Universität Stuttgart

Investigating the impact of induced calcite precipitation on the capillary pressure-saturation relation: Experimental plans

SFB 1313 Seminar 2018

Johannes Hommel: Own project, associated to C05

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SFB 1313,

Project C05

SFB 1313, Project C05: What is it about?

- Investigate changes in the pore space and the associated alteration of the permeability.
- Use Magnetic Resonance Imaging (MRI) and X-ray computer microtomography (µCT) to asses changes in porous media.
- Measure porosity-permeability relations for different fluid-solid reactions:
  - salt precipitation during evaporation,
  - microbially-induced calcite precipitation,
  - dissolution during chemical stimulation.

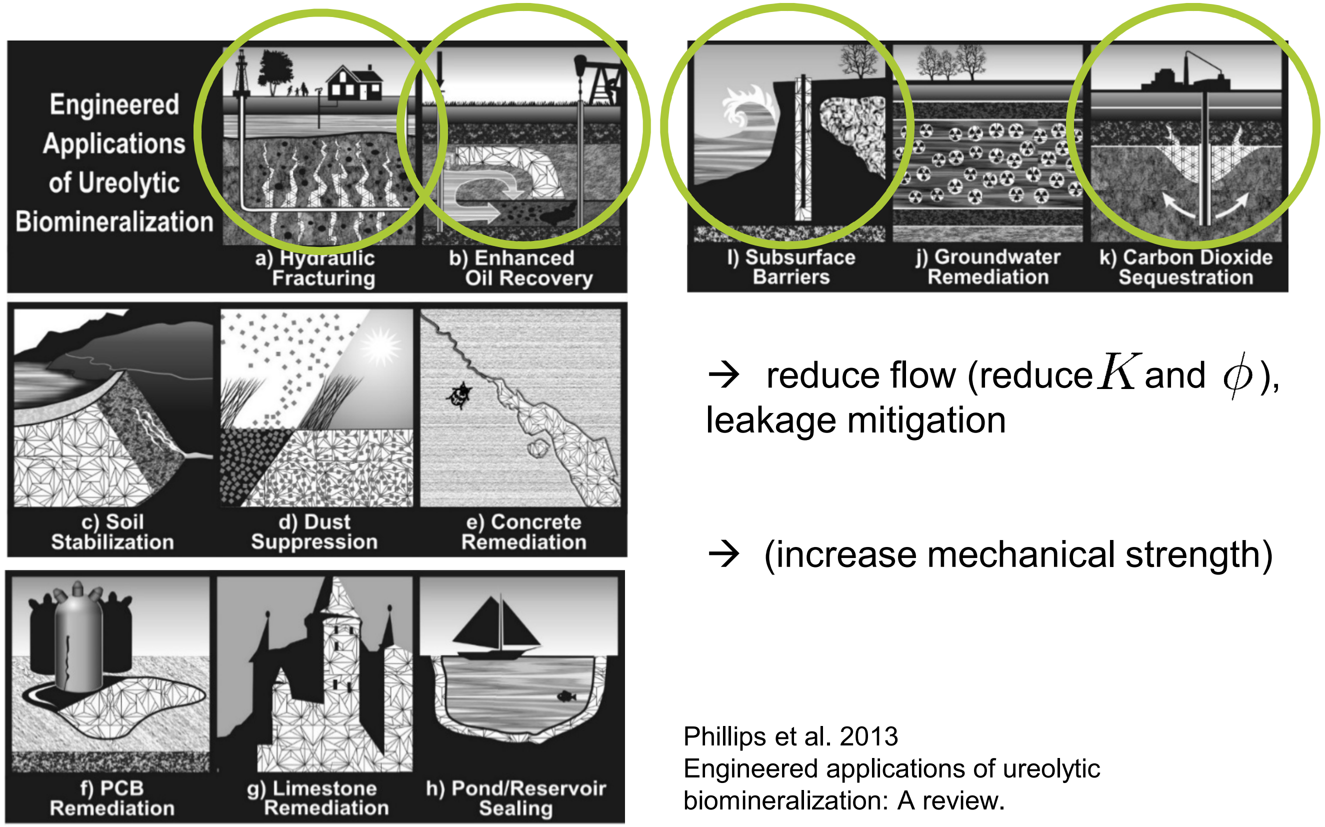
- Who: Sander Huisman, Andreas Pohlmeier, Holger Steeb, + student

Own Project:

Existing Model Concept

Experiments

Why investigate Induced Calcite Precipitation (ICP)?



