GCEP Global Climate & Energy Project

Supri-C Affiliates Meeting
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Modeling Sub-Core Scale Permeability Distributions in Sandstone Cores

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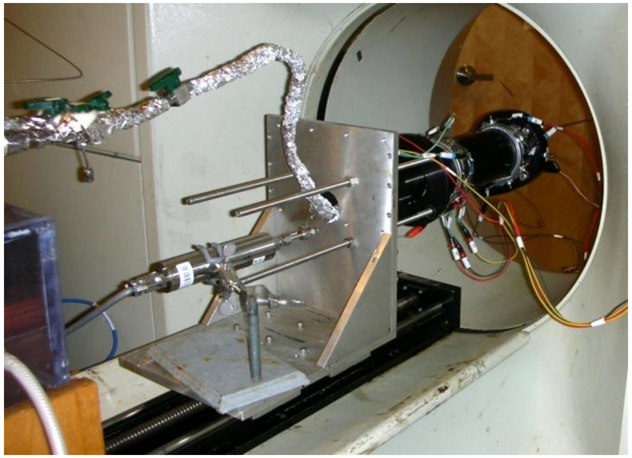
Science and technology for a low GHG emission world.

Motivation

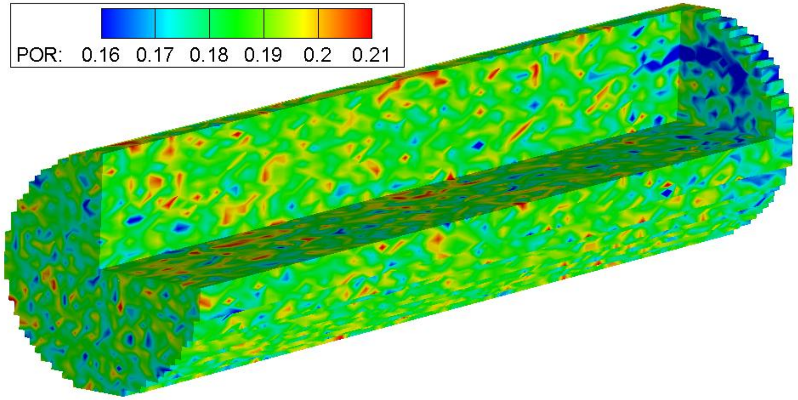
- What are we doing?
  - Conduct CO_2-brine core flooding experiments at reservoir conditions
  - Conduct simulations of CO_2-brine core flooding experiments
  - Study the effects of relative permeability, capillary pressure and heterogeneity on the distribution of CO_2 at the sub-core scale
- Why are we doing it?
  - Experimental results provides saturation distribution in actual rock cores
  - Investigate sensitivity of saturation distributions to rock and fluid properties
  - Enable development of methods to accurately predict CO_2 distribution

Recap - Experiments

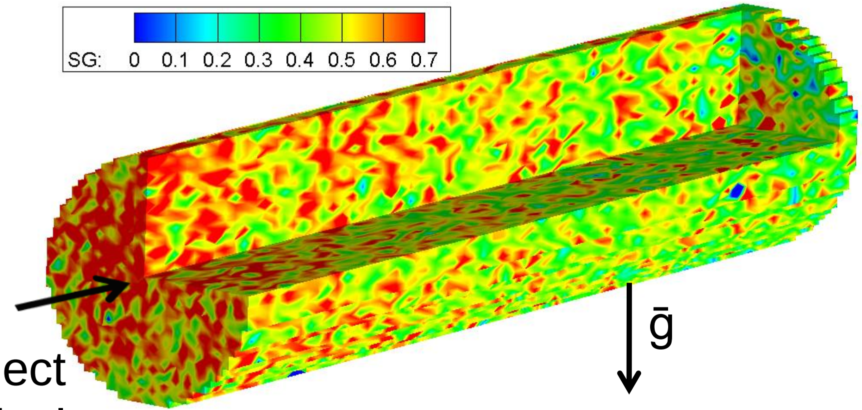
- Experiments
- Simulation Input
- Permeability
- Simulation Results



