# Numerical investigation of microbially induced calcite precipitation as leakage mitigation technology

International Research Training Group nupus

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## Motivation

With increasing intensity of subsurface use, ensuring separation between different layers with competitive uses becomes more and more important. The risk of polluting upper layers, e.g. used for drinking water production, by for example $CO_2$ storage in the subsurface or fracking could be reduced with sealing technologies like microbially induced calcite precipitation (MICP). Other applications of MICP are discussed in [4].

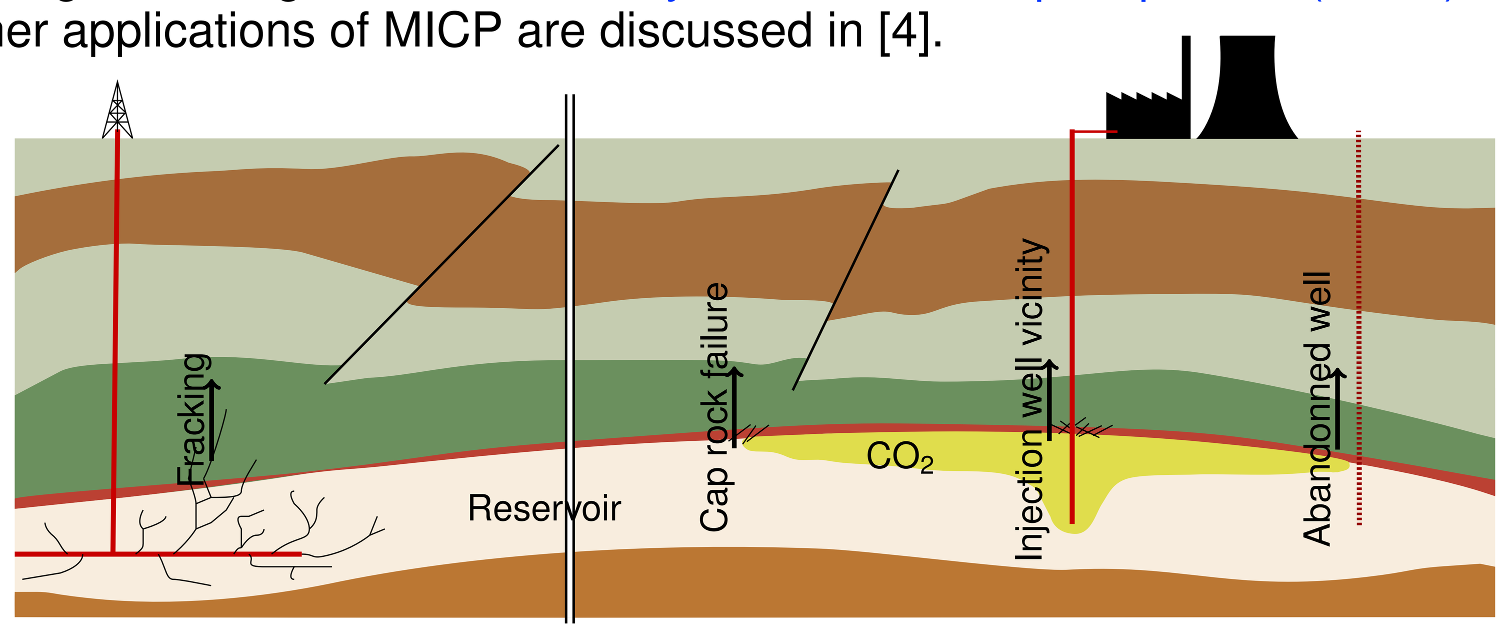


Figure 1: *Potential application sites of MICP as a sealing technology in the subsurface.*

MICP has several advantages compared to the technological standard, injection of cement [5]:

- low viscosity ⇒ reduced injection pressure and increased radial extend.
- catalyzed reactions in the medium ⇒ plugging is dependent on injection scheme ⇒ porosity and permeability distribution can be engineered.