→ reduce flow (reduce K and ϕ), leakage mitigation

→ (increase mechanical strength)

Phillips et al. 2013
Engineered applications of ureolytic biomineralization: A review.

Important Reactions

Urease or ureolytic microbes are injected or thermal ureolysis occurs

Ureolysis agent: enzyme → **EICP**, microbes →**MICP**, thermal → **TICP**

$$CO(NH_2)_2 + 2\,H_2O \xrightarrow[]{\text{temperature, urease}} 2\,NH_3 + H_2CO_3$$ ureolysis

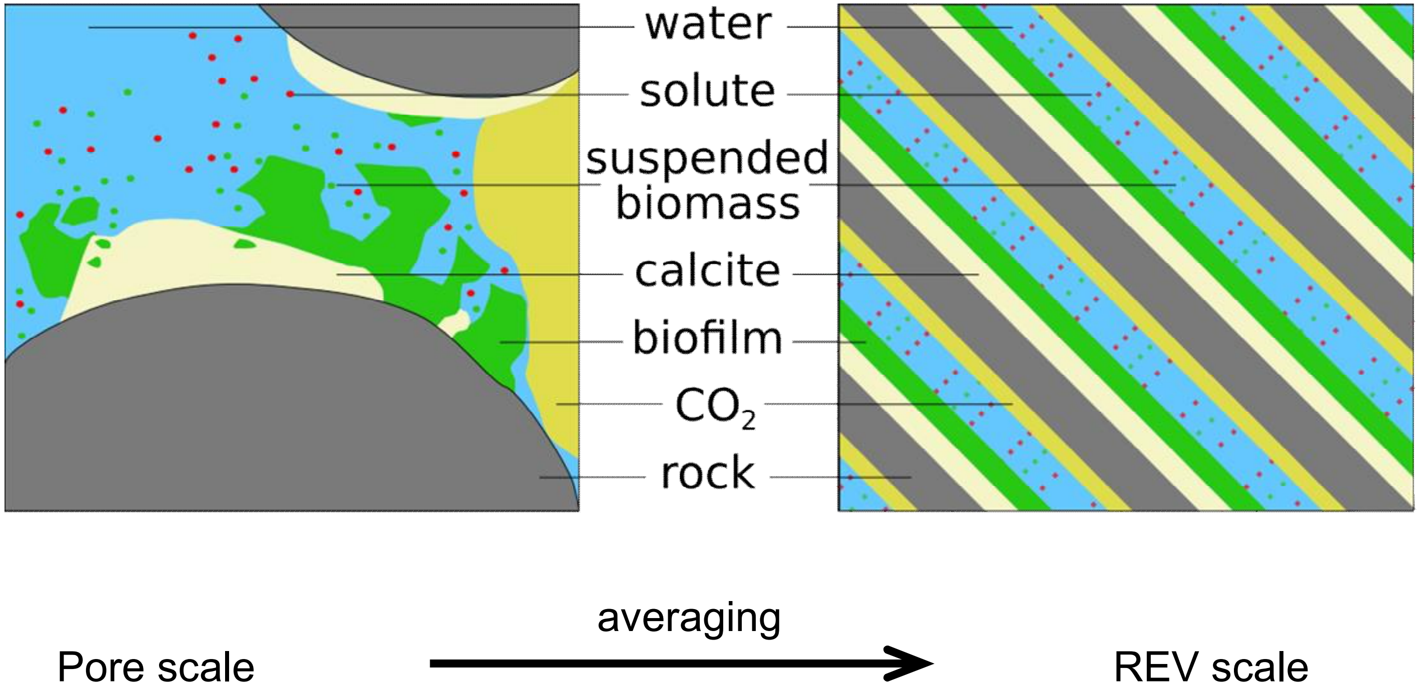
$$H_2CO_3 \longleftrightarrow HCO_3^- + H^+$$ dissociation of carbonic acid

$$HCO_3^- \longleftrightarrow CO_3^{2-} + H^+$$ dissociation of bicarbonate ion

$$2\,NH_4^+ \longleftrightarrow 2\,NH_3 + 2\,H^+$$ dissociation of ammonia

$$Ca^{2+} + CO_3^{2-} \longleftrightarrow CaCO_3 \downarrow$$ calcite precipitation/dissolution

