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Modeling field-scale applications of microbially induced calcium carbonate precipitation

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Motivation and Setup

In 2014, the first field-scale application of MICP to mitigate leakage was performed in a fractured sandstone formation at a depth of 340.8 m [3].

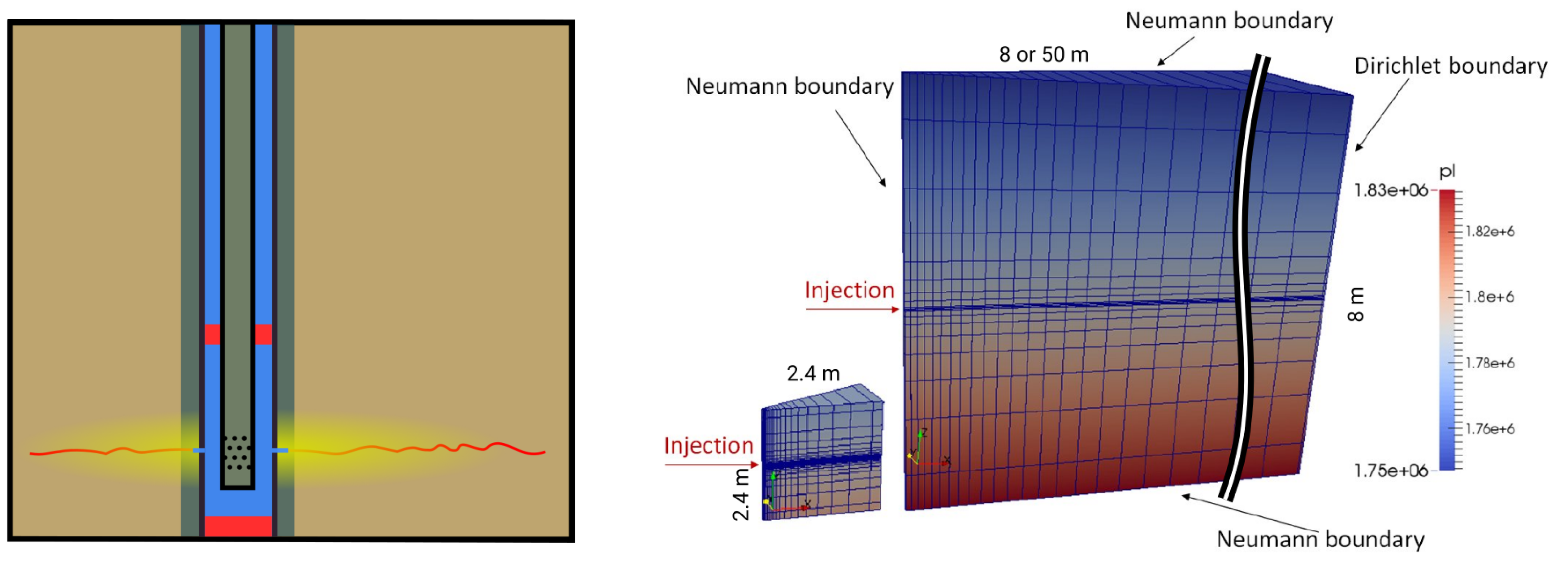

Figure 1: *Schematic cross section of the well and formation for the field-scale MICP application (left) and the radial simulation domain and grid with the initial and boundary conditions (right).*

Three simulation domains of various sizes were investigated to asses the influence of the domain size and the high-permeable layer extent:

- small: 2.4 m×2.4 m domain with a 1.6 m radius high-permeable layer
- large: 8 m×8 m domain with a 4 m radius high-permeable layer
- extended: 8 m×50 m domain with a 2 m radius high-permeable layer

Model Concept

The MICP model is discussed in detail in Hommel et al. [2]. It includes reactive two-phase multi-component transport including two solid phases.

$$\text{solid phases:} \frac{\partial}{\partial t}(\phi_\lambda \rho_\lambda) = q^\lambda_{\text{reactions}}$$