Porosity



Steady State Saturation at 100% CO_2 Injection

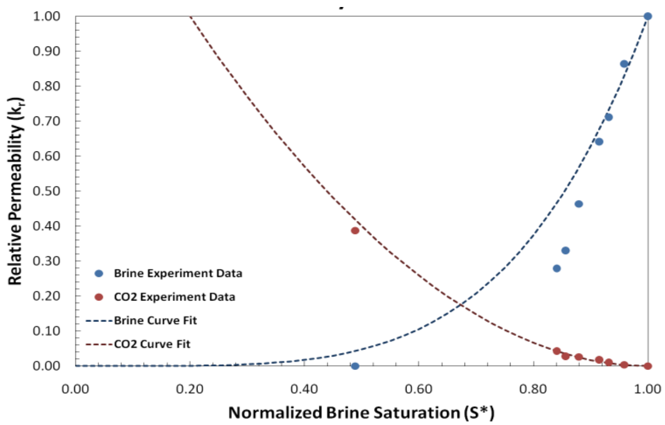


Inject Supercritical CO_2

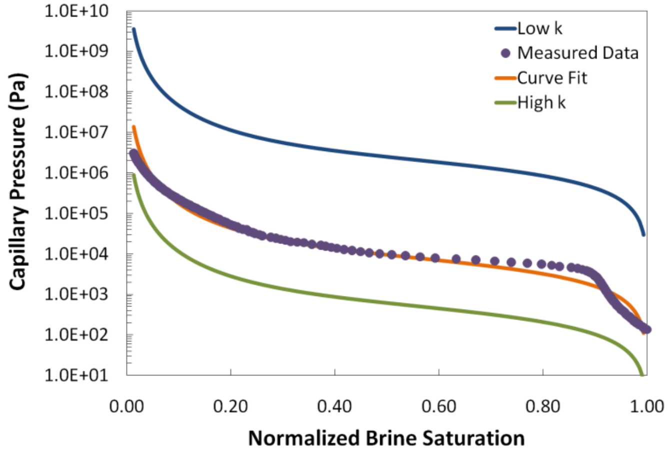
Recap - Simulations

- Experiments
- Simulation Input
- Permeability
- Simulation Results

Relative Permeability



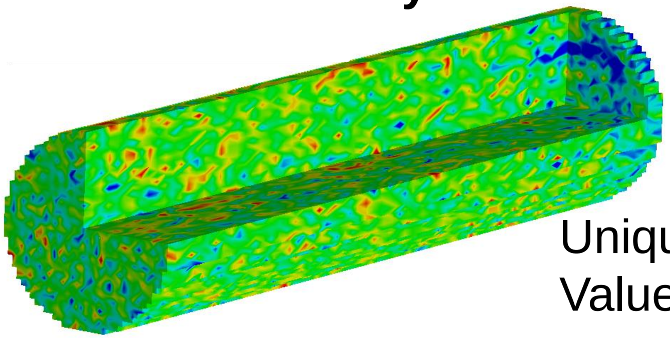
Capillary Pressure



Core-Average

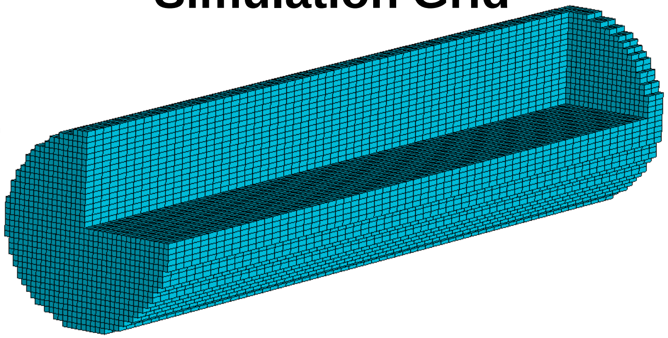
Unique Curves

Porosity



Unique Values

Simulation Grid

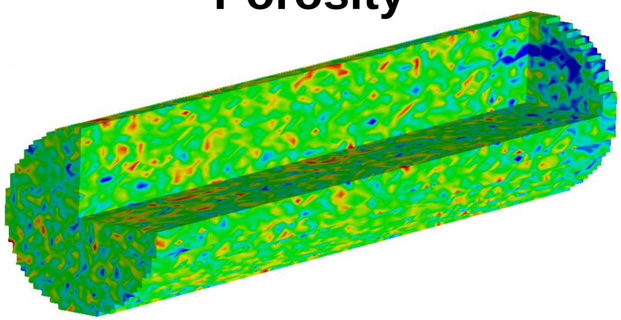


Recap - Permeability

- Experiments
- Simulation Input
- Permeability
- Simulation Results

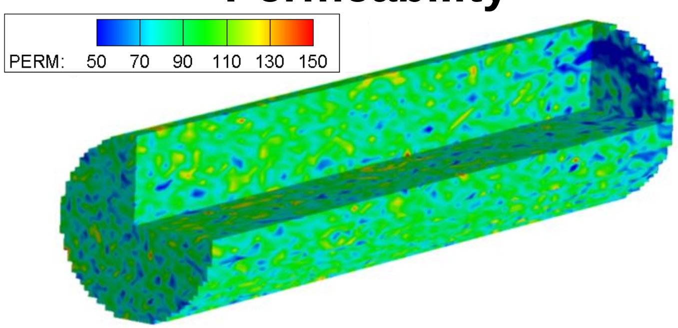