Model Concept: Scale



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Balance Equations

- Mass balance equation of components

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

- Mass balance for the immobile components / solid phases:

$$\frac{\partial}{\partial t}\left(\rho_\varphi \phi_\varphi\right) = q^\varphi$$

- Energy balance:

$$\frac{\partial}{\partial t}\left(\left(1-\phi_0\right)\rho_\mathrm{s} c_\mathrm{s} T\right) + \sum_\varphi \left[\frac{\partial}{\partial t}\left(\phi_\varphi \rho_\varphi c_\varphi T\right)\right] + \sum_\alpha \left[\frac{\partial}{\partial t}\left(\phi \rho_\alpha u_\alpha S_\alpha\right) - \nabla\cdot\left(\rho_\alpha h_\alpha \mathbf{v}_\alpha\right)\right] - \nabla\cdot\left(\lambda_\mathrm{pm}\nabla T\right) = q^\mathrm{h}$$

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Sources & Sinks: Common

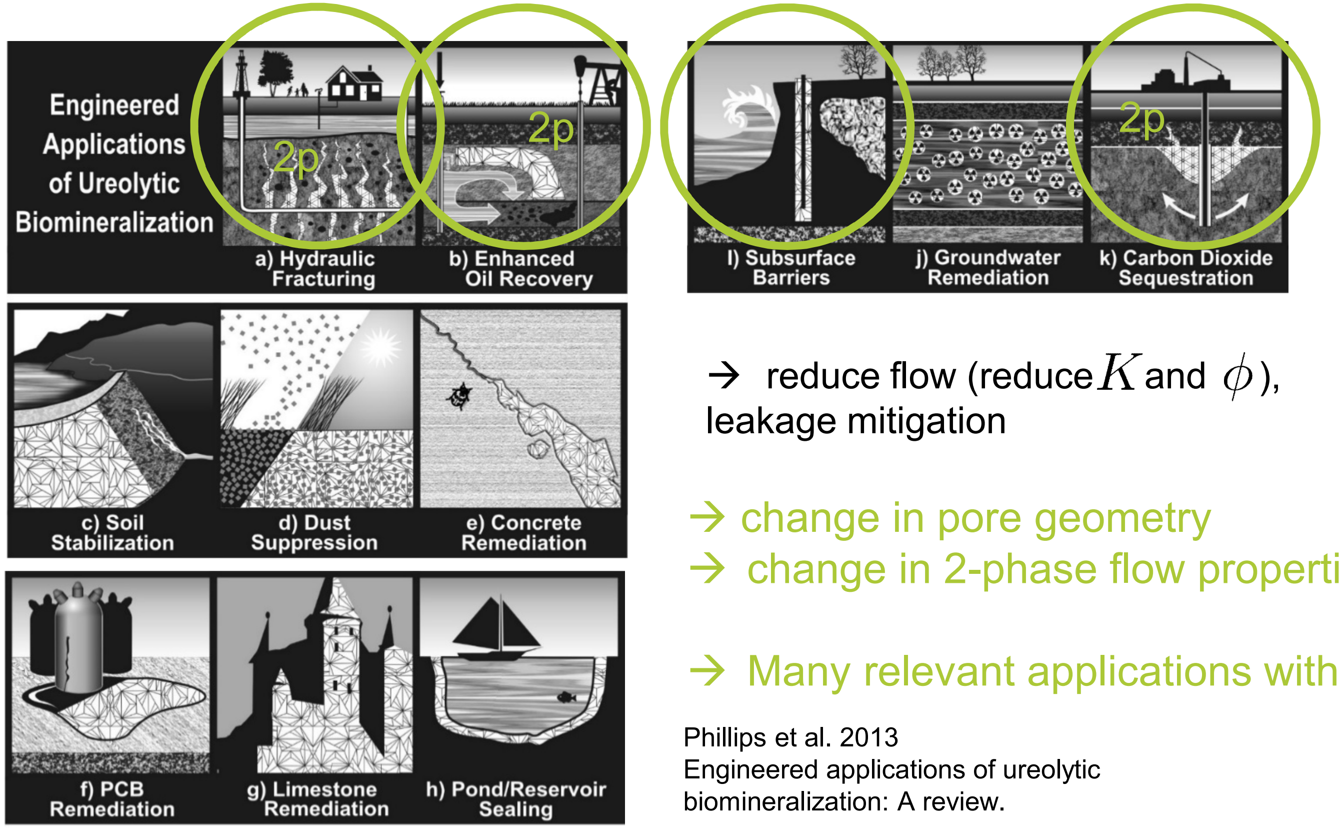
$$
\begin{aligned}
&\text{Urea:} & q^{\mathrm{urea}} &= -r_{\mathrm{urea}}\\
&\text{Total nitrogen:} & q^{\mathrm{NH_{tot}}} &= 2r_{\mathrm{urea}}\\[1em]
&\text{Calcium:} & q^{\mathrm{Ca^{2+}}} &= r_{\mathrm{diss}} - r_{\mathrm{precip}}\\
&\text{Total carbon:} & q^{\mathrm{C_{tot}}} &= r_{\mathrm{urea}} + r_{\mathrm{diss}} - r_{\mathrm{precip}}\\
&\text{Calcite:} & q^{\mathrm{c}} &= r_{\mathrm{precip}} - r_{\mathrm{diss}}
\end{aligned}
$$

