An Experimental Study of CO_2 Exsolution and Relative Permeability

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Motivation

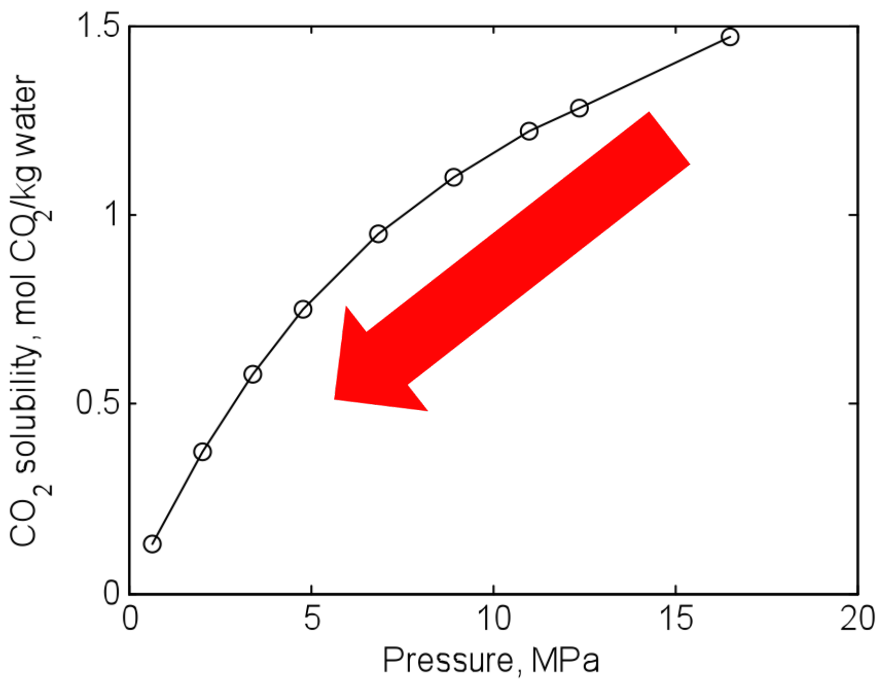
- Dissolution trapping is generally viewed as favorable trapping mechanism

- But, what are the risk of dissolution trapping?

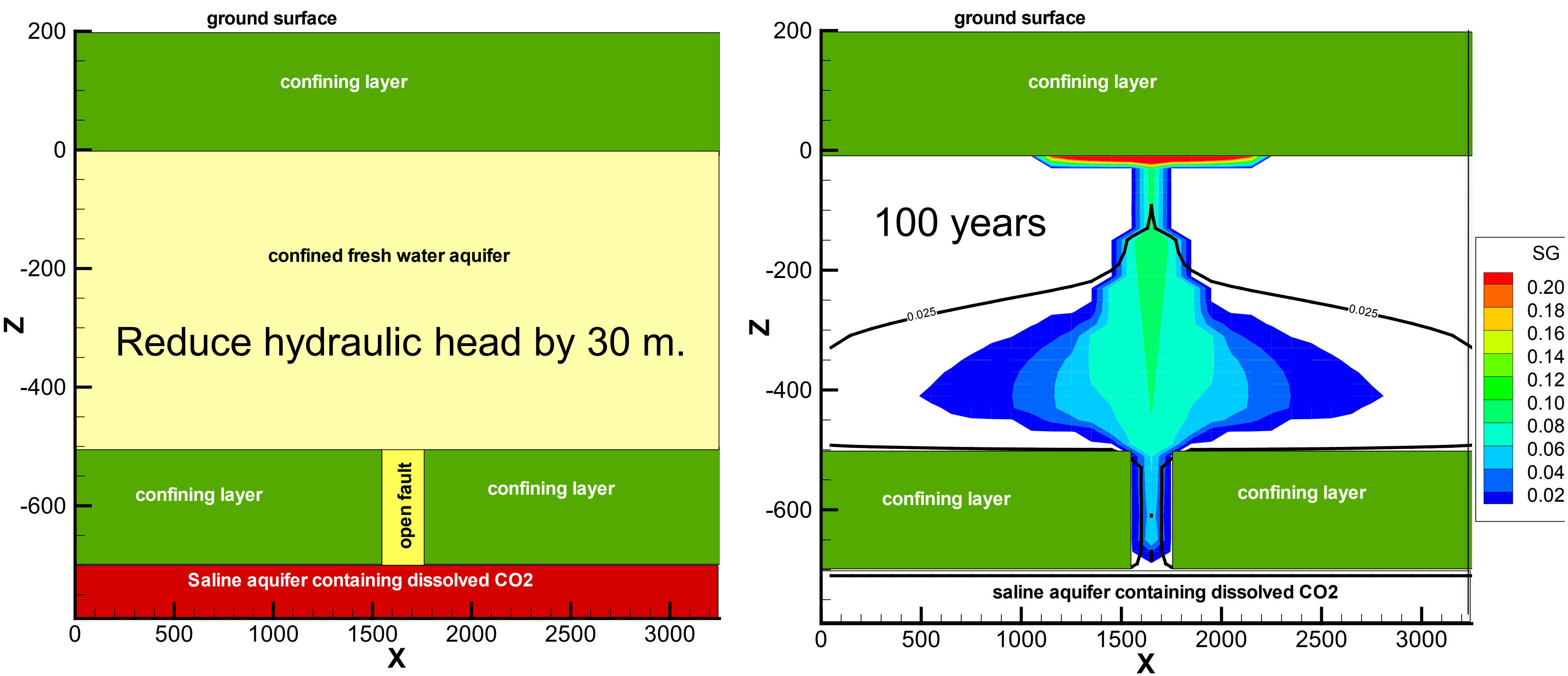
⇨ CO_2 saturated brine

⇨ Brine migration through the seal

⇨ Exsolution of CO_2 as the pressure decreases creates separate phase CO_2



Simulated Results of Pumping a Shallow Aquifer



TOUGH2-ECO2N simulation of the effects of groundwater extraction on brine migration and CO_2 exsolution.

