GCEP Global Climate & Energy Project

Battelle Remediation of Chlorinated and Recalcitrant Compounds Conference
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Experimental and Numerical Studies of CO_2-Brine Systems for CO_2 Capture and Sequestration

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Science and technology for a low GHG emission world.

Motivation

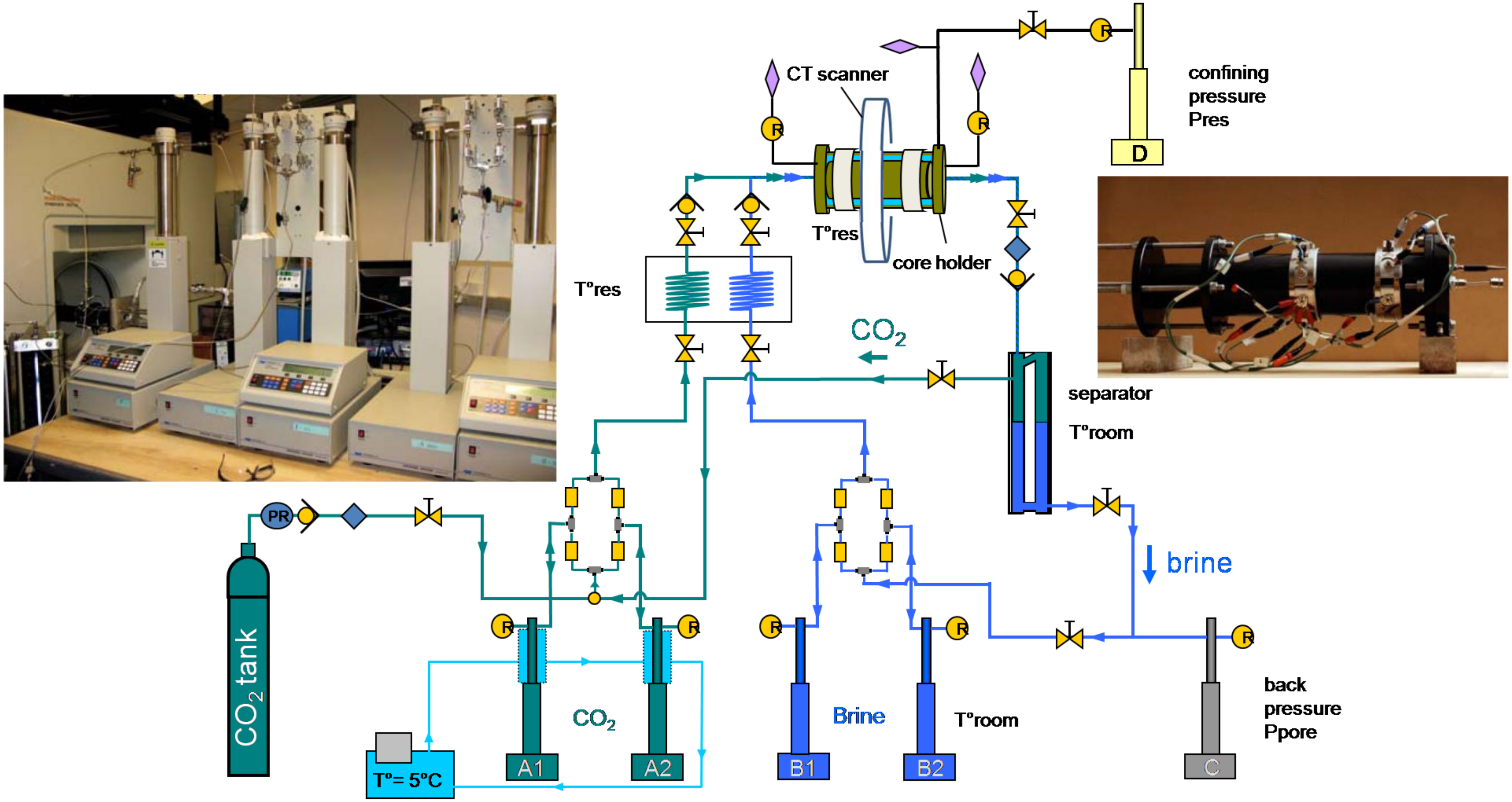
- Questions
  - How does CO_2 behave in a subsurface porous media environment?
    - Unfavorable Mobility Ratio
  - What controls the distribution of CO_2 in porous media?
  - How can we use simulations to study the behavior of CO_2?
- Approaches
  - Conduct core flooding experiments at subsurface conditions
  - Simulate the experiments to validate our physical understanding
  - Test the effect of parameters on saturation distribution
    - Heterogeneity
    - Capillary pressure
    - Gravity

Outline

- Experiment with Random Heterogeneity
  - Replicate a simple case
  - How do we simulate core flooding experiments?
  - New method for calculating sub-core scale permeability

- Experiment with Structured Heterogeneity
  - What is the influence of structured heterogeneity?
  - When is this type of heterogeneity important?

Experimental Setup

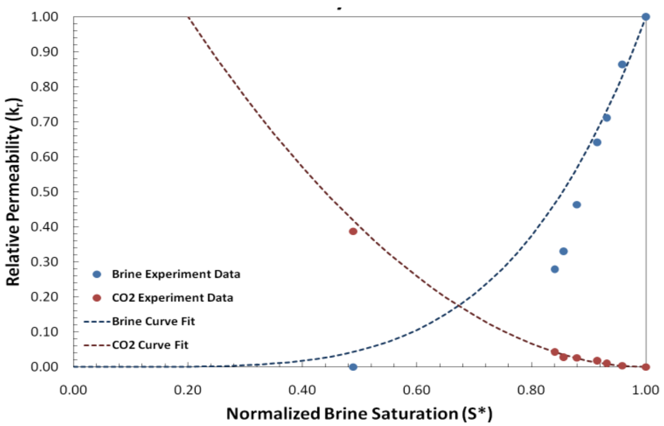


1 – Simulating Experiments

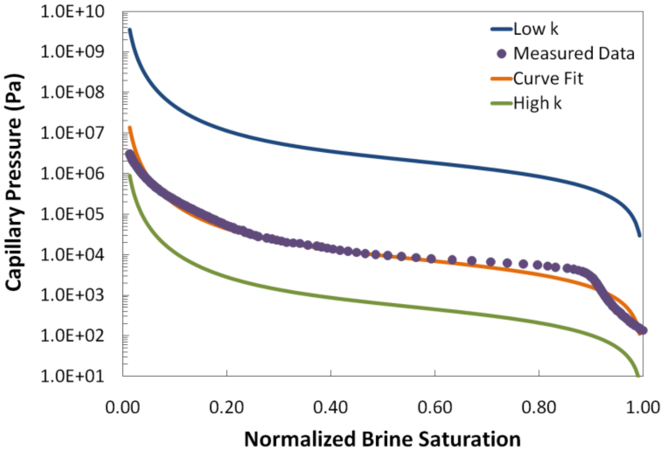
Measured data inputs and calculated inputs