$$
\begin{aligned}
&\text{Precipitation rate} & r_{\mathrm{precip}} &= f\left(A_{\mathrm{interface}},\ \Omega = \frac{[\mathrm{Ca^{2+}}][\mathrm{CO_3^{2-}}]}{K_{\mathrm{sp}}},\ T\right)\\
&\text{Dissolution rate} & r_{\mathrm{diss}} &= f\left(A_{\mathrm{interface}},\ \Omega = \frac{[\mathrm{Ca^{2+}}][\mathrm{CO_3^{2-}}]}{K_{\mathrm{sp}}},\ \mathrm{pH},\ T\right)\\[1em]
&\text{Ureolysis rate (MICP)} & r_{\mathrm{urea}}^{\mathrm{MICP}} &= f\left(\phi_{\mathrm{biofilm}},\ C_{\mathrm{w}}^{\mathrm{urea}}\right)\\[1em]
&\text{Ureolysis rate (EICP)} & r_{\mathrm{urea}}^{\mathrm{EICP}} &= f\left(\phi_{\mathrm{e}},\ C_{\mathrm{w}}^{\mathrm{e}},\ \mathrm{pH},\ C_{\mathrm{w}}^{\mathrm{urea}},\ C_{\mathrm{w}}^{\mathrm{NH_4^+}},\ T\right)\\[1em]
&\text{Ureolysis rate (TICP)} & r_{\mathrm{urea}}^{\mathrm{TICP}} &= f\left(C_{\mathrm{w}}^{\mathrm{urea}},\ T\right)
\end{aligned}
$$

Model Summary

- Complex REV-scale models for
  - Two-phase flow and transport
  - biogeochemical reactions
- MICP: 10 years of development
- EICP and TICP: under development
- No impact of ICP on two-phase flow yet!

Why is the capillary pressure-saturation relation relevant for modeling ICP?



→ reduce flow (reduce K and ϕ), leakage mitigation

→ change in pore geometry
→ change in 2-phase flow properties!

→ Many relevant applications with 2p!

Phillips et al. 2013
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Experimental plans: EICP and p_c-S_w

Adapting Capillary Pressure

- First step: implementing Leverett scaling of capillary pressure[1]:

$$J(S_\mathrm{w}) = \mathrm{const.}(S_\mathrm{w}) = \frac{p_\mathrm{c}(\phi)}{\sigma\cos\Theta}\sqrt{\frac{K(\phi)}{\phi}} = \frac{p_{\mathrm{c},0}}{\sigma\cos\Theta}\sqrt{\frac{K_0}{\phi_0}}$$

Assuming that $\sigma\cos\Theta$ is constant:

$$\rightarrow p_\mathrm{c}(S_\mathrm{w},\phi) = p_\mathrm{c}(S_\mathrm{w},\phi_0)\sqrt{\frac{K_0\phi}{K(\phi)\phi_0}}$$

[1] M. Leverett. “Capillary behaviour in porous solids”. In: Transactions of the AIME 142 (1941), pp. 159–172.