Analog from oil production

- Solution Gas Drive

  ⇨ gas exsolves from oil

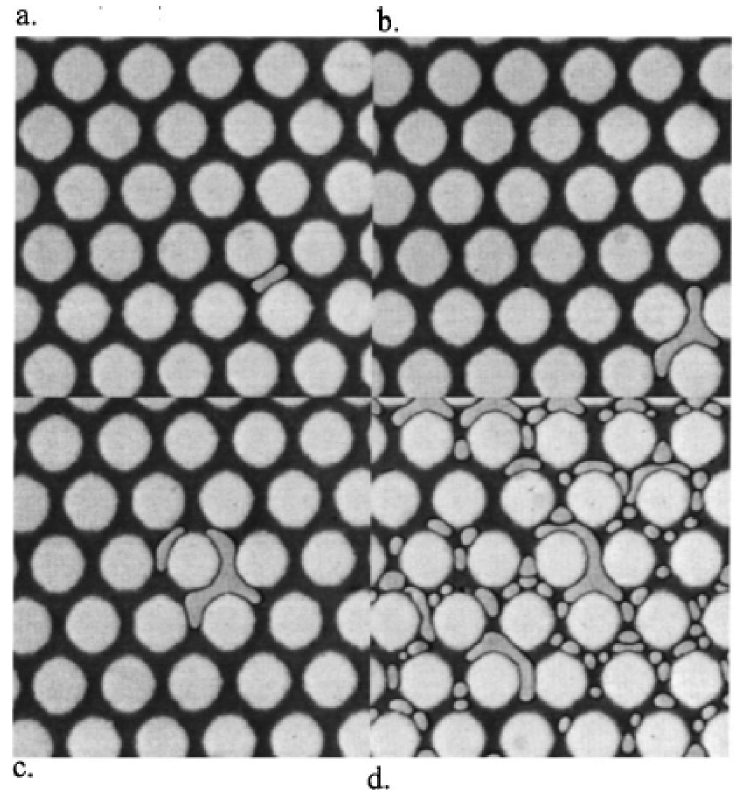
- Insights from Petroleum Industry

  ⇨ critical gas saturation (1% ~ 40%)

  ⇨ intermittent gas flow

  ⇨ low gas mobility

Low gas mobility hypothesized to result from high oil viscosity.



Nucleation, growth, migration and breakup of gas bubbles

R. Bora, B.B. Maini, A. Chakma: "Flow Visualization Studies of Solution Gas Drive Process in Heavy Oil Reservoirs Using a Glass Micromodel". SPE Reservoir Eval. & Eng. **3**(3), June 2000.

Objective

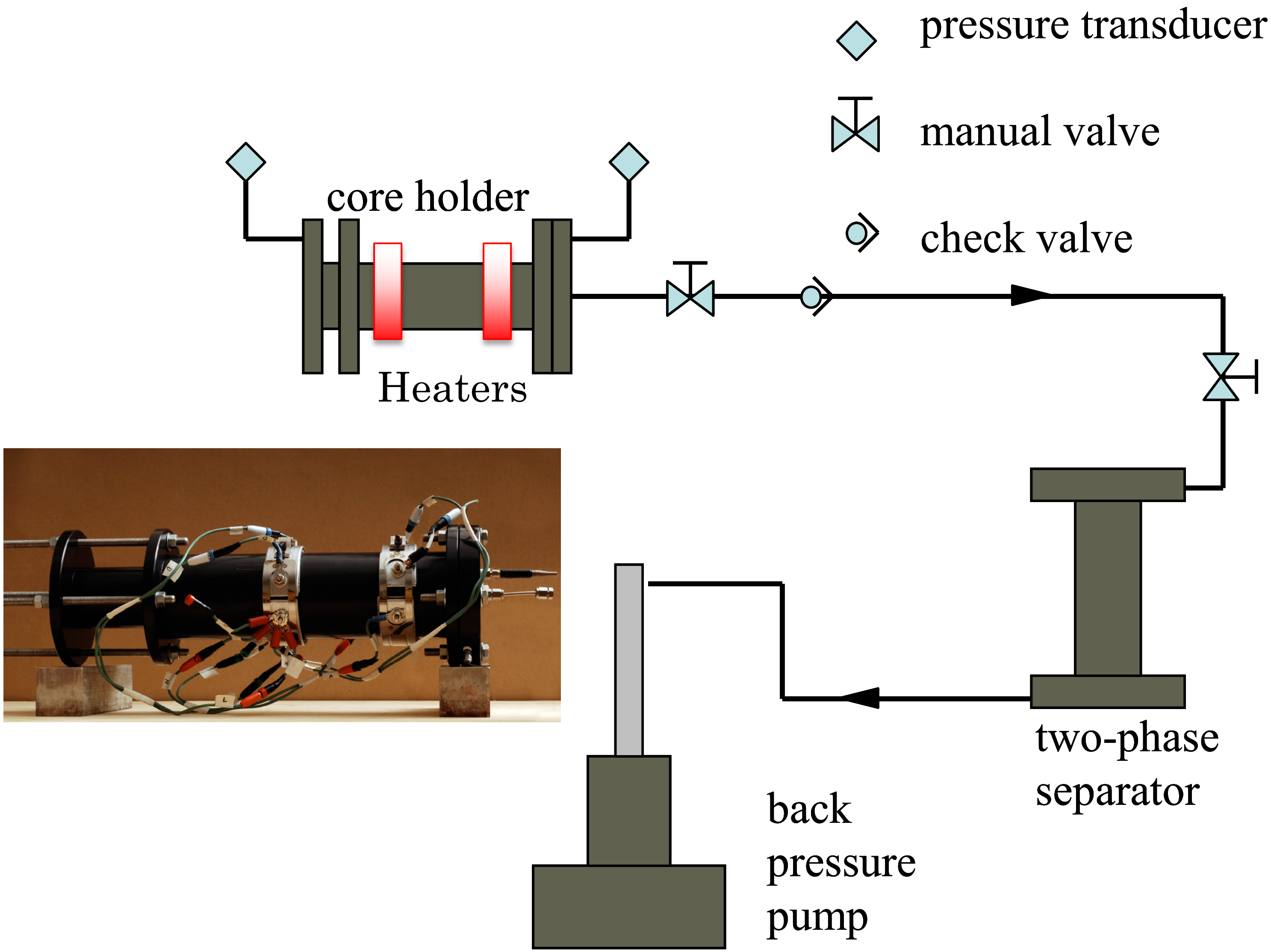
Questions:

- Can we observe the evolution of an exsolved CO_2 phase?
- What are the flow properties of exsolved CO_2 phase?
- What is the fate of exsolved CO_2?