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

- processes determining the distribution of biomass:
  - growth: $r_{\mathrm{growth}} = \mu\, \rho_{\text{biofilm}}\, \phi_{\text{biofilm}} \frac{C_w^{O_2}}{C_w^{O_2}+K_{O_2}} \frac{C_w^{\text{substrate}}}{C_w^{\text{substrate}}+K_{\text{substrate}}}$,
  - decay: $r_{\mathrm{decay}} = k_{\text{decay}}\, \rho_{\text{biofilm}}\, \phi_{\text{biofilm}}$,
  - attachment: $r_{\mathrm{attachment}} = (c_{a,1}\, \phi_{\mathrm{biofilm}} + c_{a,2})\, S_w\, \phi\, C_w^{\text{bacteria}}$,
  - detachment: $r_{\mathrm{detachment}} = c_{d,1}\,(S_w\, \phi\, |\nabla p_w|)^{0.58} + c_{d,2}\, \mu$,
- (bio-) chemical reactions:
  - microbially catalyzed ureolysis: $CO(NH_2)_2 + 2H_2O \xrightarrow{\text{urease}} 2NH_3 + H_2CO_3$,
    $r_{\text{urea}} = k_{\text{urease}}\, k_{\text{ub}}\, \rho_{\text{biofilm}}\, \phi_{\text{biofilm}} \frac{m^{\text{urea}}}{m^{\text{urea}}+K_{\text{urea}}}$.
  - influence of NH_3 on the pH: $NH_3 + H^+ \longleftrightarrow NH_4{}^+ \Rightarrow$ increase in pH,
  - precipitation (and dissolution) of calcite: $Ca^{2+} + CO_3{}^{2-} \longleftrightarrow CaCO_3\downarrow$,
    $r_{\mathrm{precipitation}} = k_{\mathrm{precipitation}}\, A_{\mathrm{sw}}\, (\Omega - 1)^{n_{\mathrm{precipitation}}}$,
    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_{sw}.
- clogging: $\phi = \phi_0 - \phi_{\mathrm{calcite}} - \phi_{\mathrm{biofilm}} \Rightarrow K = K_0 \left(\frac{\phi-\phi_{\mathrm{crit}}}{\phi_0-\phi_{\mathrm{crit}}}\right)^3$

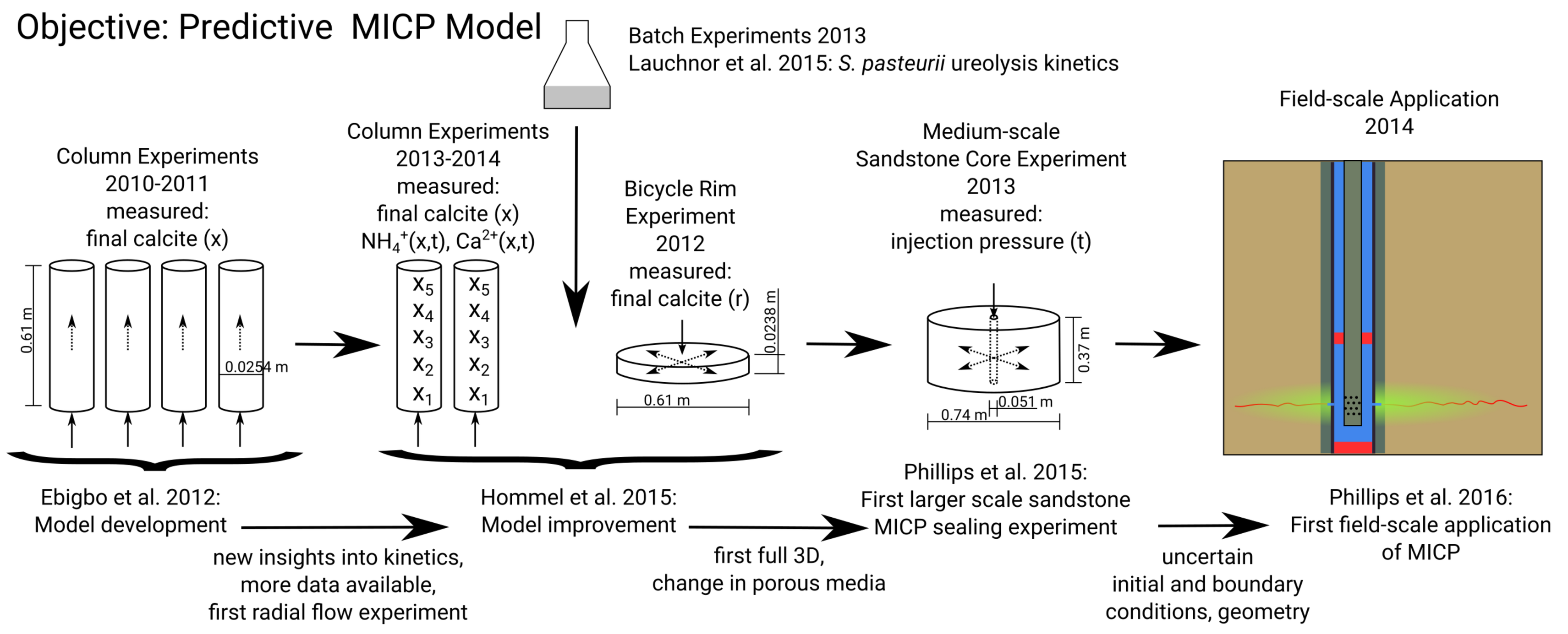

Figure 2: *Model development prior to the field-scale modeling [1].*

Results

Field observations [3]:

- significant decrease in injectivity ≈45 h after the first injections
- significant decrease in pressure decay after well shut in
- $CaCO_3$ detected in cores 1.8 m above the injection point
- total of 24 mineralization and 6 microbial injections during 4 days

Model results [1]:

- significant decrease in permeability close to the well for all scenarios investigated
- significant increase in injection pressure ≈48 h after the first injections
- $CaCO_3$ reaches about 1 m above the injection point
- the most recent model calibration (to 1D column results, [2]) underestimates the permeability reduction

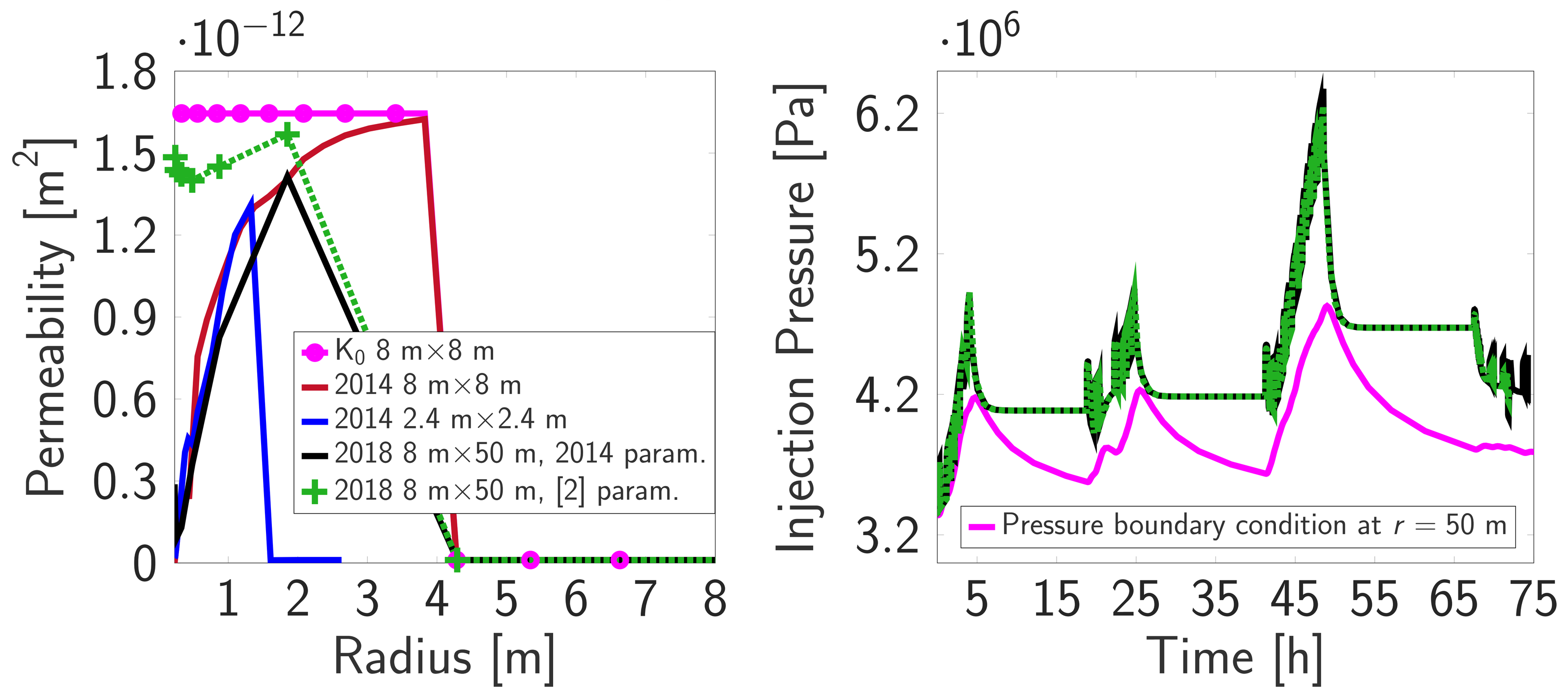

Figure 3: *Final and initial permeability along the radius through the high-permeable layer as predicted by simulations for various grids, domain sizes, and injection strategies (left). Injection pressure for the 2018 simulations and the pressure boundary condition (at 50 m) over time (right). Note that the initial permeability on the left is only shown for the "large" 8 m×8 m scenario.*