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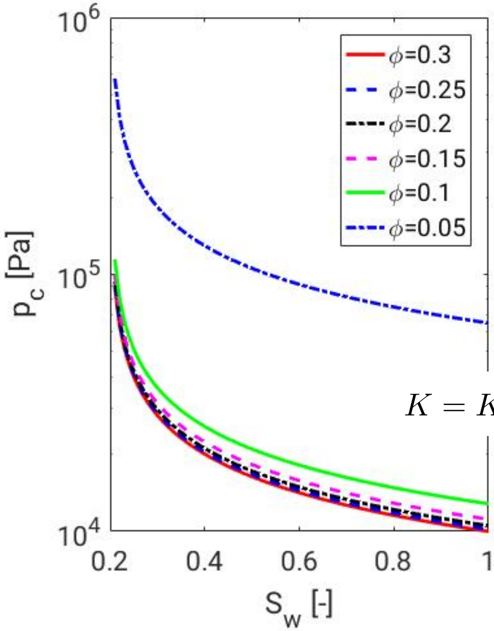

$$K = K_0\left(\frac{\phi-\phi_\mathrm{crit}}{\phi_0-\phi_\mathrm{crit}}\right)^3$$

Mainly a modification of the entry pressure, as:

$$p_\mathrm{c}(S_\mathrm{w},\phi_0) = p_\mathrm{d}\left(\frac{S_\mathrm{w}-S_{\mathrm{w,r}}}{1-S_{\mathrm{w,r}}}\right)^{-\frac{1}{\lambda}}$$

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Adapting Capillary Pressure

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Assuming that $\sigma \cos\Theta$ is constant:

$$\rightarrow p_\mathrm{c}(S_\mathrm{w}, \phi) = p_\mathrm{c}(S_\mathrm{w}, \phi_0)\sqrt{\frac{K_0 \phi}{K(\phi)\phi_0}}$$

- Second step: experimental investigation:
$p_\mathrm{c}(S_\mathrm{w})$ measurements of samples mineralized to various degrees.

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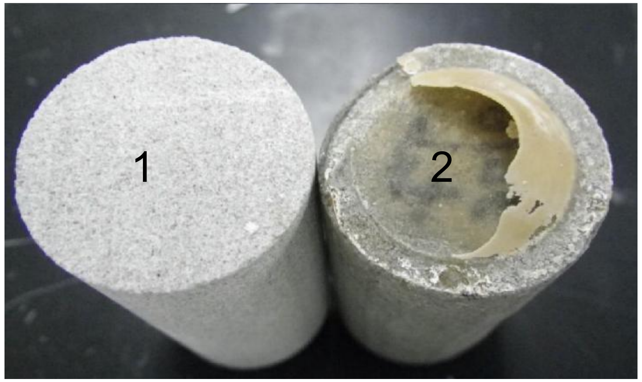
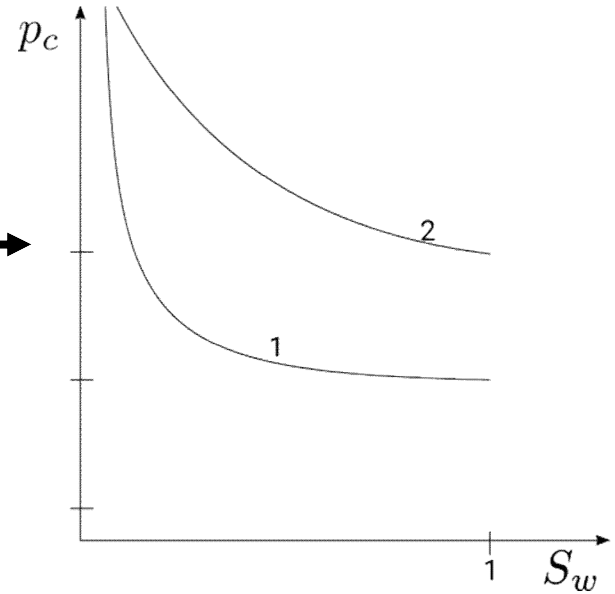
Adapting Capillary Pressure: Planned Experiments





Is Leverett scaling of capillary pressure sufficient?

$$p_{\mathrm{c}}(S_{\mathrm{w}}, \phi) = p_{\mathrm{c}}(S_{\mathrm{w}}, \phi_0)\sqrt{\frac{K_0 \phi}{K(\phi)\phi_0}} = p_{\mathrm{d},0}\sqrt{\frac{K_0 \phi}{K(\phi)\phi_0}} \left(\frac{S_{\mathrm{w}} - S_{\mathrm{w,r}}}{1 - S_{\mathrm{w,r}}}\right)^{-\frac{1}{\lambda}}$$