Approach:

- Conduct core-scale exsolution experiments with a CT scanner
- Calculate relative permeability curves for exsolved CO_2 phase and water

Experimental Setup

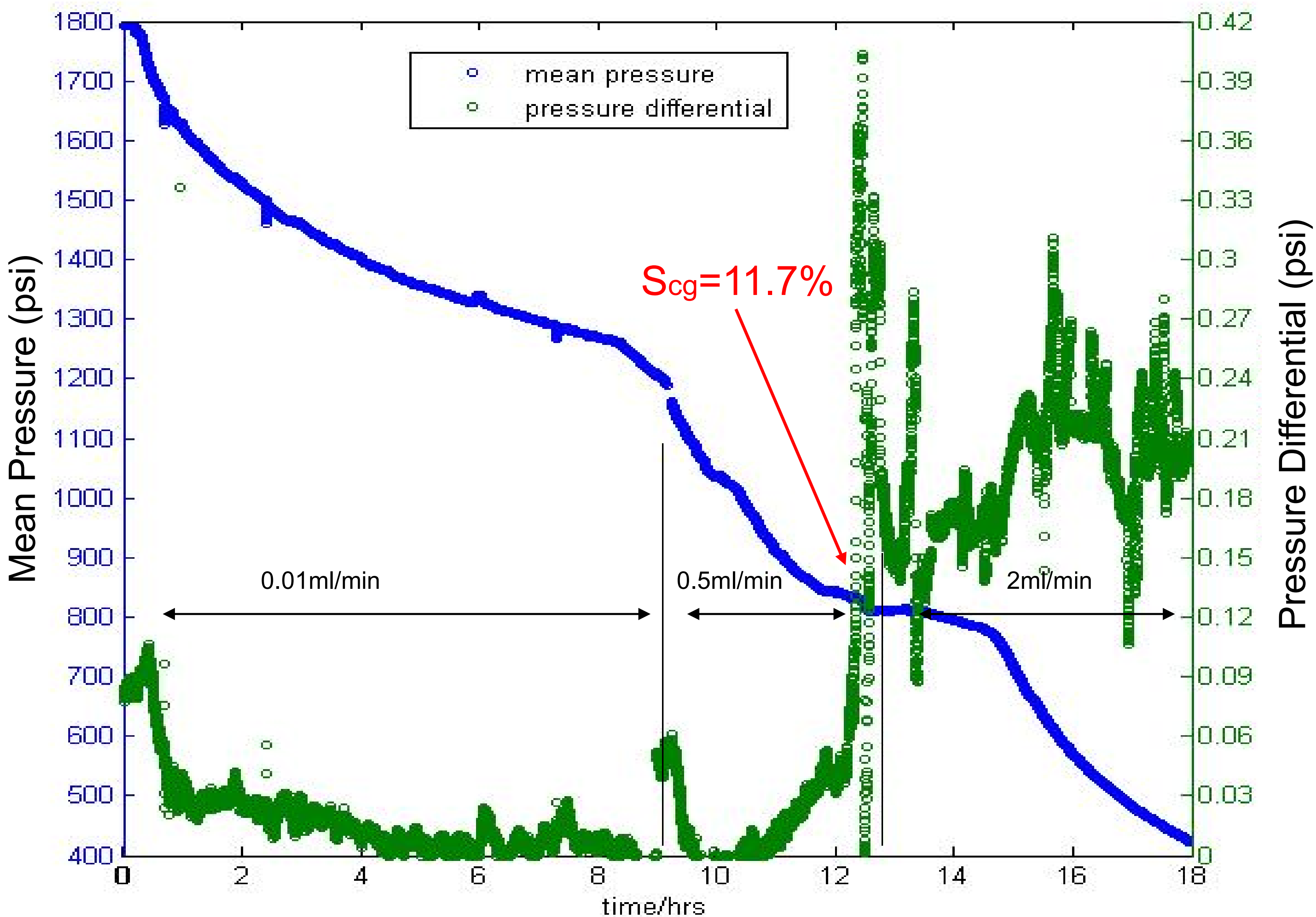


Experimental Procedure

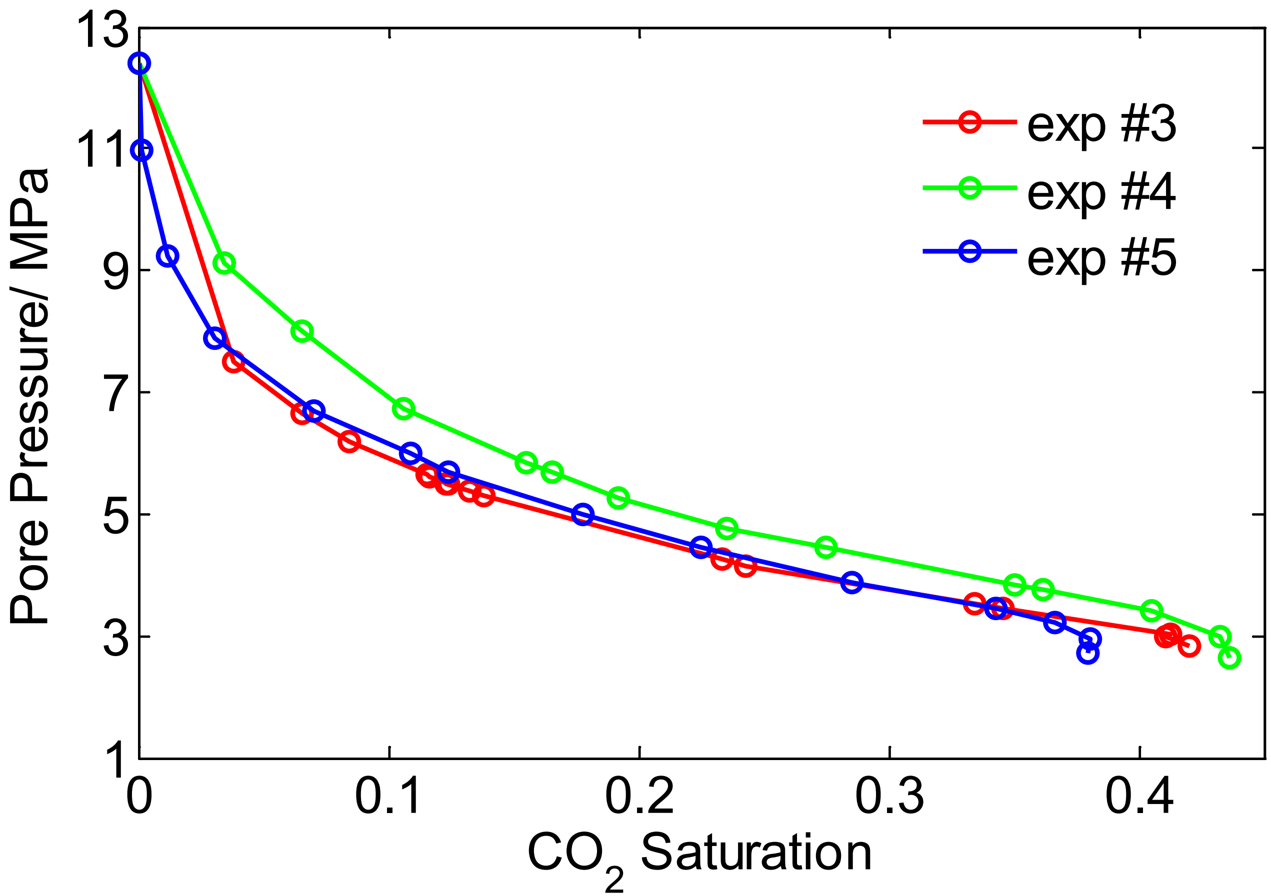
1. Pre-equilibrate water and CO_2 at storage reservoir pressure and temperature (12.4 MPa and 50^{o}C)
2. Inject pre-equilibrated fluid into water saturated rock
3. Extract fluid at a series of constant volumetric flow rates while measuring pressure upstream and downstream of the core
4. Measure saturation using X-Ray CT scans of the core periodically (10 replicates at each location)