Simulation Input

Relative Permeability



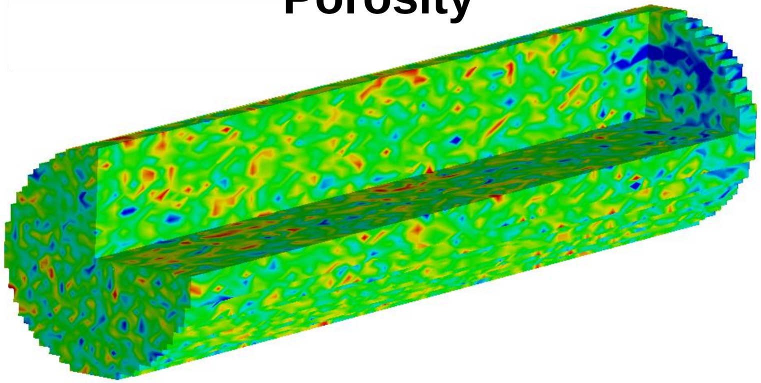
Capillary Pressure



Core-Average

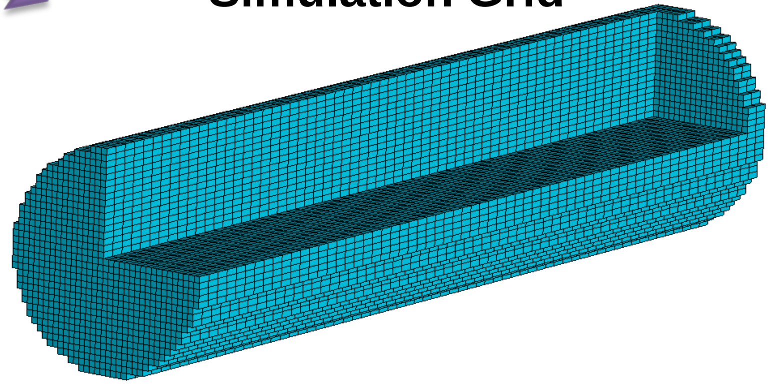
Unique Curves

Porosity



Unique Values

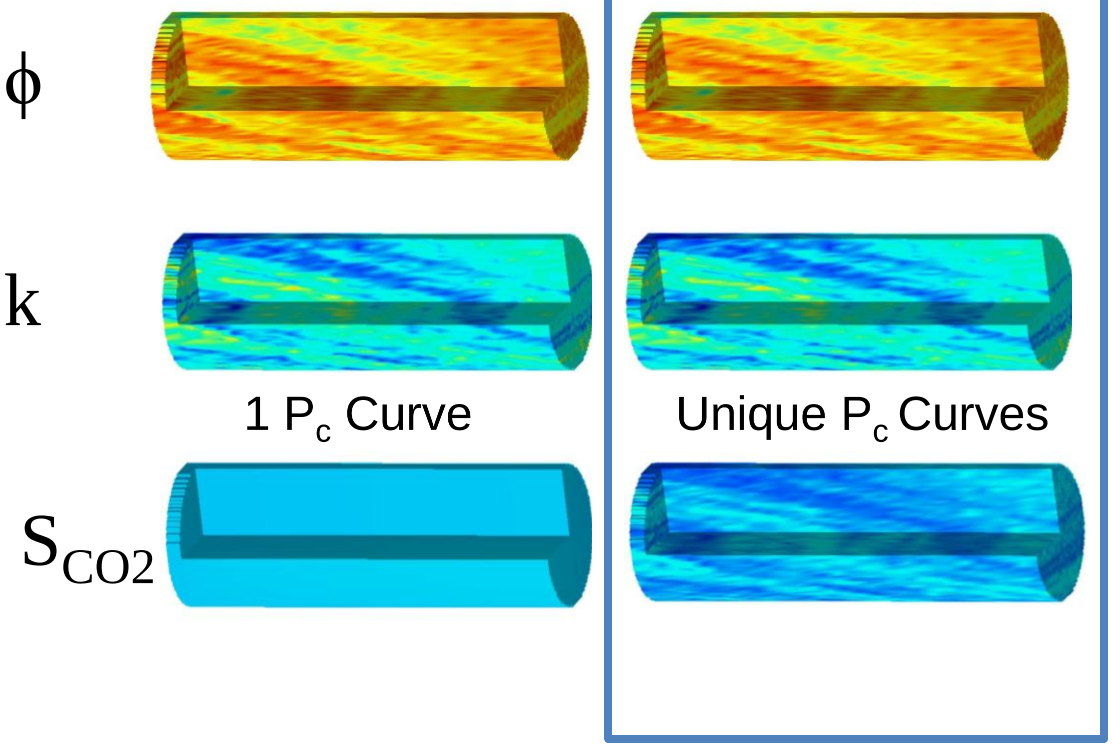
Simulation Grid



Aside – Why Scaled P_c?

Conventional Simulations

Variable Pc Curves are absolutely required to replicate the measured spatial variation in saturation



Procedure:

1. Measure P_c
2. Determine A,B, λ_1,λ_2

$$J(S_{w,i}) = A\left(\frac{1}{S_{*,i}^{\lambda_1}} - 1\right) + B\left(1 - S_{*,i}^{\lambda_2}\right)^{1/\lambda_2}$$

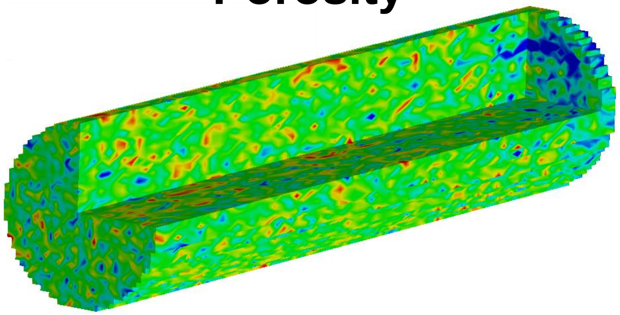
3. Scale J-Function to all grid blocks ϕ_i, k_i

$$P_c = \sigma \cos\theta \sqrt{\frac{\phi}{k}} J(S_w)$$

How to Calculate Permeability?

