection region, \Rightarrow **homogeneous reduction of porosity and permeability**.

A disadvantage is the need for elaborate injection schemes to achieve homogeneous precipitation.

\Rightarrow MICP is a promising sealing technology that needs further research before it can be meaningfully applied on field scale.

Goals

Improve an existing numerical model [1] to be able to simulate a realistic field-scale sealing application of MICP.

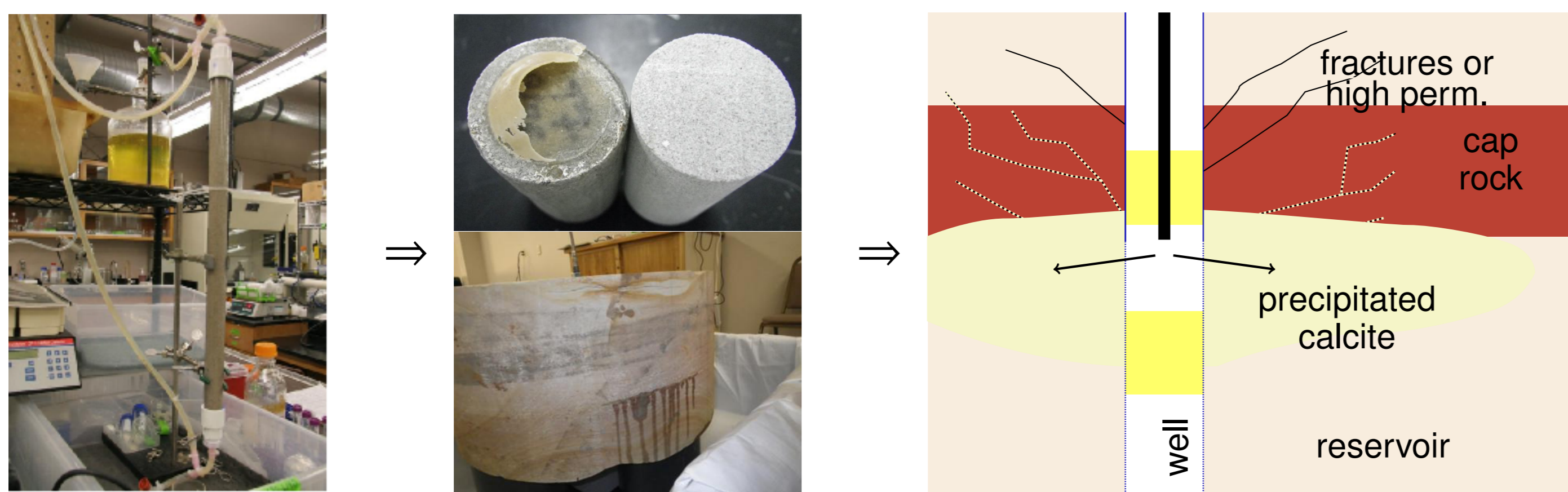


Figure 2: Experiments with different complexity used to develop the model and a sketch of field-scale application of MICP. Photographs from [1] and [2].

Relevant processes

Several physical and (bio-) chemical processes are important for MICP:

- **two-phase multi-component flow**,
- processes determining the **distribution of biomass**:
 - **growth**: $r_{\text{growth}} = f(\text{biomass, substrate, oxygen})$,
 - **decay**: $r_{\text{decay}} = f(\text{biomass, calcite precipitation rate, pH})$,
 - **attachment**: $r_{\text{attachment}} = f(\text{suspended and attached biomass})$,
 - **detachment**: $r_{\text{detachment}} = f(\nabla p_w, r_{\text{growth}}, \text{attached biomass})$,
- (bio-) chemical **reactions**:
 - microbially catalyzed **ureolysis**: $\text{CO}(\text{NH}_2)_2 + 2\text{H}_2\text{O} \xrightarrow{\text{urease}} 2\text{NH}_3 + \text{H}_2\text{CO}_3$,
 - influence of NH₃ on the pH: $\text{NH}_3 + \text{H}^+ \leftrightarrow \text{NH}_4^+$,
 - **precipitation** (and dissolution) of **calcite**: $\text{Ca}^{2+} + \text{CO}_3^{2-} \leftrightarrow \text{CaCO}_3 \downarrow$,

$$r_{\text{precipitation}} = k_{\text{precipitation}} A_{\text{sw}} (\Omega - 1)^{n_{\text{precipitation}}},$$

which is depended on the **calcite saturation state** $\Omega = \frac{[\text{Ca}^{2+}][\text{CO}_3^{2-}]}{K_{\text{sp}}}$ and the water-solid **surface Area** A_{sw} .