5. Calculate flow rate of water and CO_2 from mass balance based on S, P and T data.

Two experiments were conducted on a Berea sandstone (963mD), exp #3 and exp #4, and one was conducted on a Mount Simon sandstone (15mD), exp #5

Typical Pressure Data Set



Measured Exsolved CO_2 Saturations



Pore pressure versus average CO_2 saturation during depressurization

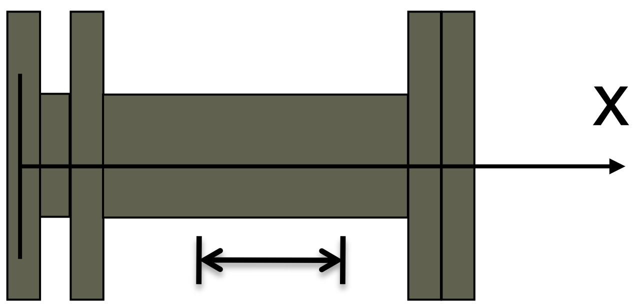
Relative Permeability Calculation

Assume: 1D problem

Constant pressure drop

Uniform density

Uniform saturation



L = core length

$$k_{r_w} = \frac{\mu_w L q_w}{2Ak\Delta p} \quad and \quad k_{r_g} = \frac{\mu_g L q_g}{2Ak\Delta p}$$