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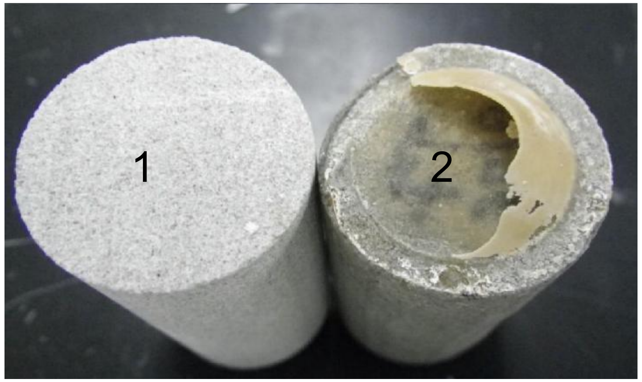
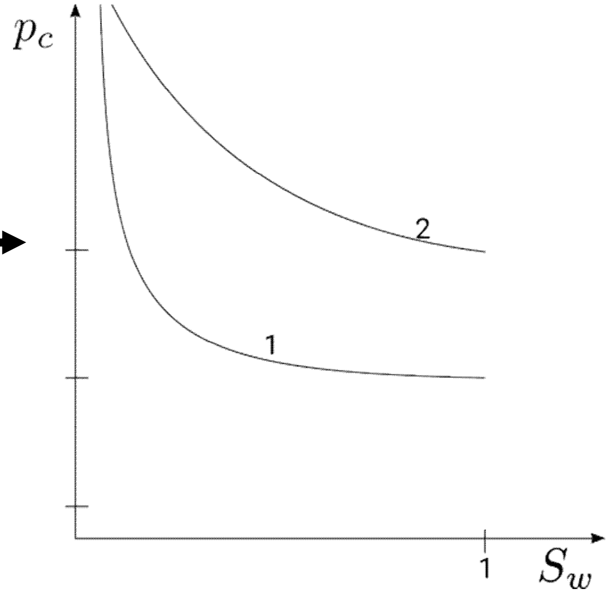
Adapting Capillary Pressure: Planned Experiments





Or is there a need for more complex $p_{\mathrm{c}}(S_{\mathrm{w}}, \phi)$ relations?

$$p_{\mathrm{c}}(S_{\mathrm{w}}) = p_{\mathrm{d}} \left(\frac{S_{\mathrm{w}} - S_{\mathrm{w,r}}}{1 - S_{\mathrm{w,r}}} \right)^{-\frac{1}{\lambda}} \rightarrow p_{\mathrm{c}}(S_{\mathrm{w}}, \phi) = p_{\mathrm{d}}(\phi) \left(\frac{S_{\mathrm{w}} - S_{\mathrm{w,r}}(\phi)}{1 - S_{\mathrm{w,r}}(\phi)} \right)^{-\frac{1}{\lambda(\phi)}}$$