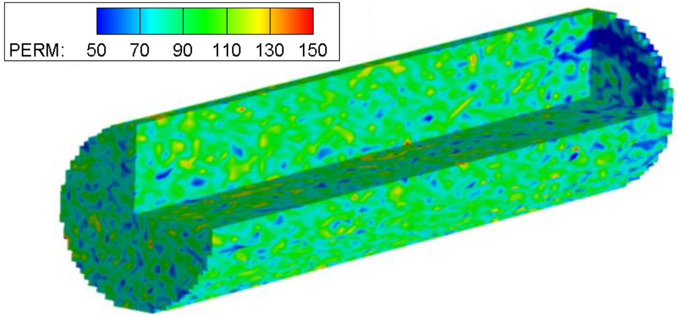
Porosity Method

Porosity



$$k_i = c_o \frac{\phi_i^3}{(1-\phi_i)^2}$$

Permeability



Cap. Pressure Method

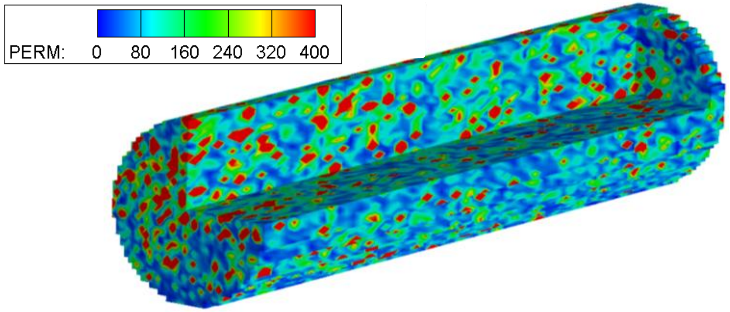
Porosity

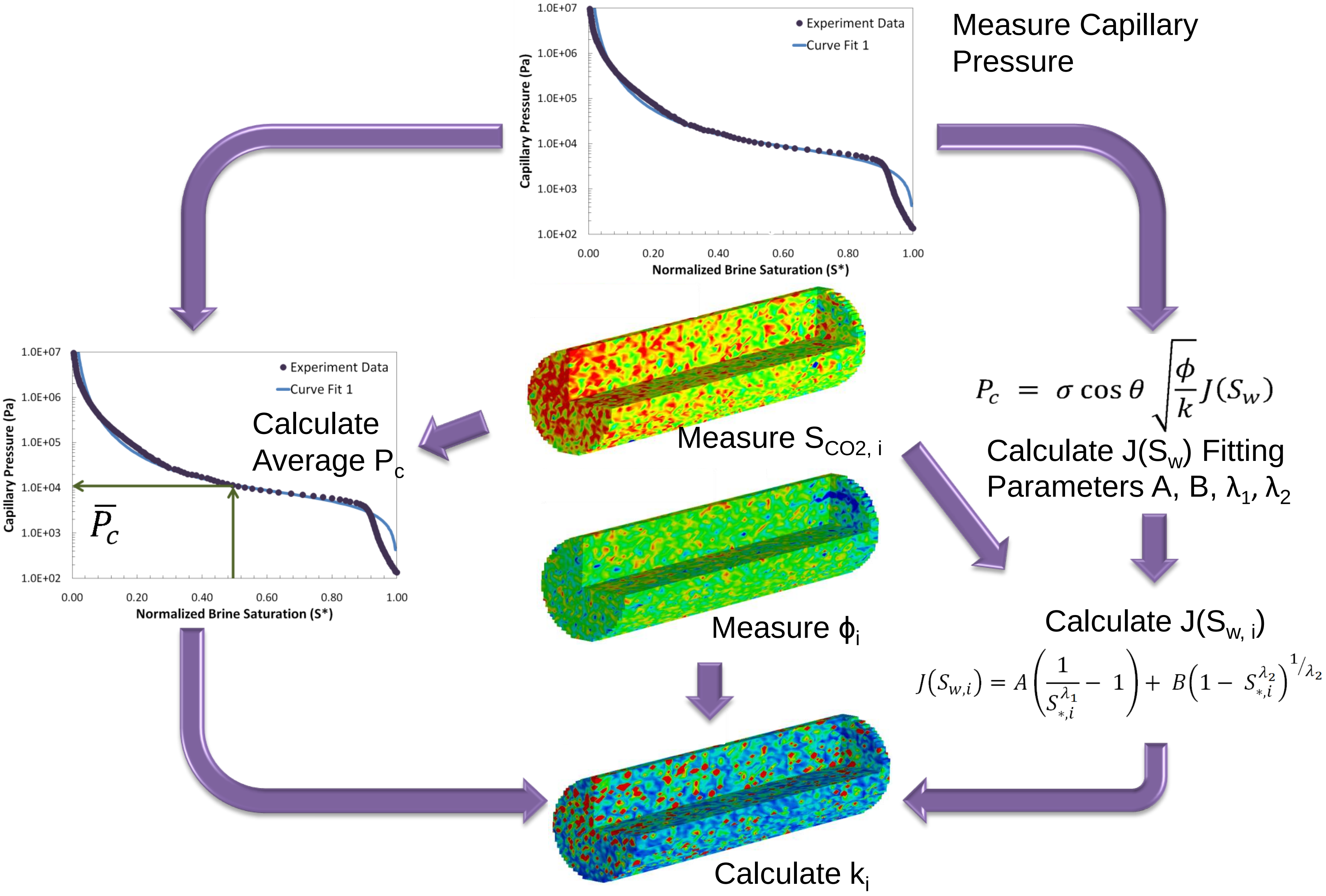
Saturation

Capillary Pressure

$$k_i = c_o \frac{1}{\overline{P}_c^2} \phi_i \left[J\left(S_{w,i}\right)^2 \right] (\sigma \cos\theta)^2$$

Permeability





Measure Capillary Pressure

Calculate Average P_c

Measure $S_{CO2, i}$

Measure ϕ_i

$$P_c = \sigma \cos\theta \sqrt{\frac{\phi}{k}} J(S_w)$$

Calculate $J(S_w)$ Fitting Parameters A, B, λ_1, λ_2

Calculate $J(S_{w,\,i})$

$$J(S_{w,i}) = A\left(\frac{1}{S_{*,i}^{\lambda_1}} - 1\right) + B\left(1 - S_{*,i}^{\lambda_2}\right)^{1/\lambda_2}$$