Porosity Method

Porosity



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

Permeability



Equations Tested

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

2 $$k_i = c_o \frac{\phi_i^{1.42}}{(1-\phi_i)^2}$$

3 $$k_i = c_o \frac{\phi_i^5}{(1-\phi_i)^2}$$

4 $$k_i = c_o \frac{(\phi_i-\phi_c)^3}{(1-\phi_i+\phi_c)^2}$$

5 $$k_i = c_o\left(6.2\phi_i + 1493\phi_i^2 + 58(10\phi_i)^{10}\right)$$

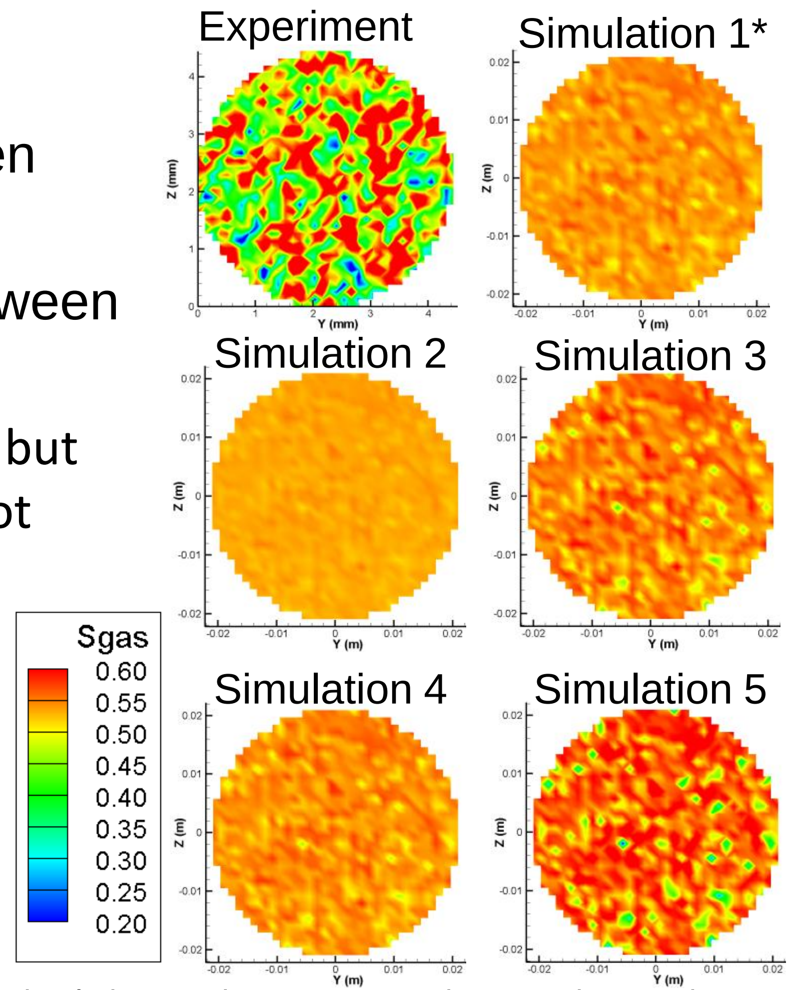
*Krause, M.H., Perrin, J.-C., & Benson, S.M. 2009. Modeling Permeability Distributions in a Sandstone Core for History Matching Coreflood Experiments. SPE #126340