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

## Model concept

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

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

The source and sink term $q^\kappa$ includes the creation or disintegration of the component $\kappa$ due to chemical reactions.
Biofilm and calcite are immobile, hence the mass balance only yields a storage and a source term: $\frac{\partial}{\partial t}(\phi_\lambda \rho_\lambda) = q^\lambda$

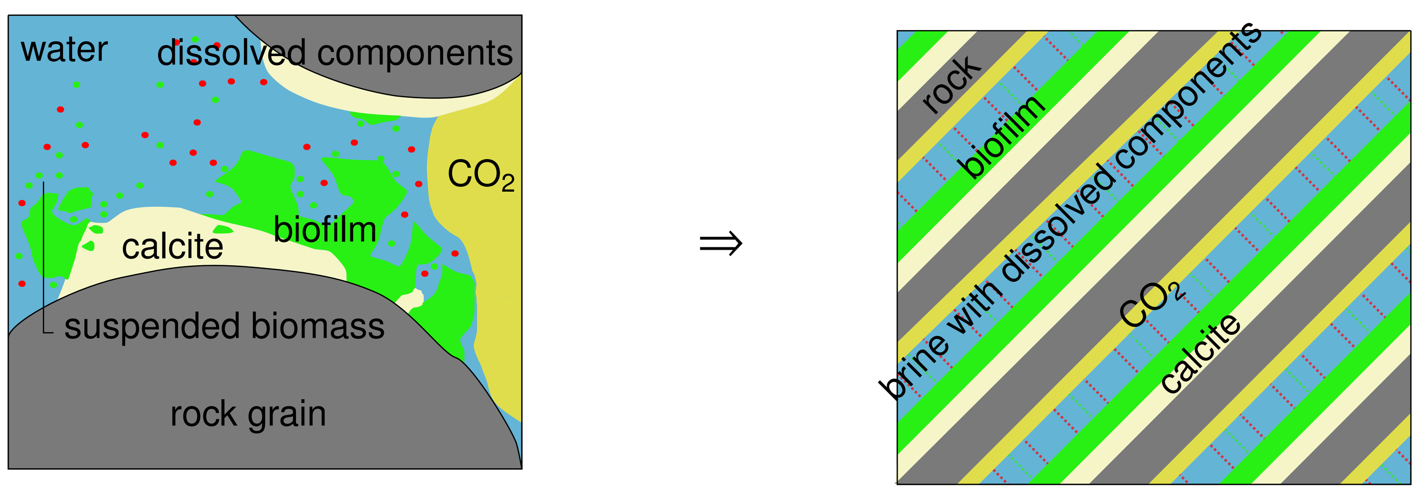


Figure 2: *Model relevant phases and distribution of components in the phases at pore scale and REV-scale, modified from [2].*

### Relevant processes

Several bio- and geo-chemical processes, in combination with solute transport, are important for MICP:

- processes determining the distribution of biomass:
  - growth: $r_{\mathrm{growth}} = f(\text{biomass, substrate, oxygen})$,
  - decay: $r_{\mathrm{decay}} = f(\text{biomass, calcite precipitation rate, pH})$,
  - attachment: $r_{\mathrm{attachment}} = f(\text{suspended and attached biomass})$,
  - detachment: $r_{\mathrm{detachment}} = f(\nabla p_{\mathrm{w}}, r_{\mathrm{growth}}, \text{attached biomass})$,
- (bio-) chemical reactions:
  - microbially catalyzed ureolysis: $CO(NH_2)_2 + 2\,H_2O \xrightarrow{\text{urease}} 2\,NH_3 + H_2CO_3$,
  - influence of $NH_3$ on the pH: $NH_3 + H^+ \leftrightarrow NH_4^+$,
  - precipitation (and dissolution) of calcite: $Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3\downarrow$,

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

    which is depended on the calcite saturation state $\Omega = \frac{[Ca^{2+}][CO_3^{2-}]}{K_{\mathrm{sp}}}$ and the water-solid surface Area $A_{\mathrm{sw}}$.
  - clogging: $\phi = \phi_0 - \phi_{\mathrm{calcite}} - \phi_{\mathrm{biofilm}} \Rightarrow K = K_0\left(\frac{\phi-\phi_{\mathrm{crit}}}{\phi_0-\phi_{\mathrm{crit}}}\right)^3$

DuMu$^x$ Simulations are performed using the open-source simulator DuMu$^x$.

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## Experiment

The numerical model [2] was not able to correctly picture the permeability reduction due to MICP [3]. We hypothesize this to result from the simplification that the geometry is assumed to be constant during MICP.