Calculate k_i

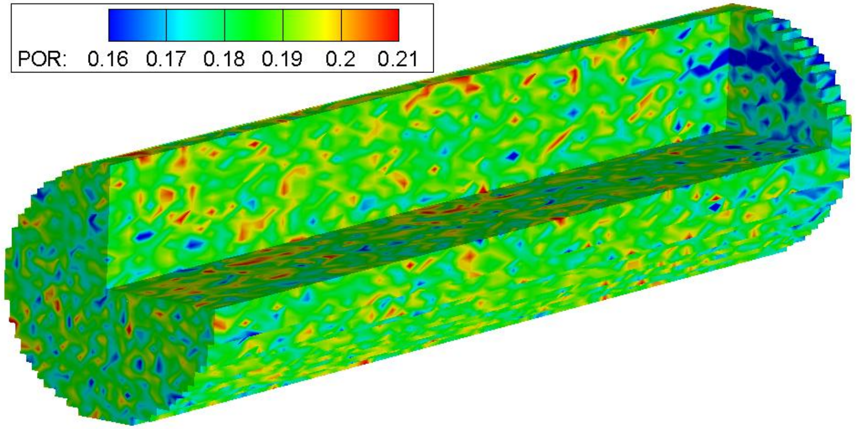
$$k_i = c_o \frac{1}{\overline{P}_c^{\,2}} \phi_i \left[J(S_{w,i})^2\right] (\sigma \cos\theta)^2$$

2 – Random Heterogeneity

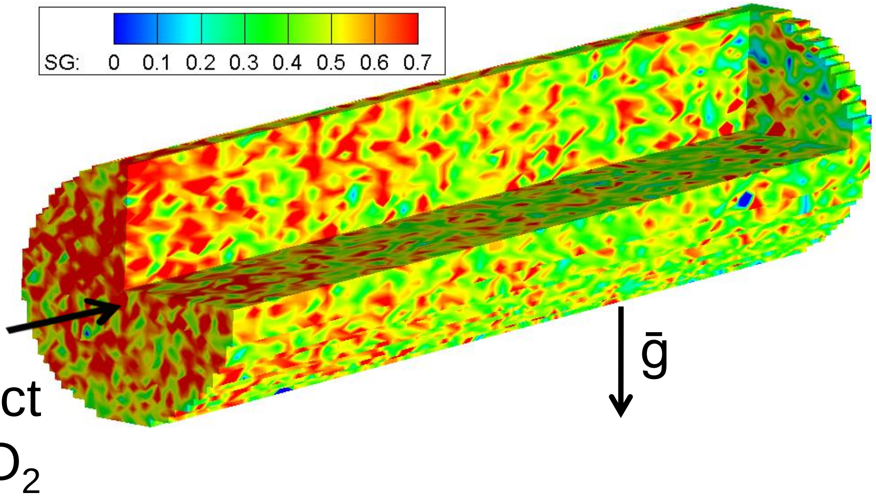
Simple Berea core with a random distribution of minor heterogeneity

Observations – Random Heterogeneity

Porosity

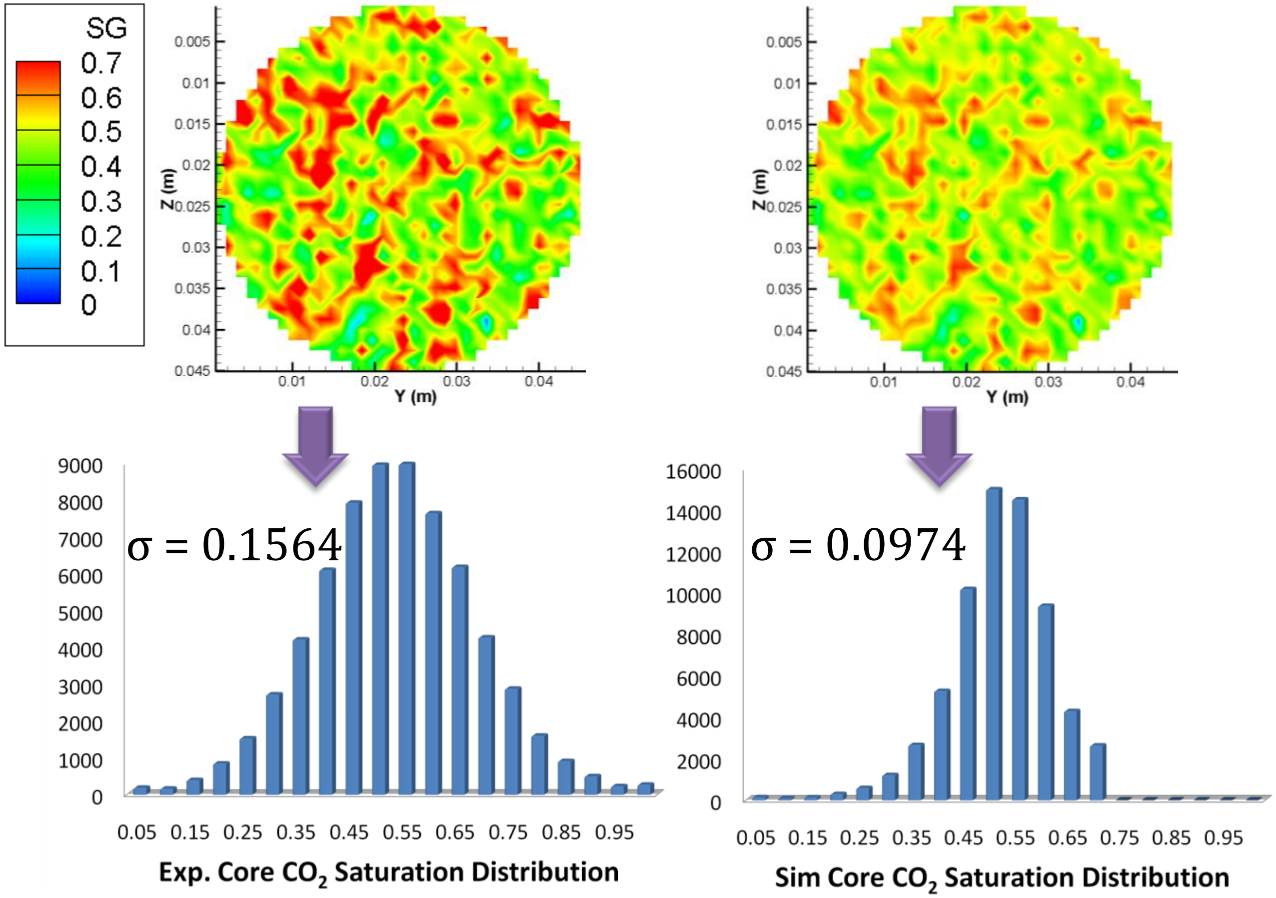


Steady State S_{CO2} at 100% CO_2 Injection



Experimental Conditions		
T = 50°C	Image Grid = 3x1.27x1.27 (mm)	k_{ave} = 85 md
P = 12.41 MPa	Core Length = 20.2 cm	ϕ_{ave} = 18.5 %
Brine = 6500 ppm NaCl	Core Radius = 5.08 cm	q = 3 ml/min