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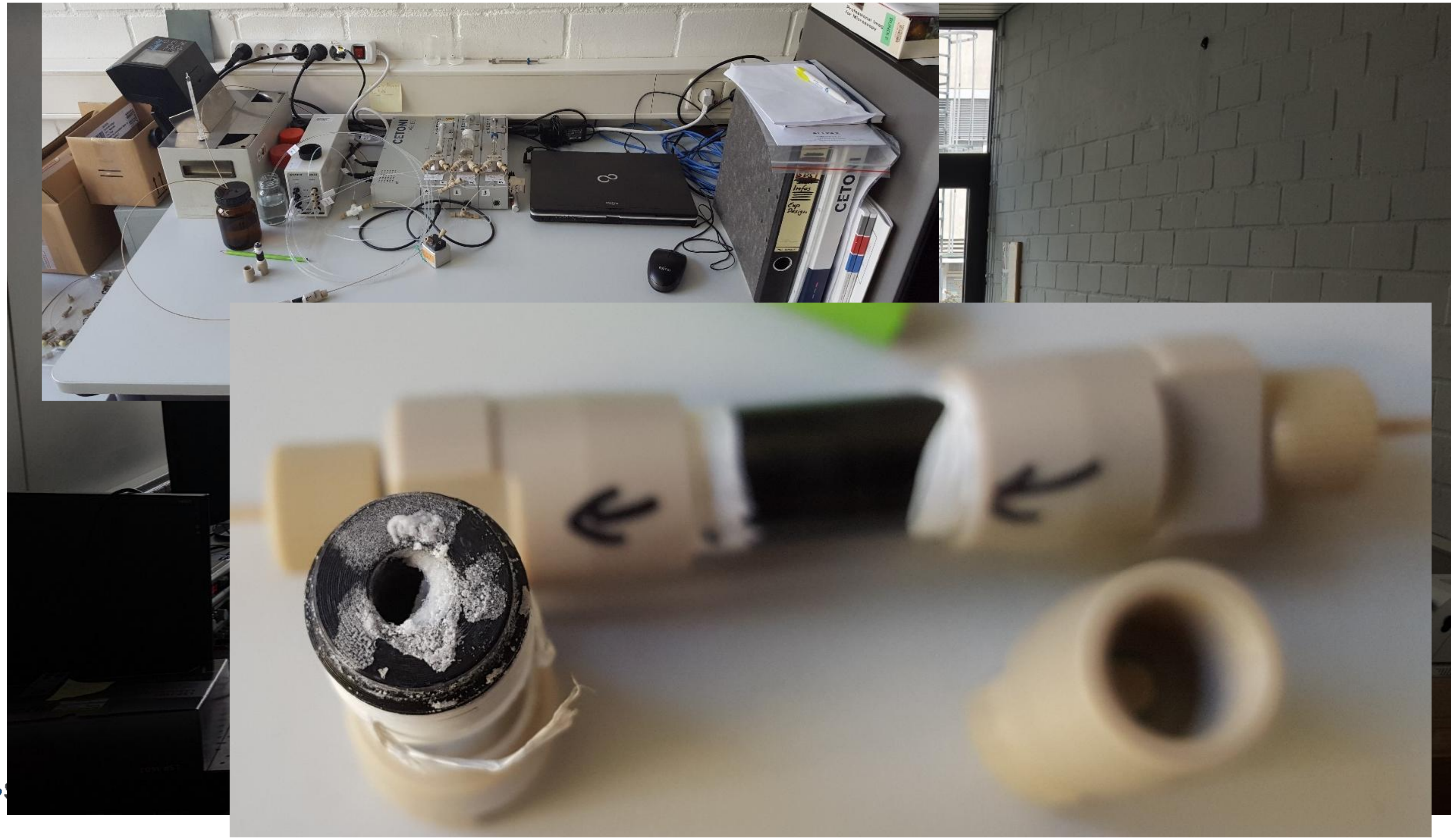
State of the lab in spring

State of the lab at the moment:



Collaborations




- Montana State University: kinetics, lab and field-scale experiments

- C04 and C05: share experimental data (porosity, permeability) obtained at different scales with different methods

  - C04: 2D exp., µm-cm scale, Microscope and µCT images, M/EICP, experiments and pore-(network)-scale modeling

  - C05: 3D exp., cm-dm scale, MRI and µCT images, MICP, salt prec/diss, experiments only

  - Own project: 3D exp., mm-cm scale, µCT images, EICP (exp.), M/E/TICP (REV-scale model)
- Other projects?

Universität Stuttgart
Institut für Wasser- und Umweltsystemmodellierung
Lehrstuhl für Hydromechanik und Hydrosystemmodellierung

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Interface-Driven Multi-Field Processes in Porous Media

Thank you!

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DuMu^X All simulations conducted with DuMu^X www.dumux.org