where

$\Delta p = pressure\ drop\ (Pa)$

$\mu = viscosity\ (Pa - s)$

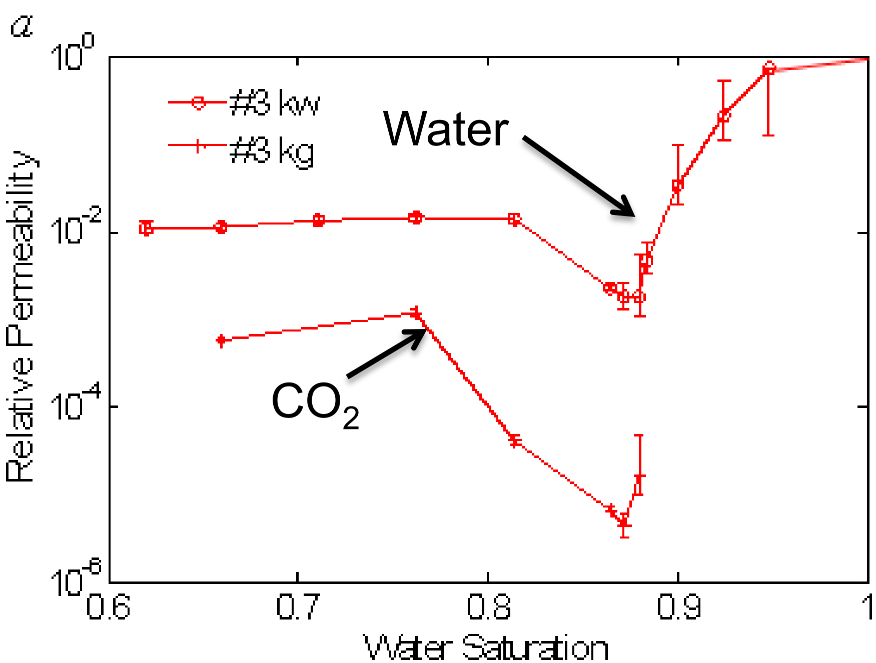
$q = volumetric\ \ flow\ rate\ (m^3/s)$

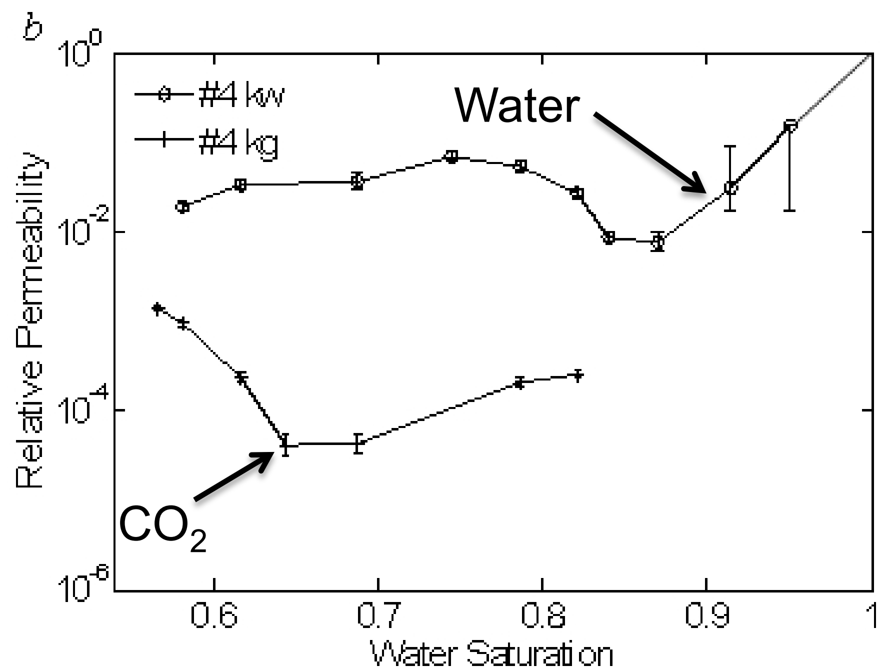
$A = Area\ (m^2)$

$k = permeability\ (m^2)$

$L = length\ (m)$

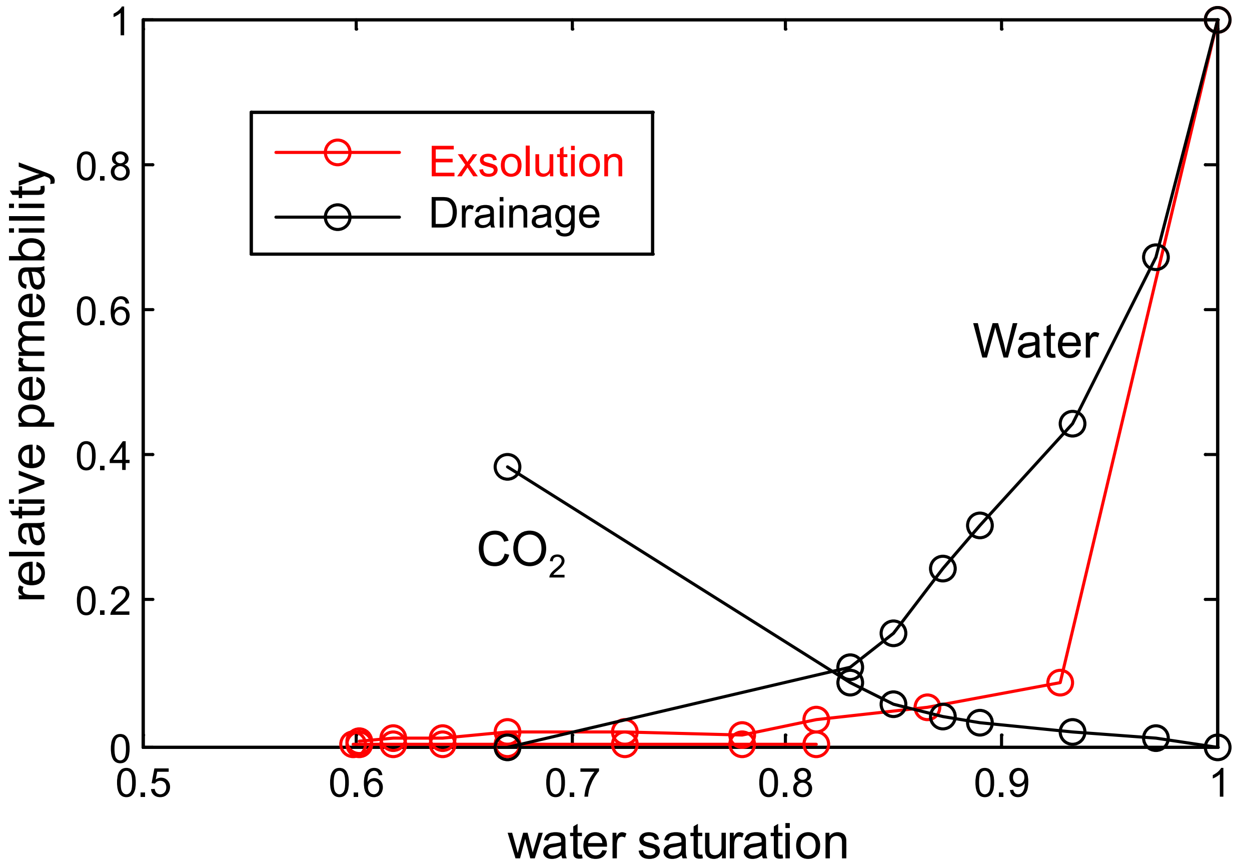
Relative Permeability Curve





Relative Permeability Curves for the Berea Sandstone

Comparison to Drainage Relative Permeability Curve

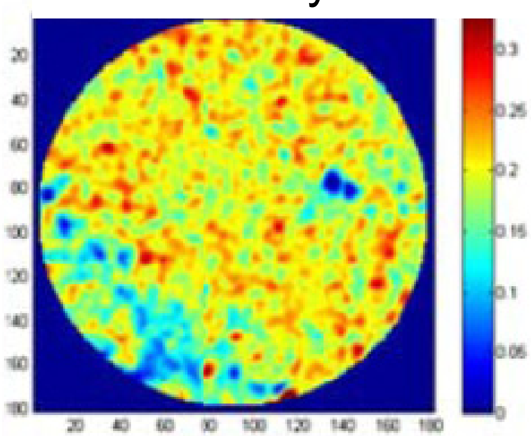


Why is the relative permeability of exsolved CO_2 so low?