Model Concept

The REV-scale model includes reactive two phase multi component flow. For mobile components, a volume averaged mass balance equation is solved:

$$\sum_{\alpha} \left[\frac{\partial}{\partial t} (\phi \rho_{\alpha} x_{\alpha}^{\kappa} S_{\alpha}) + \nabla \cdot (\rho_{\alpha} x_{\alpha}^{\kappa} \mathbf{v}_{\alpha}) - \nabla \cdot (\rho_{\alpha} \mathbf{D}_{\text{pm},\alpha} \nabla x_{\alpha}^{\kappa}) \right] = q^{\kappa}$$

The source and sink term q^{κ} includes the creation or disintegration of the component κ due to chemical reactions.

Biofilm and calcite are immobile, hence the mass balance only yields a storage and a source term: $\frac{\partial}{\partial t} (\phi_{\lambda} \rho_{\lambda}) = q^{\lambda}$

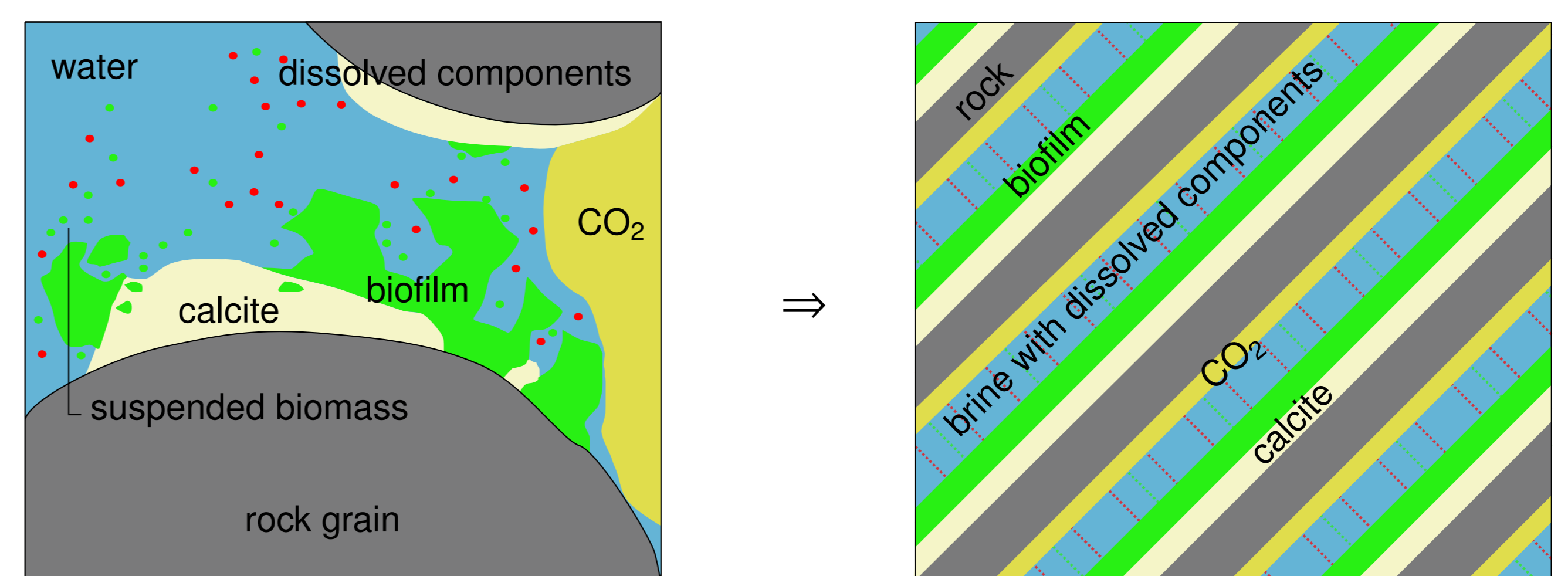


Figure 3: Model relevant phases and distribution of components in the phases at pore scale and REV-scale, modified from [1].