P_c Method Saturation Results



Experiment

P_c Result (12)

σ = 0.1564

σ = 0.0974

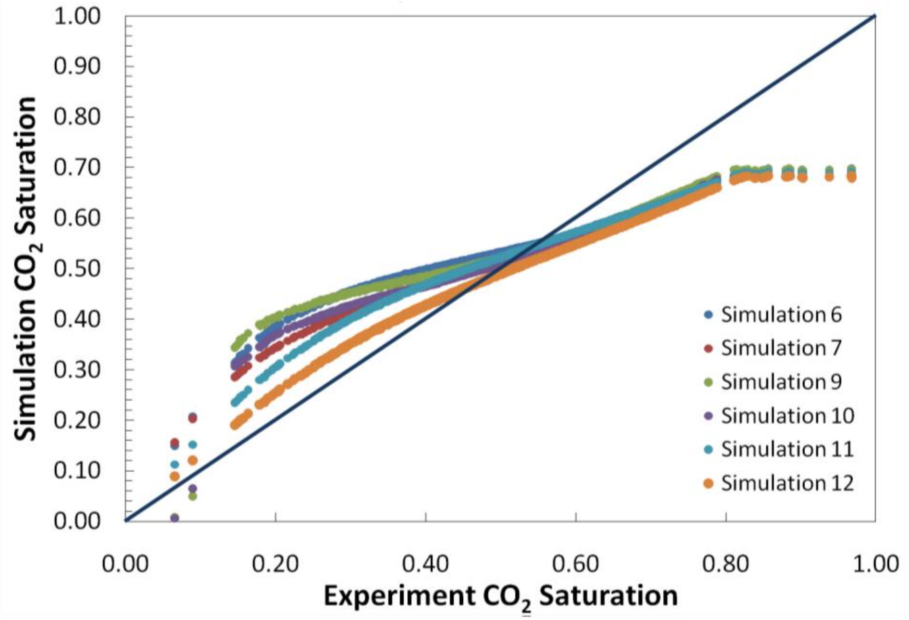
P_c Method Results

Conclusions:

- Clear correlation between experimental measurement and numerical prediction
- Statistically significant match of both core and sub-core scale experimental measurements

Simulation	Sub-Core CO_2 Saturation R^2	Core ΔP Error (%)	Core S_{CO2} Error (%)
6	0.620	-8.87	6.03
7	0.744	-6.37	2.73
9	0.664	-8.47	5.27
10	0.731	-5.76	2.43
11	0.779	-7.08	2.68
12	0.805	0.03	-3.21

Saturation Comparison for Slice 33*



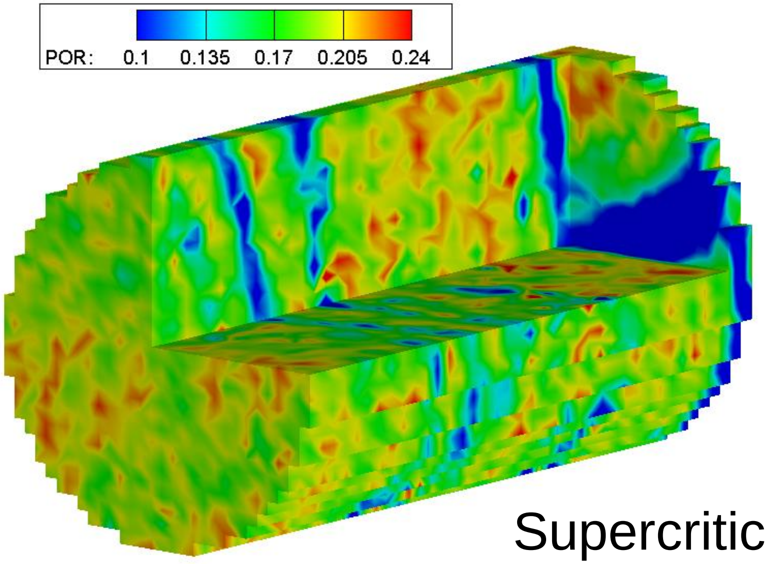
* Difference in simulations is just J-function fitting parameters A, B, λ_1, λ_2

2 – Structured Heterogeneity

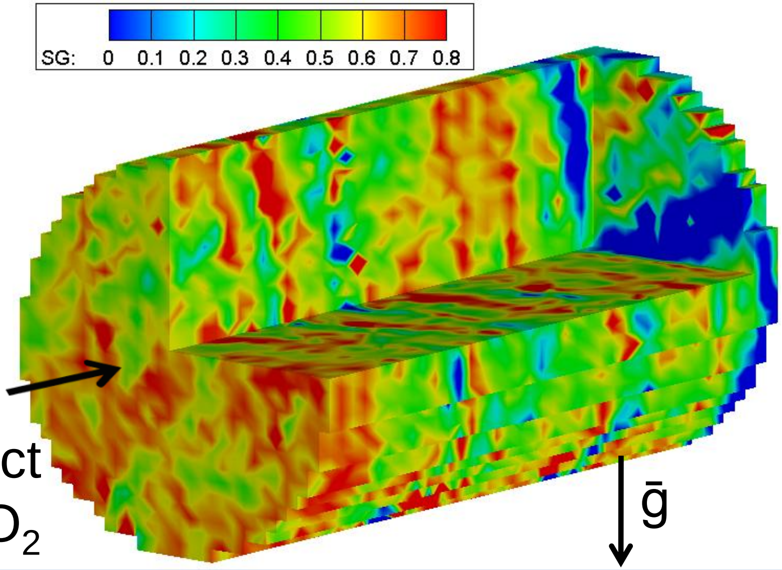
Complex core from Australian Otway Basin Pilot Project Waare C Reservoir