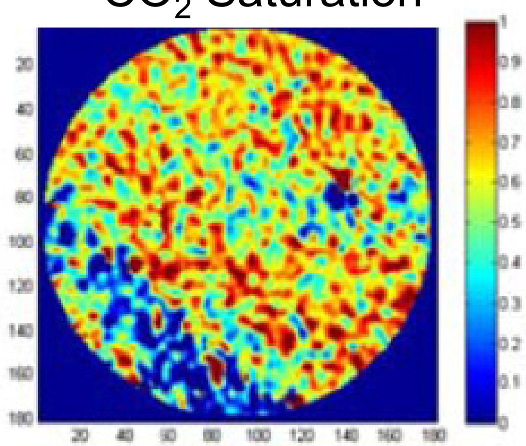
CO_2 Saturation vs. Porosity in a Typical Drainage Experiment

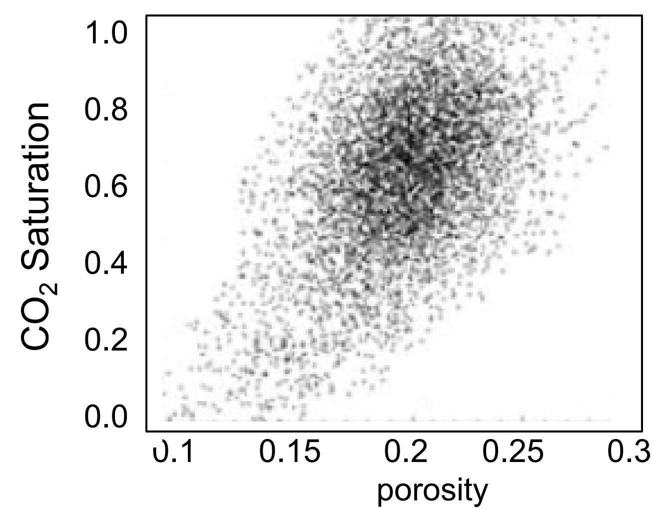
- Weak but significant correlation observed in standard core flooding experiments.
- Water and CO_2 develop separate flow paths which limits interference between the phases

Porosity



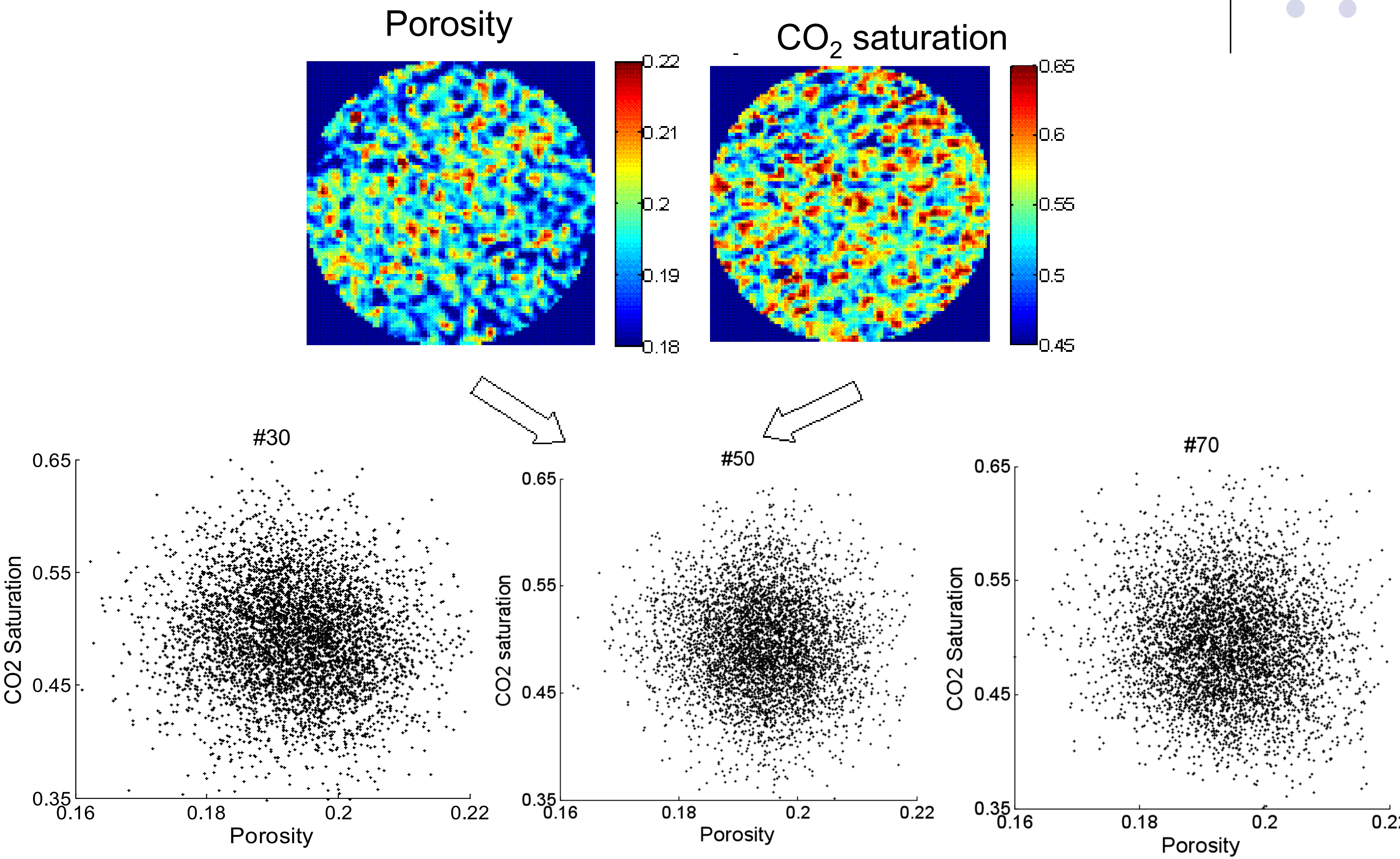
CO_2 Saturation





J.-C Perrin and S. M. Benson: "An Experimental Study on the Influence of Sub-Core Scale Heterogeneities on CO2 Distribution in Reservoir Rocks". Transport in porous media, DOI 10.1007/s11242-009-9426-x, 2009.

Distribution of Exsolved CO_2



Why is the Relative Permeability so Low?