Supplementary equations

- $\phi = \phi_0 - \phi_{\text{calcite}} - \phi_{\text{biofilm}}$
- $K = K_0 \left(\frac{\phi - \phi_{\text{crit}}}{\phi_0 - \phi_{\text{crit}}} \right)^3$
- $\sum_i z_i m_i = 0$
- $x_w^{\text{CO}_2}$ and x_n^w calculated according to Spycher and Pruess [3]
- $x_n^{\text{O}_2}$ calculated with Henry's law

Preliminary Results

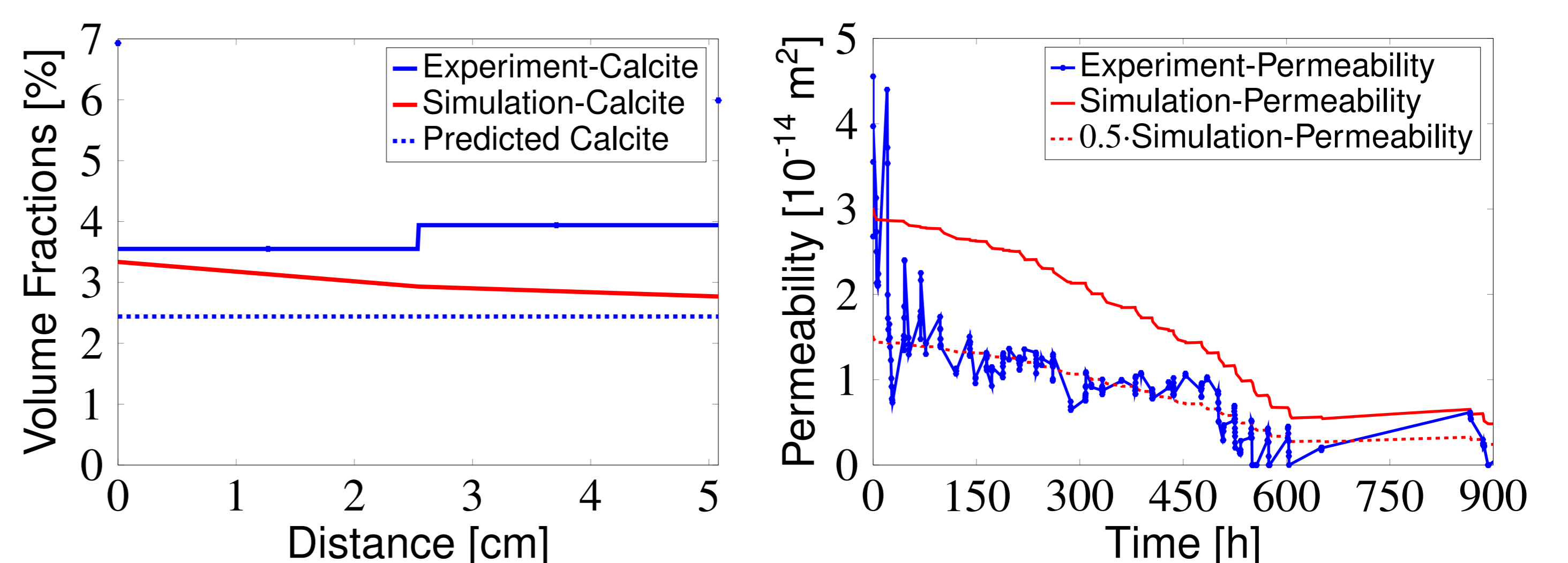


Figure 4: Comparison between experimental data and simulation results for MICP in a 2.54cm diameter sandstone core (see top picture in the middle of Figure 2) under reservoir pressure conditions. Measured and predicted volume fraction of calcite compared to simulation results after 21 MICP injection cycles (left). Permeability calculated from experimental pressure difference versus simulated permeability (right).

Outlook

The high computational effort restricts the application at the moment to small domain sizes. In order to simulate large 3-D experiments or field scale applications, the computational cost per grid node has to be reduced. At the moment the focus is on implementing a scheme to decouple chemical reactions and transport calculations.

Literature

- [1] A. Ebigbo, A. J. Phillips, R. Gerlach, R. Helmig, A. B. Cunningham, H. Class, and L. H. Spangler. Darcy-scale modeling of microbially induced carbonate mineral precipitation in sand columns. *Water Resources Research*, 48(7):W07519, July 2012.
- [2] A. J. Phillips, E. Lauchnor, J. Eldring, R. Esposito, A. C. Mitchell, R. Gerlach, A. B. Cunningham, and L. H. Spangler. Potential CO₂ Leakage Reduction through Biofilm-Induced Calcium Carbonate Precipitation. *Environmental science & technology*, pages 2–9, August 2012.
- [3] N. Spycher and K. Pruess. CO₂-H₂O mixtures in the geological sequestration of CO₂. II. Partitioning in chloride brines at 12–100°C and up to 600 bar. *Geochimica et Cosmochimica Acta*, 69(13):3309–3320, July 2005.