Recap – Porosity-Based Results

Conclusions:

- No qualitative match between simulations and experiment
- No statistical correlation between simulations and experiment
- Core-average match is good, but porosity-based methods are not accurate at sub-core scale

Simulation	Sub-Core CO_2 Saturation R^2	Core ΔP Error (%)	Core S_{CO2} Error (%)
1	-0.004	-3.50	4.59
2	0.003	-1.77	3.61
3	-0.045	-5.91	5.62
4	-0.022	-4.28	4.89
5	-0.133	-10.21	7.10

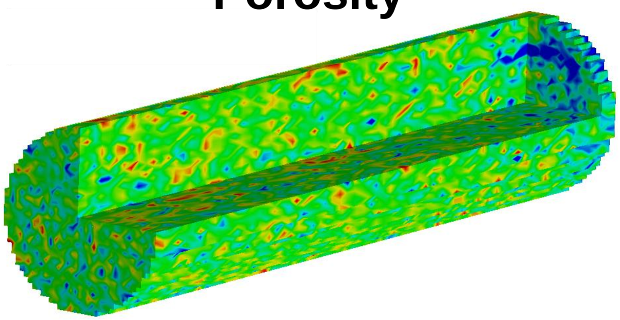


*Simulation numbers correspond to equation numbers

Revisit - Permeability

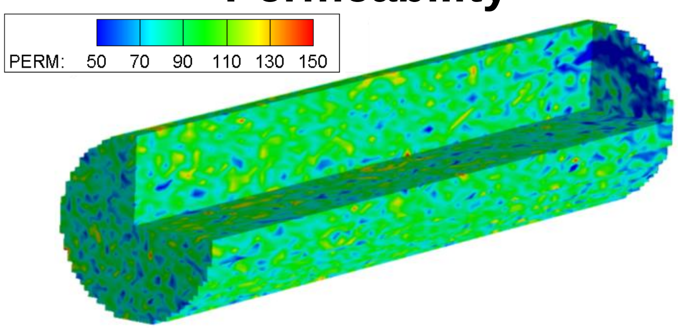
Porosity Method

Porosity



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

Permeability



Cap. Pressure Method

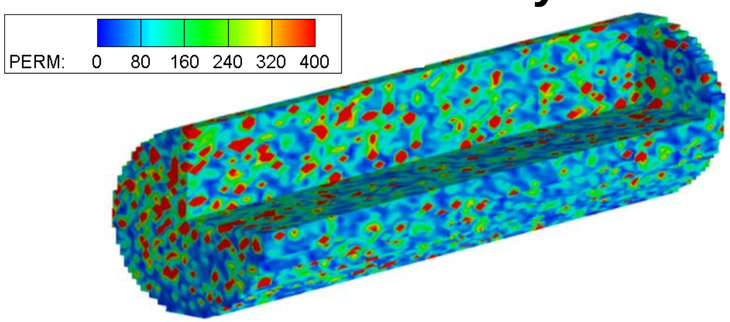
Porosity

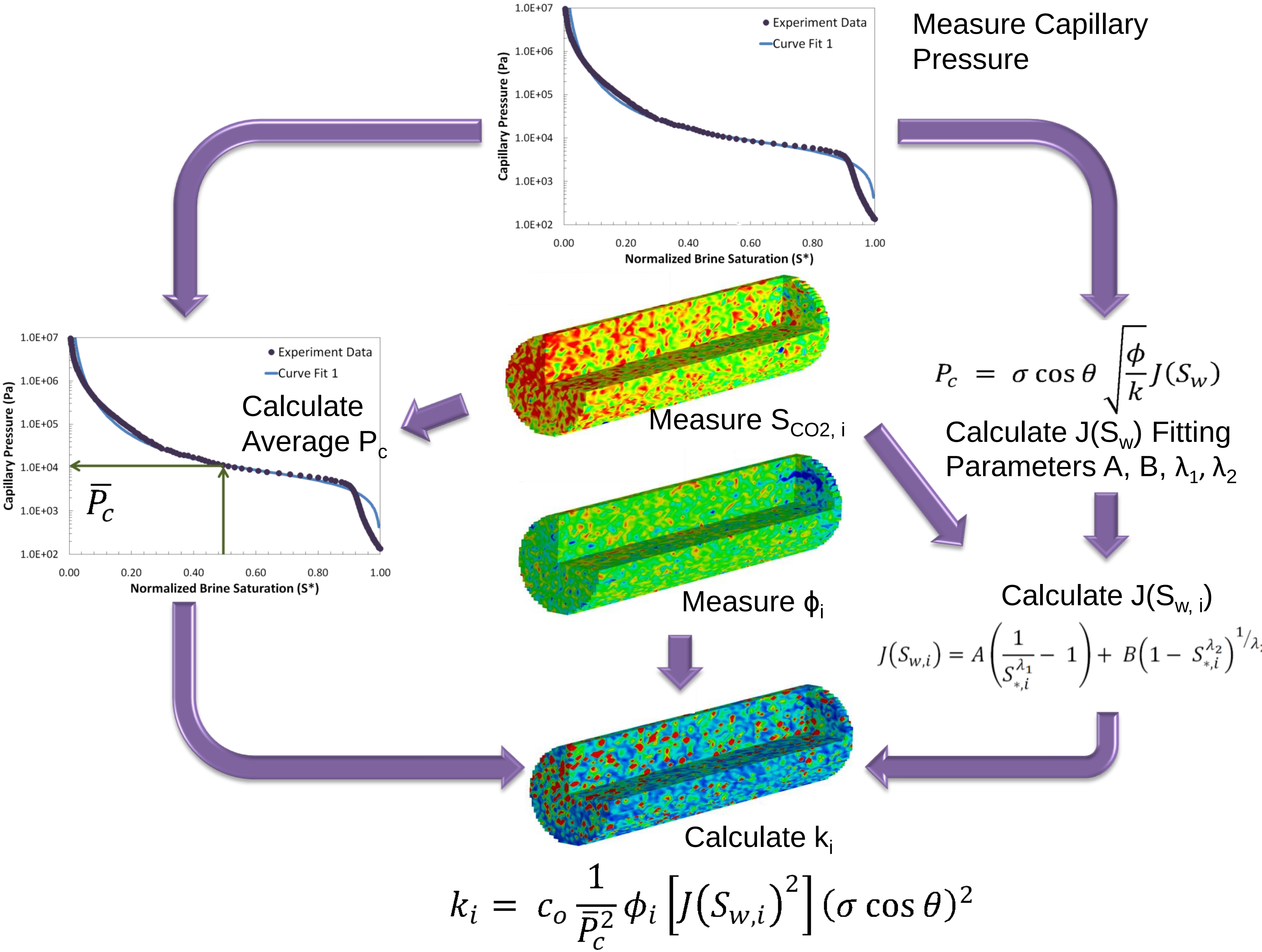
Saturation

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

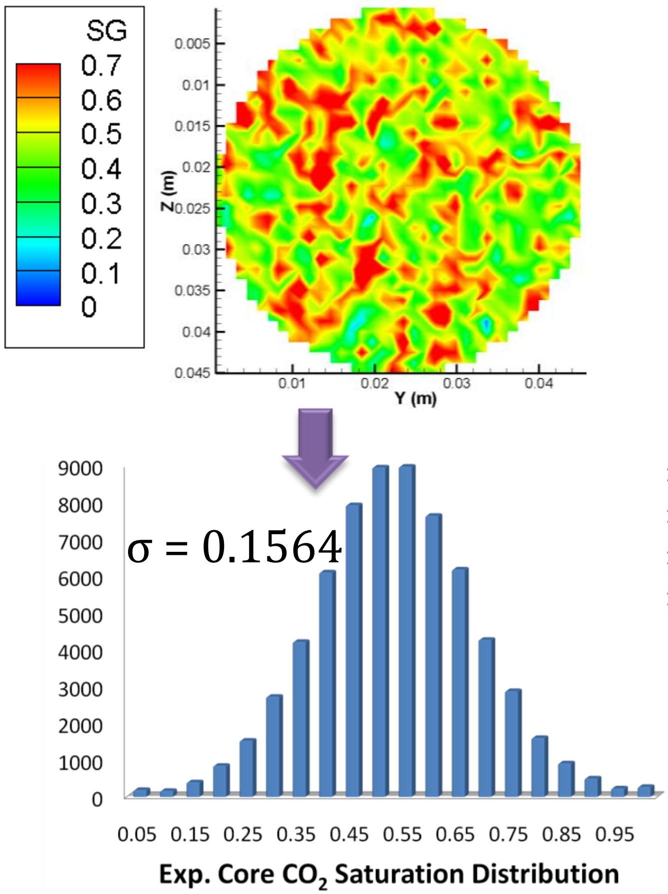




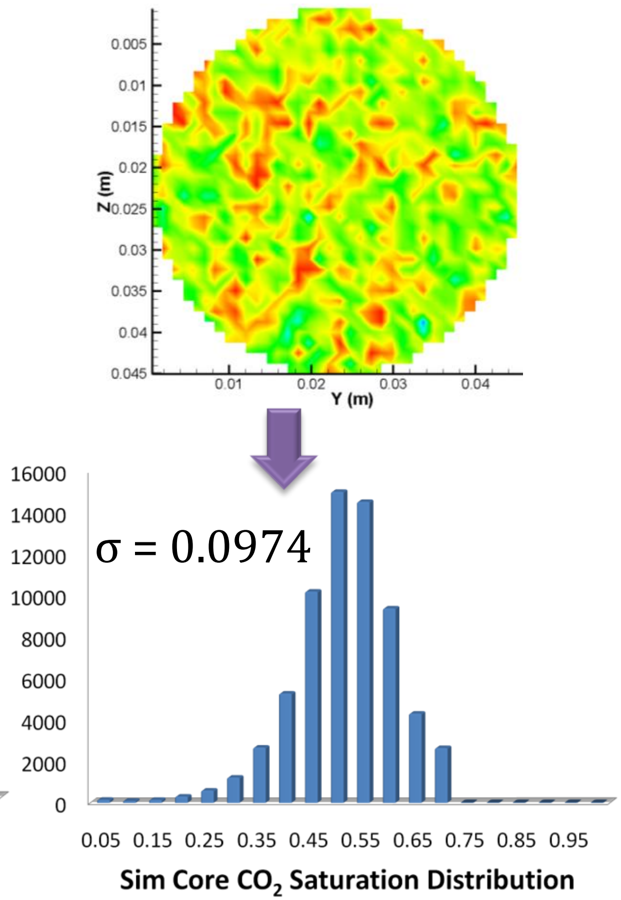
Measure Capillary Pressure
Experiment Data
Curve Fit 1
Capillary Pressure (Pa)
Normalized Brine Saturation (S*)
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
0.00
0.20
0.40
0.60
0.80
1.00
Calculate Average P_c
$\overline{P}_c$
Measure $S_{CO2, i}$
Measure ϕ_i
$P_c = \sigma \cos\theta \sqrt{\frac{\phi}{k}} J(S_w)$
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
$k_i = c_o \frac{1}{\overline{P}_c^2} \phi_i \left[J(S_{w,i})^2\right] (\sigma \cos\theta)^2$