Hypothesis

- Homogeneous exsolution throughout the pore spaces
- CO_2 bubble block water flow leading to low k_{rw}
- CO_2 bubbles form a poorly connected phase which leads to low k_{rCO2}

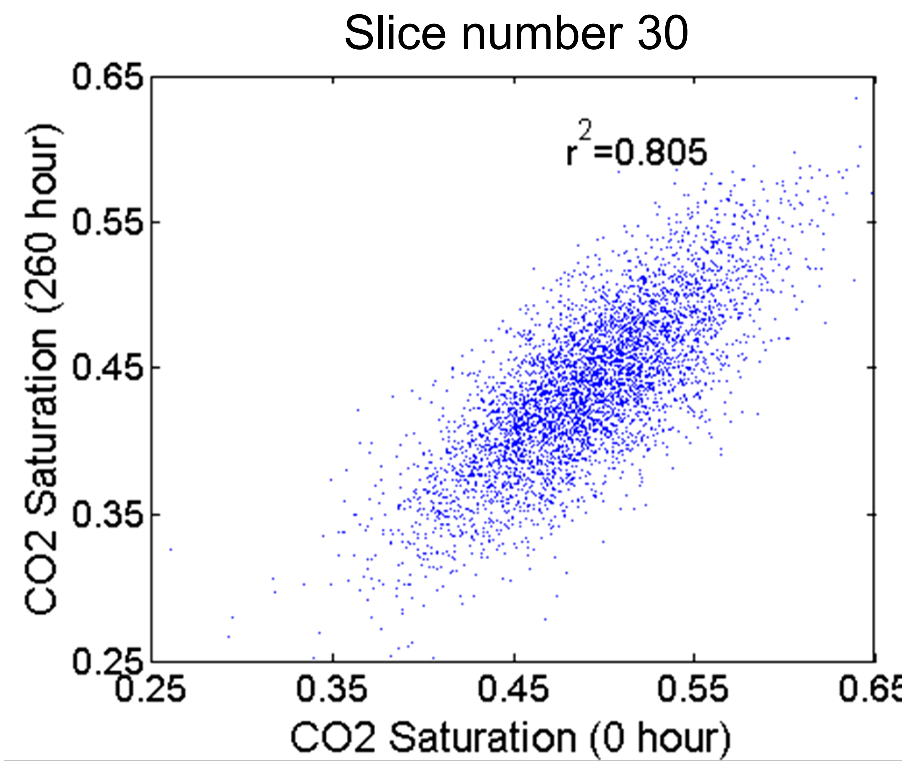
Micromodel studies now underway to test this hypothesis.

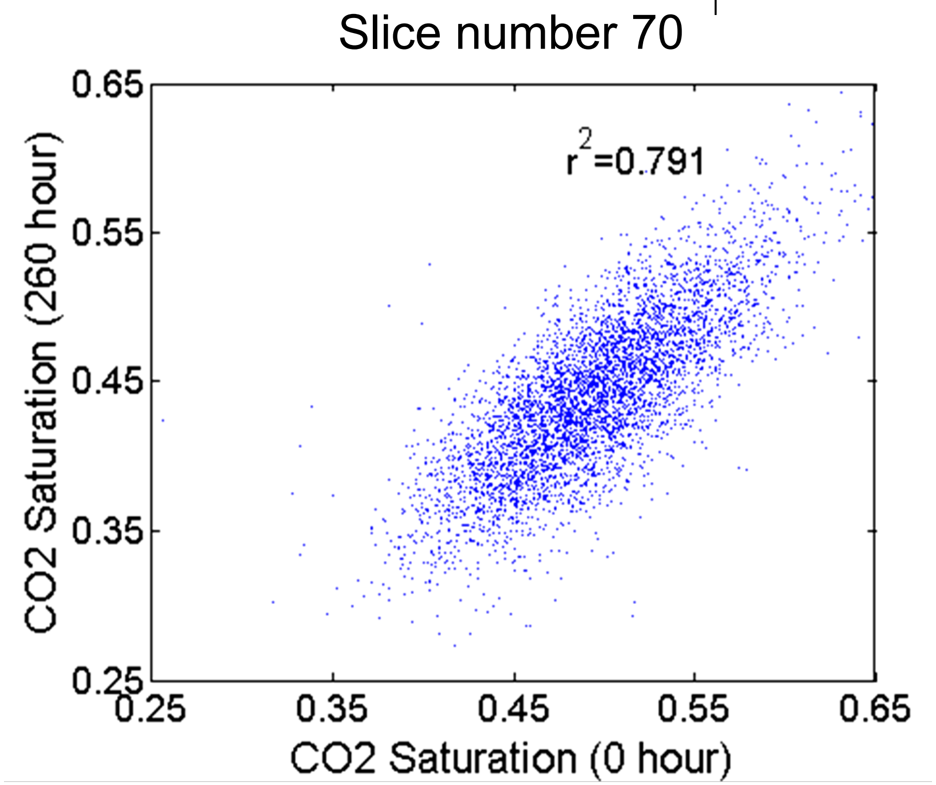
Conclusion

- Significant amount of CO_2 exsolves from solution as pressure drops
- Critical gas saturation of 11.7%~15.5%
- Relative permeability to both phases is very low, much lower than expected based on drainage relative permeability curves
- CO_2 exsolves homogeneously throughout the rock
  - Explains the low relative permeability to water
  - Exsolved gas bubble are disconnected, explaining low relative permeability to CO_2
- Low relative permeability persists over periods of 11 day observation period
  - No re-distribution of CO_2 was observed during equilibration period
- Suggests that exsolution poses little risk for geological storage
- Significant reduction in both water and CO_2 mobility could be favourable for storage security after injection by preventing CO_2's migration or even block possible leakage paths