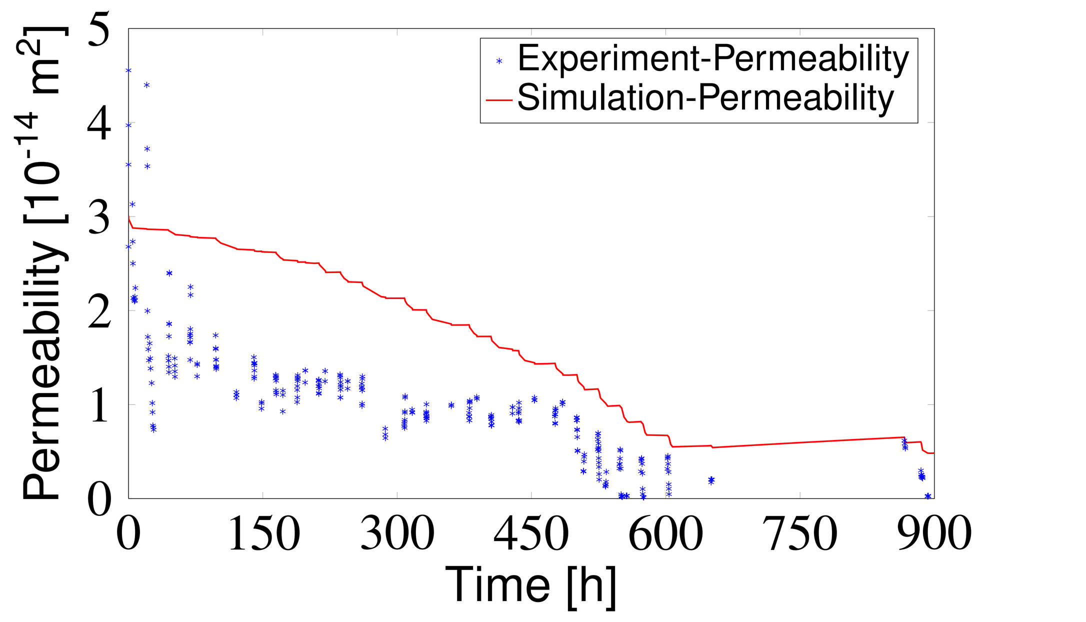


Figure 3: *Comparison between experimental permeability, calculated from the measured pressure difference, and simulation results for MICP in a 2.54cm diameter sandstone core under reservoir pressure conditions.*

Experiments at the Center for Biofilm Engineering (CBE) with biofilm growth in micro flow cells will be conducted to improve the model description of the prosity-permeability relation. Simultaneous measurements of pressure difference between in and outlet of the flow cell and imaging of the biofilm will allow to correlate biofilm growth with permeability reduction. A fluorescent *E. coli* strain is used for more accurate measurement of the biofilm volume fraction in the flow cell as described in [1].

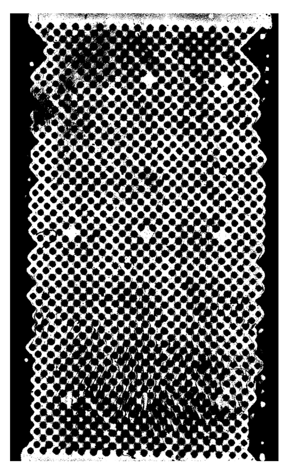

Figure 4: *Pore space (white) of the flow cell after 3 days of biofilm growth for the first test experiment.*

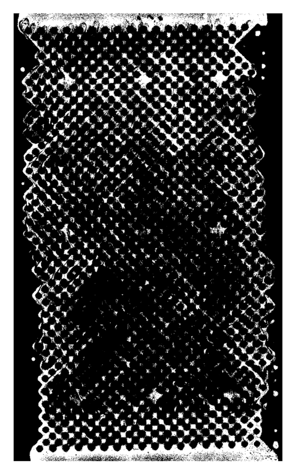

Figure 5: *Pore space (white) of the flow cell after 8 days of biofilm growth for the first test experiment.*

⇒

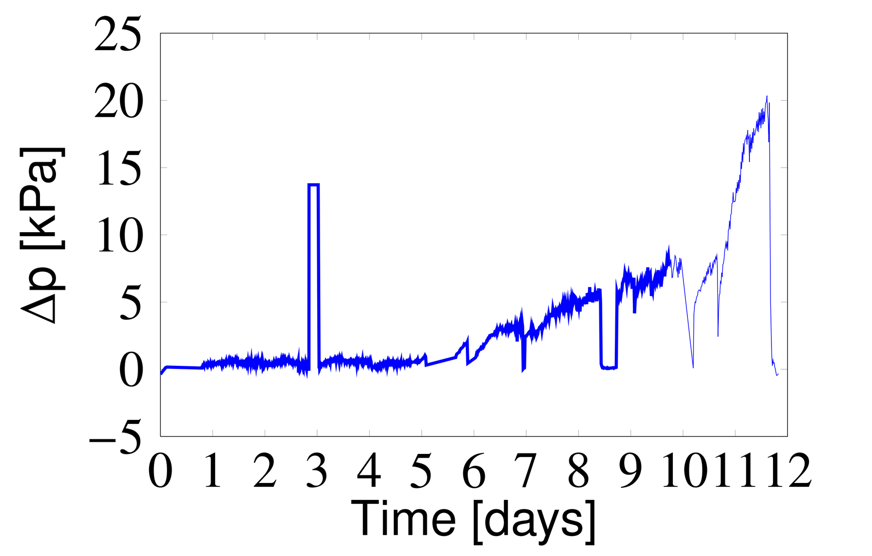


Figure 6: *Measured pressure difference between influent and effluent port of the flow cell for the first test experiment.*