Observations – Random Heterogeneity

Porosity



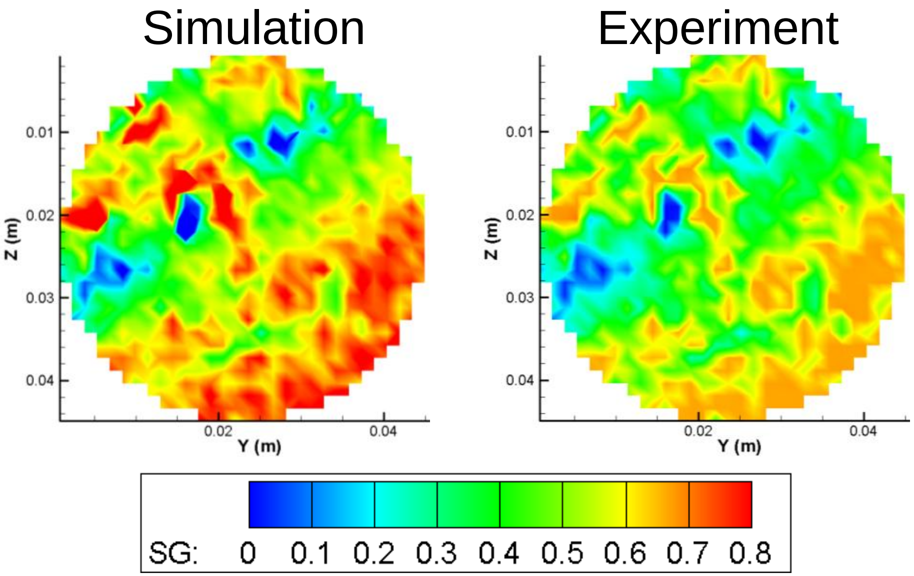
Steady State S_{CO2} at 100% CO_2 Injection



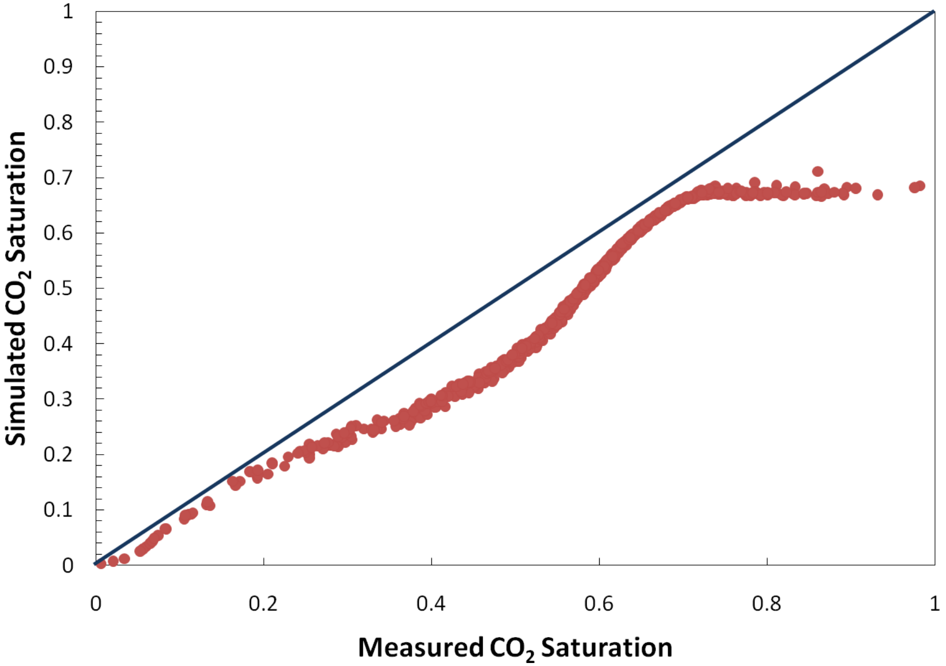
Experimental Conditions		
T = 63°C	Image Grid = 2x1.54x1.54 (mm)	k_{ave} = 63 md
P = 12.41 MPa	Core Length = 8.3 cm	ϕ_{ave} = 18.04 %
Brine = 6500 ppm NaCl	Core Radius = 5.08 cm	q = 3 ml/min

Results with Strong Heterogeneity

- Similar trend to homogeneous Berea
- Good qualitative and quantitative match


Simulation

Experiment



Conclusions

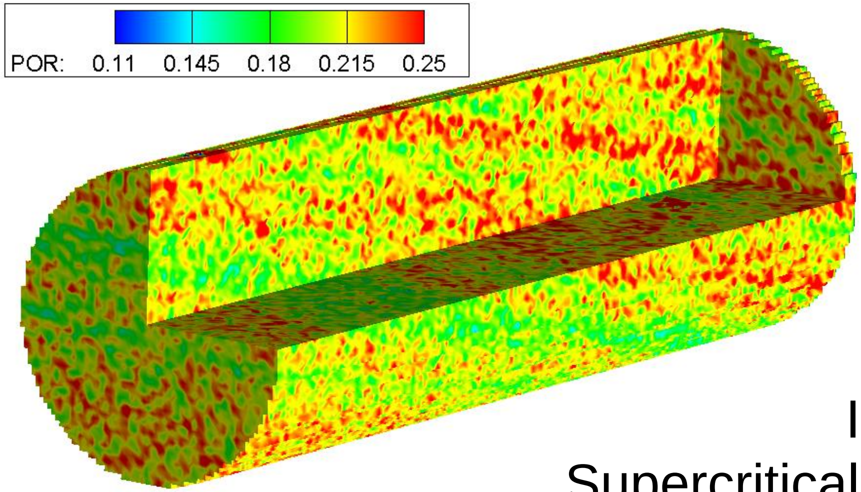
- Porosity alone is not enough information to derive sub-core scale permeability
- Capillary pressure based method gives an excellent quantitative match to experimental result
- Method works for homogeneous and heterogeneous cores
- Leverett scaling law is important for accurately representing variable capillary pressure curves

3 – Average Saturation Effect

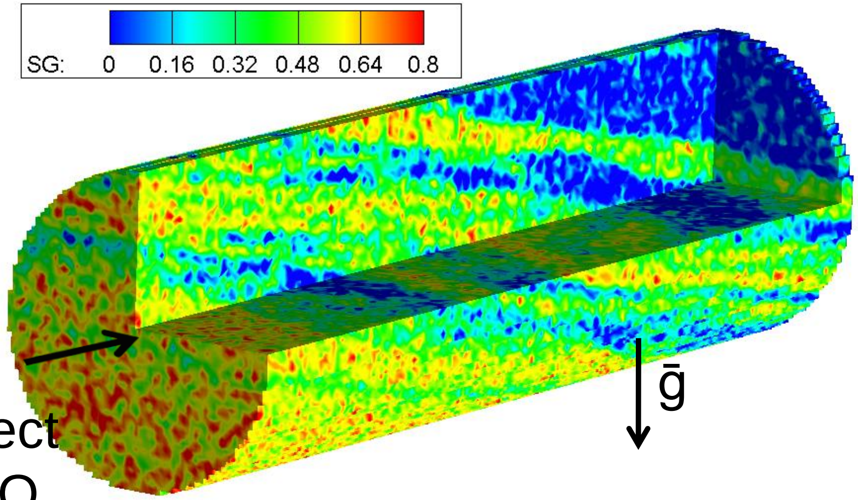
When does strong structured heterogeneity influence average CO_2 saturation?