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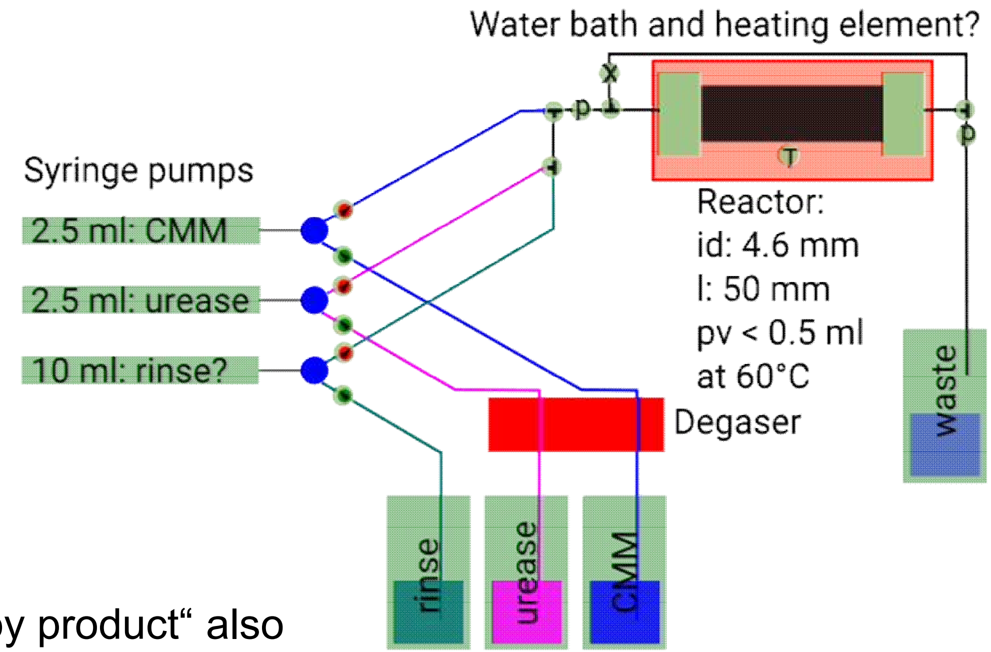
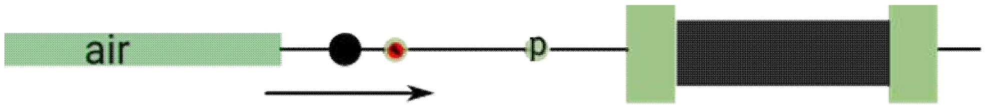
Experiment setup sketch for mineralization

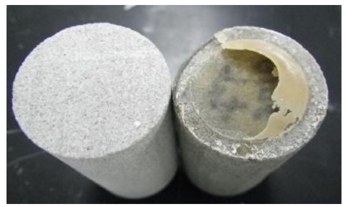


as a „by product“ also measuring porosity-permeability relation

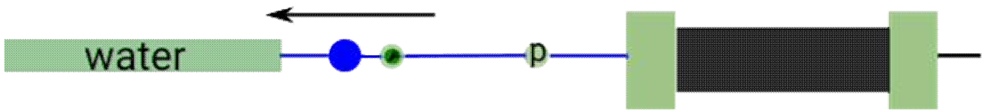
→ Relevant for Leverett scaling

Experiment setup sketch for p_c-S_w relations

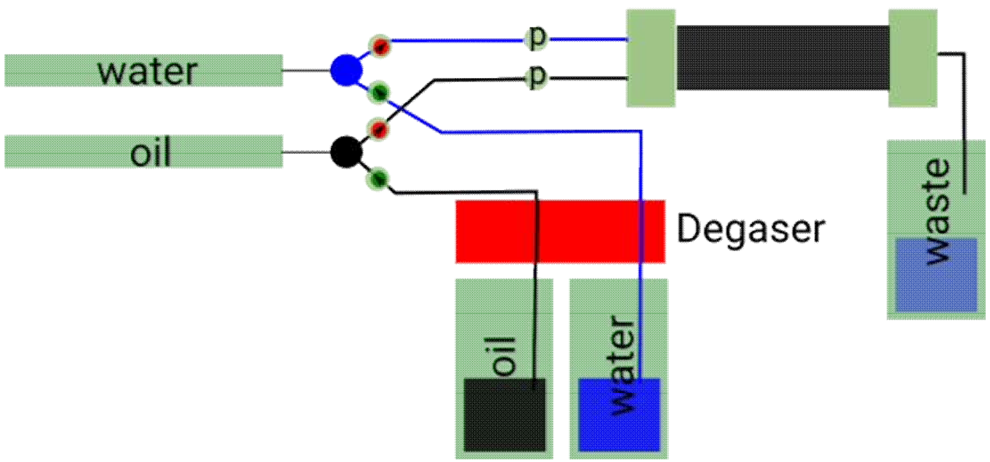


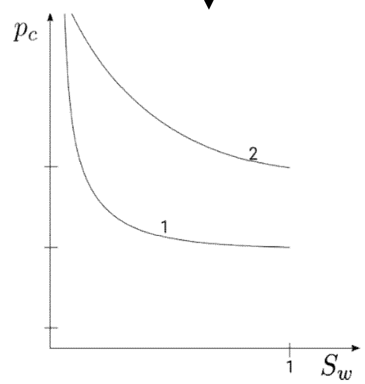


Syringe pumps: either injecting air or extracting water



Or simultaneous injection of oil and water





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