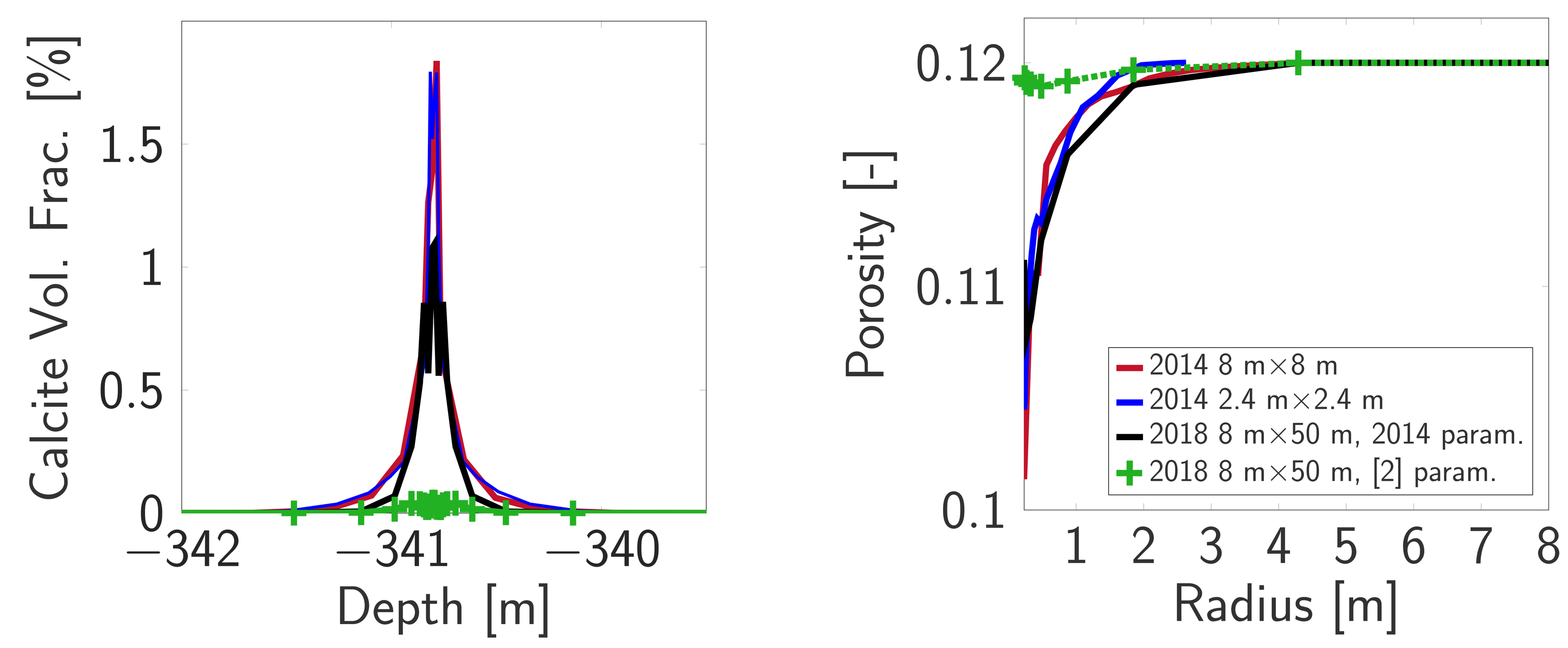

Figure 4: *Calcite volume fractions at the inner radius over depth predicted by simulations on various simulation domain sizes (left) and radial porosity distribution at the height of the high-permeable layer (right).*

More detailed results and discussions will be published in Cunningham et al. [1].

Literature

[1] Cunningham, A. B., Class, H., Ebigbo, A., Gerlach, R., Phillips, A. J., and Hommel, J. (2018). Field-scale modeling of microbially induced calcite precipitation. *Computational Geosciences*. submitted.

[2] Hommel, J., Lauchnor, E. G., Phillips, A. J., Gerlach, R., Cunningham, A. B., Helmig, R., Ebigbo, A., and Class, H. (2015). A revised model for microbially induced calcite precipitation: Improvements and new insights based on recent experiments. *Water Resources Research*, 51(5):3695–3715.

[3] Phillips, A. J., Cunningham, A. B., Gerlach, R., Hiebert, R., Hwang, C., Lomans, B. P., Westrich, J., Mantilla, C., Kirksey, J., Esposito, R., and Spangler, L. H. (2016). Fracture Sealing with Microbially-Induced Calcium Carbonate Precipitation: A Field Study. *Environmental Science & Technology*, 50:4111–4117.