## Outlook

Once sufficient experiments have been conducted, the currently implemented Kozeny-Carman type relation will be extended by a shape factor $S$ to account for changing pore geometry or other effects of biofilm growth on permeability.

$$K = K_0\left(\frac{\phi-\phi_{\mathrm{crit}}}{\phi_0-\phi_{\mathrm{crit}}}\right)^3 \cdot S\left(\phi_{\mathrm{f}}, \phi_0\right)$$

To prove MICP to be applicable on field scale, the CBE will plugg a test well near Gorgas, Alabama in summer 2014. The numerical model will be used to determine promising injection strategies and to analyze the experimental data.

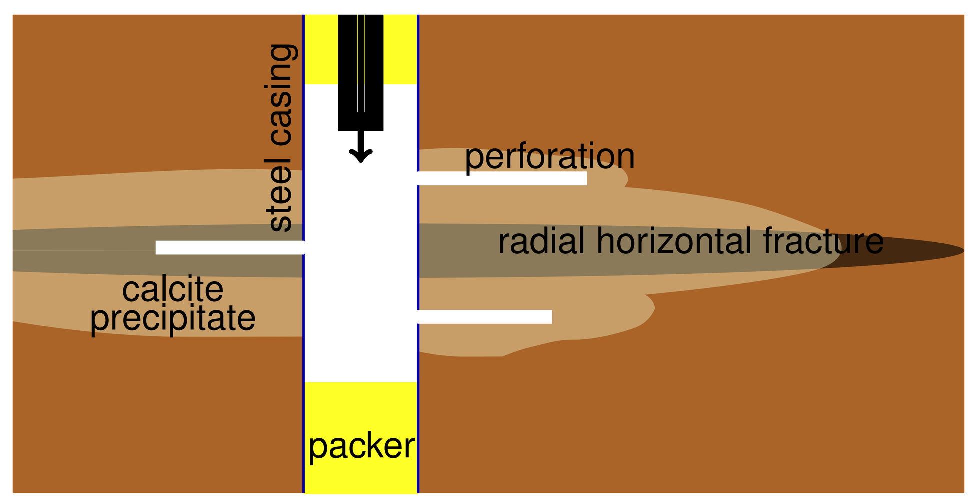


Figure 7: *Sketch of the injection region of the Gorgas test well.*

## Literature


[1] James Connolly, Megan Kaufman, Adam Rothman, Rashmi Gupta, George Redden, Martin Schuster, Frederick Colwell, and Robin Gerlach. Construction of two ureolytic model organisms for the study of microbially induced calcium carbonate precipitation. *Journal of microbiological methods*, 94(3):290–9, September 2013.

[2] Anozie Ebigbo, Adrienne J Phillips, Robin Gerlach, Rainer Helmig, Alfred B Cunningham, Holger Class, and Lee H Spangler. Darcy-scale modeling of microbially induced carbonate mineral precipitation in sand columns. *Water Resources Research*, 48(7):W07519, July 2012.

[3] Johannes Hommel, Alfred B Cunningham, Rainer Helmig, and Anozie Ebigbo. Numerical Investigation of Microbially Induced Calcite Precipitation as a Leakage Mitigation Technology. In *Energy Procedia*, volume 40C, pages 392–397, 2013.

[4] Adrienne J Phillips, Robin Gerlach, Ellen Lauchnor, Andrew C Mitchell, Alfred B Cunningham, and Lee Spangler. Engineered applications of ureolytic biomineralization: a review. *Biofouling*, 29(6):715–33, January 2013.

[5] Adrienne J Phillips, Ellen Lauchnor, Joachim Joe Eldring, Richard Esposito, Andrew C Mitchell, Robin Gerlach, Alfred B Cunningham, and Lee H Spangler. Potential CO(2) Leakage Reduction through Biofilm-Induced Calcium Carbonate Precipitation. *Environmental science & technology*, pages 2–9, August 2012.