Observations – Structured Heterogeneity

Porosity



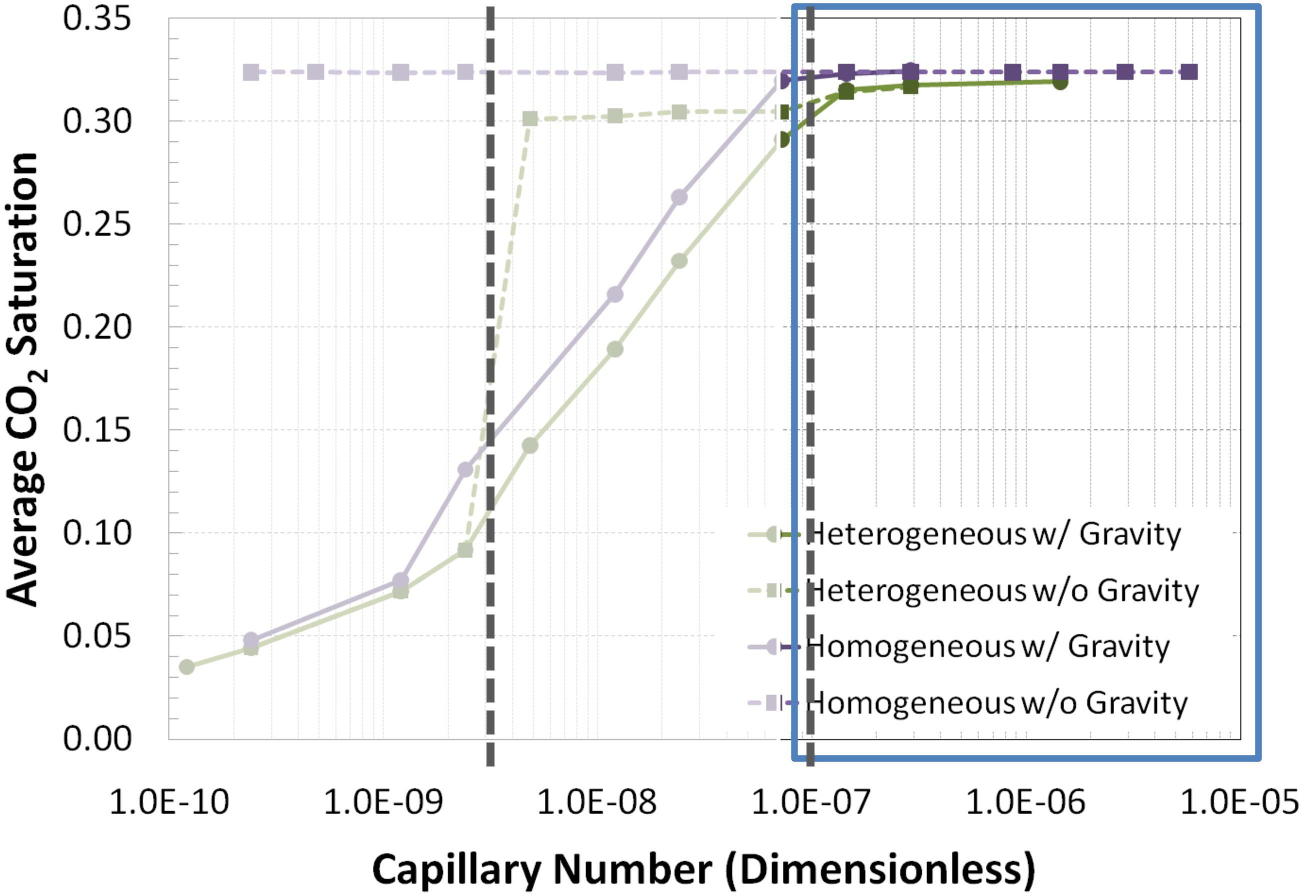
Steady State S_{CO2} at 95% CO_2 Injection



Inject Supercritical CO_2

Experimental Conditions		
T = 50°C	Image Grid = 1.5x0.76x0.76 (mm)	k_{ave} = 430 md
P = 11.72 Mpa	Core Length = 15.24 cm	ϕ_{ave} = 20.3 %
Brine = 10000 ppm NaCl	Core Radius = 5.08 cm	q = 3.6 ml/min

Viscous Flow Regime



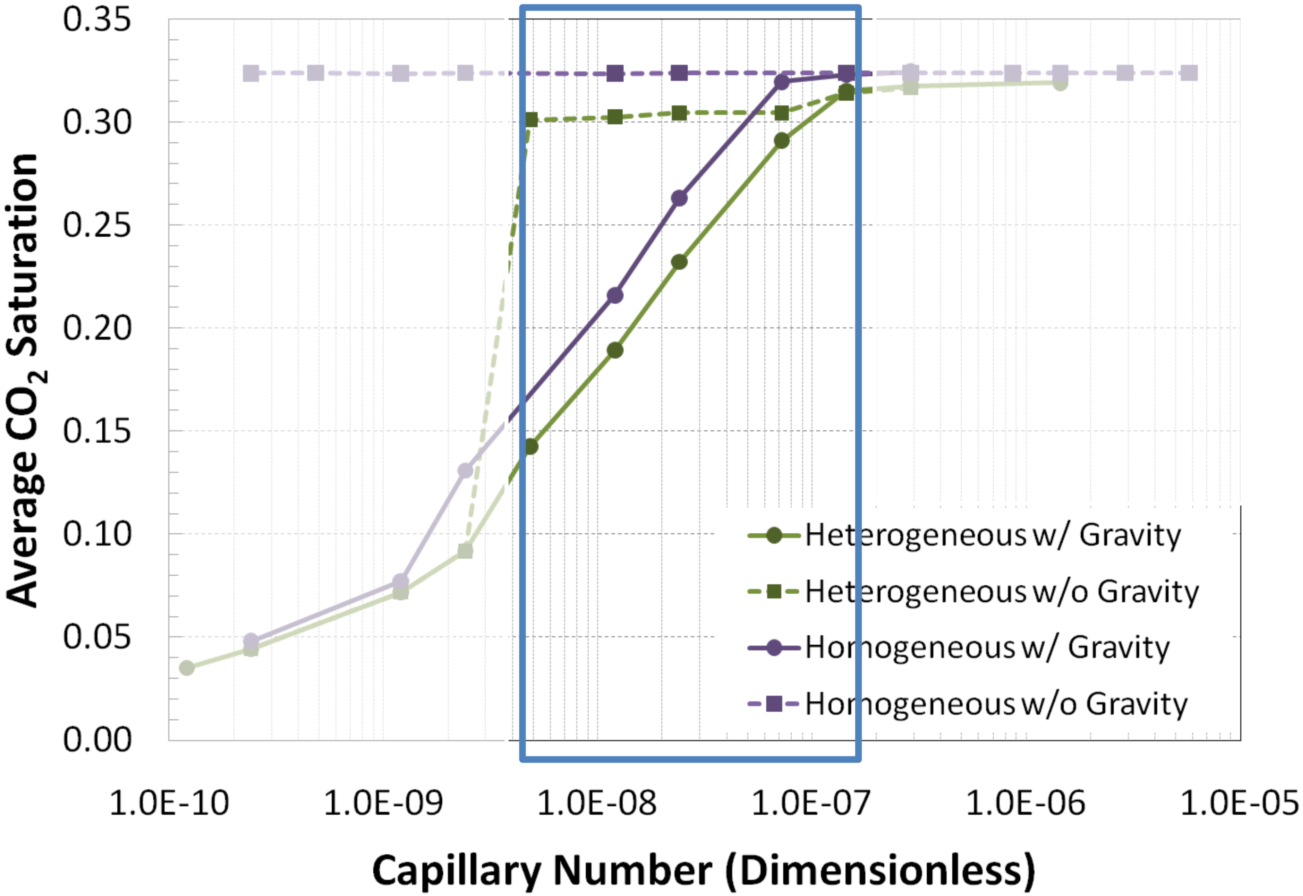
- Viscous flow dominated regime
- Average saturation independent of heterogeneity and density differences
- Predicted by Buckley-Leverett theory