Thank you

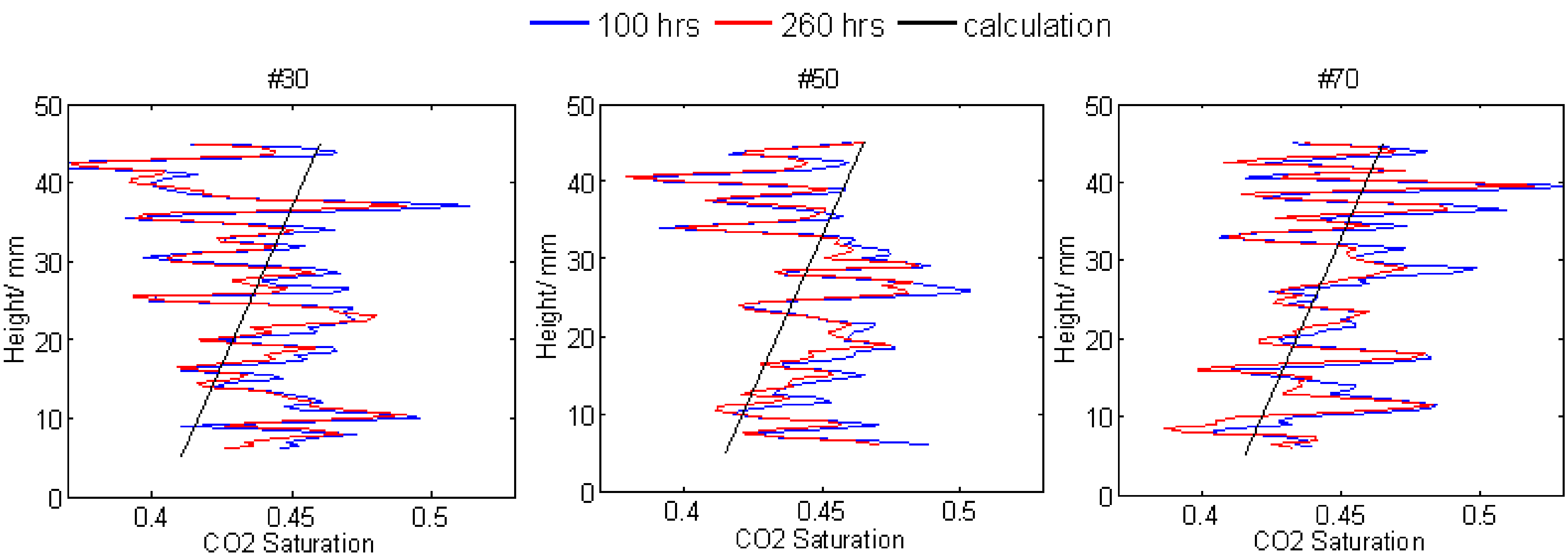
CO_2 Saturation Distributions Remain Constant Over Time





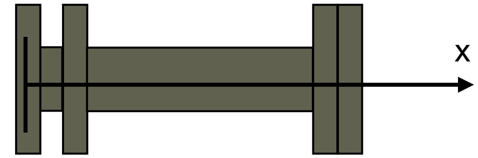
Pixel by pixel comparison of the CO_2 saturation immediately after exsolution and 260 hours later for two different portions of the core.

No Obvious Evolution Towards Gravity-Capillary Equilibrium



Lack of evolution towards gravity-capillary equilibrium supports the conclusion the low mobility persists over 260 hours.

Rel perm curve



Assume: 1D problem; $\frac{\partial p}{\partial t}, \frac{\partial S}{\partial t}, \rho, \mu, S$ do not vary with x

For gas phase:

Darcy's Law: $u = -\frac{KKr}{\mu}\nabla p$; 1D: $u_x = -\frac{KKr}{\mu}\frac{\partial p}{\partial x}$

Integration from 0 to L: $\Delta p_g = -\frac{\mu_g}{KKrg}\int_0^L u_{x,g}\,dx$

Continuity Eqn: $\frac{\partial(\rho_g \phi S_g)}{\partial t} + \nabla\cdot(\rho_g u_g) = 0$; 1D: $\frac{\partial(\rho_g \phi S_g)}{\partial t} + \frac{\partial(\rho_g u_g)}{\partial x} = 0$

$$\phi\frac{\partial(\rho_g S_g)}{\partial t} + \frac{\partial(\rho_g u_g)}{\partial x} = 0 \Rightarrow \phi(S_g\frac{\partial \rho_g}{\partial t} + \rho_g\frac{\partial S_g}{\partial t}) + (\frac{\partial \rho_g}{\partial x}u_g + \frac{\partial u_g}{\partial x}\rho_g) = 0$$

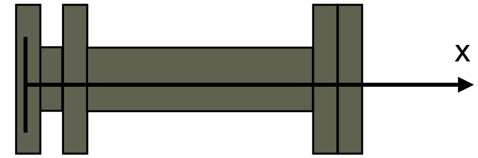
Set $a = \phi(S_g\frac{\partial \rho_g}{\partial t} + \rho_g\frac{\partial S_g}{\partial t}) \Rightarrow \frac{\partial a}{\partial x} = 0$

$$\frac{\partial \rho_g}{\partial x} = \frac{\partial \rho_g}{\partial p}\cdot\frac{\partial p}{\partial x} = \rho_g C_g\cdot\frac{\partial p}{\partial x} \approx 0, \quad \text{then} \quad a + \frac{\partial u_g}{\partial x}\rho_g = 0$$

$$u_g(x) = -a\int_0^x \frac{1}{\rho_g}dx = -\frac{a}{\rho_g}\int_0^x dx,\; u_g(L) = -\frac{a}{\rho_g}L$$

Then: $\Delta p_g = -\frac{\mu_g}{KKrg}\int_0^L u_{x,g}\,dx = -\frac{\mu_g}{KKrg}\int_0^L(-\frac{a}{\rho_g}\int_0^x dx)dx = -\frac{\mu_g L}{2\,KKrg}\frac{q_g}{A}$

Rel perm curve



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Continuity Eqn: $\frac{\partial(\rho\phi S_w)}{\partial t} + \nabla\cdot(\rho u) = 0$;   1D: $\frac{\partial(\rho\phi S_w)}{\partial t} + \frac{\partial(\rho u)}{\partial x} = 0$

Constant density: $\phi\frac{\partial(S_w)}{\partial t} + \frac{\partial(u_w)}{\partial x} = 0$

$\frac{\partial(S_w)}{\partial t}$ doesn't change with x: $u_w(x) = -\phi\frac{\partial(S_w)}{\partial t}\int_0^x dx$, $u_w(L) = -\phi\frac{\partial(S_w)}{\partial t}L$

Then:

$$\Delta p_w = -\frac{\mu_w}{KKrw}\int_0^L\left(-\phi\frac{\partial(S_w)}{\partial t}\int_0^x dx\right)dx = \frac{\mu_w}{KKrw}\frac{\phi\partial(S_w)}{\partial t}\frac{L^2}{2} = -\frac{\mu_w L}{2\,KKrw}u_w(L) = -\frac{\mu_w L}{2\,KKrw}\frac{q_w}{A}$$