q > 0.6 ml/min

f_{CO2} = 0.95

$$N_{cap} = \frac{u_t \mu_w}{\sigma}$$

Gravity Flow Regime

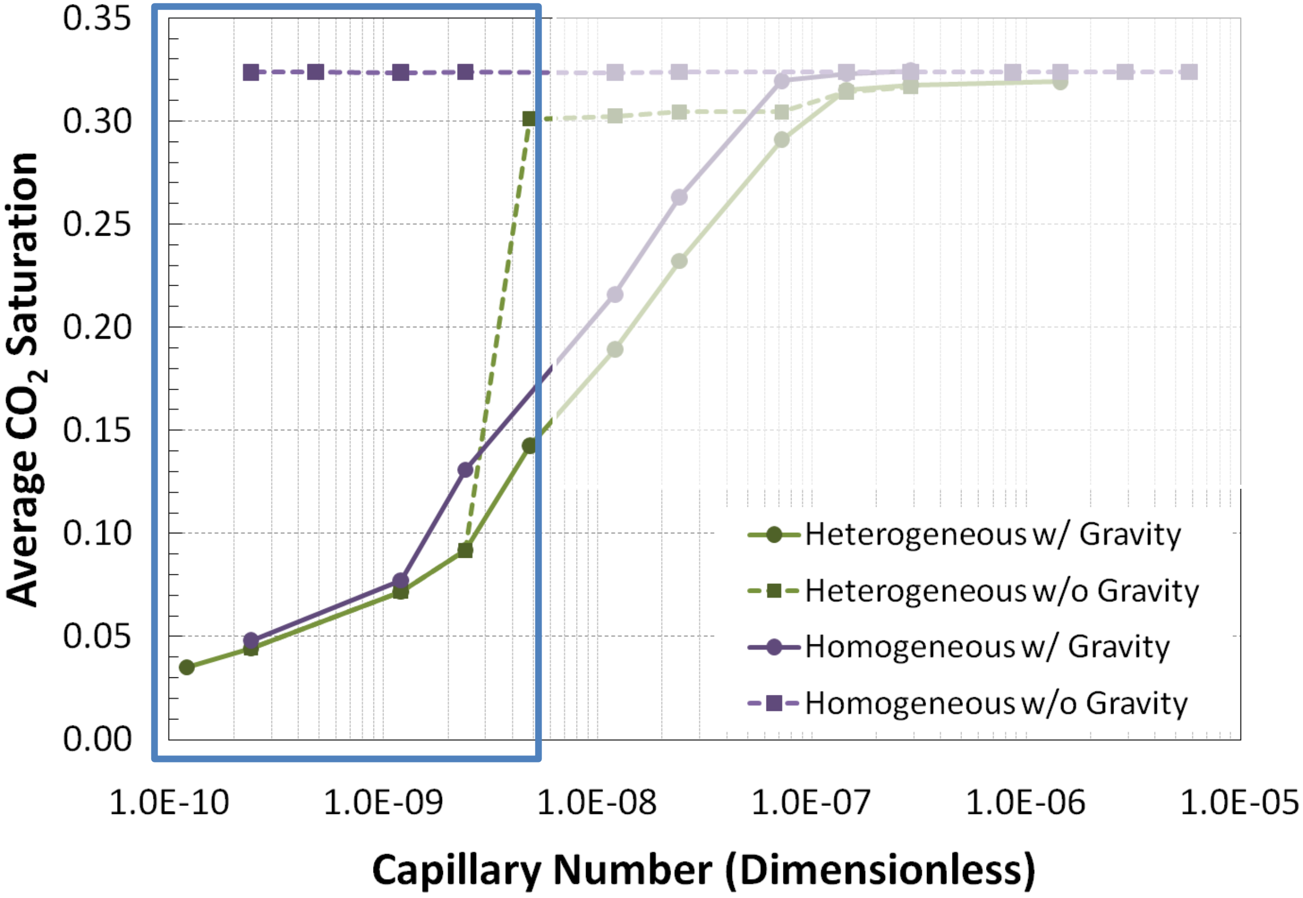


- Buoyancy difference causes a saturation rate dependency
- Average saturation decreases as flow rate decreases
- Heterogeneity has relatively small effect

q = 0.05-0.6 ml/min
f_{CO2} = 0.95

$$N_{cap} = \frac{u_t \mu_w}{\sigma}$$

Capillary Flow Regime



- Capillary forces are the dominant mechanism at low flow rates – leading edge of the plume
- Saturation is same in heterogeneous rocks with or without gravity

$q < 0.05$ ml/min
$f_{CO2} = 0.95$

$$N_{cap} = \frac{u_t \mu_w}{\sigma}$$

Conclusions

- Saturation is dependent on flow rate, but for different reasons
- Different flow regimes have different mechanisms which control CO_2 saturation
- Presence of heterogeneity decreases the average CO_2 saturation in all flow regimes
- Heterogeneity has strongest influence in capillary dominated regime