P_c Method Saturation Results

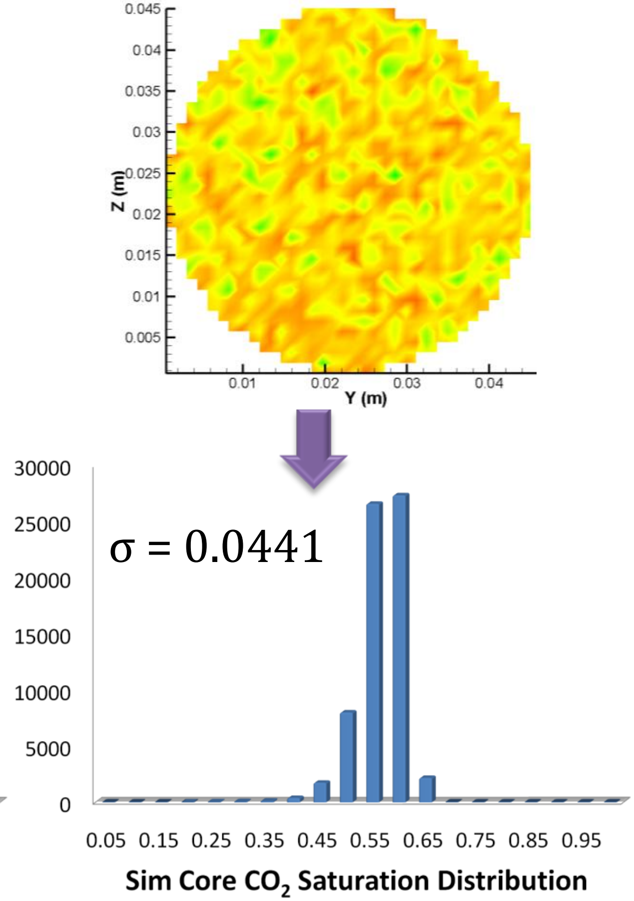
Experiment



P_c Result (12)



"Best" ϕ-Based Result (5)



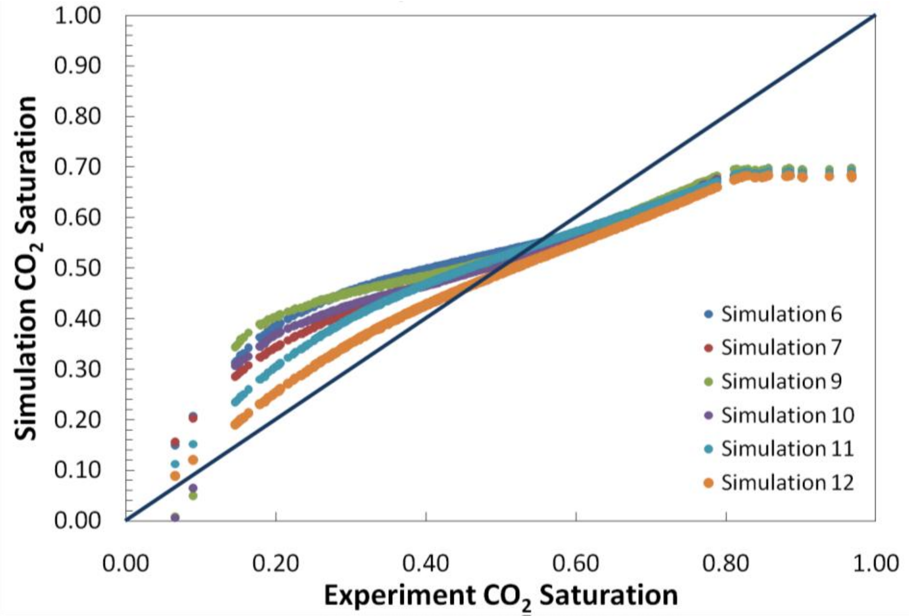
P_c Method Results

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

How Important is Grid Size?

Grid Size Effect – do porosity-based and Pc-based methods produce similar sub-core scale results as the grid coarsens?

Finest Perm Grid Coarsest Perm Grid

P_c-Method Permeability

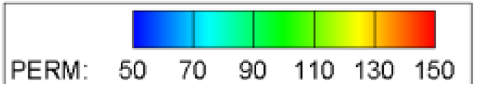
$$k_i = c_o \frac{1}{\overline{P}_c^2} \phi_i \left[J\left(S_{w,i}\right)^2\right] (\sigma \cos\theta)^2$$

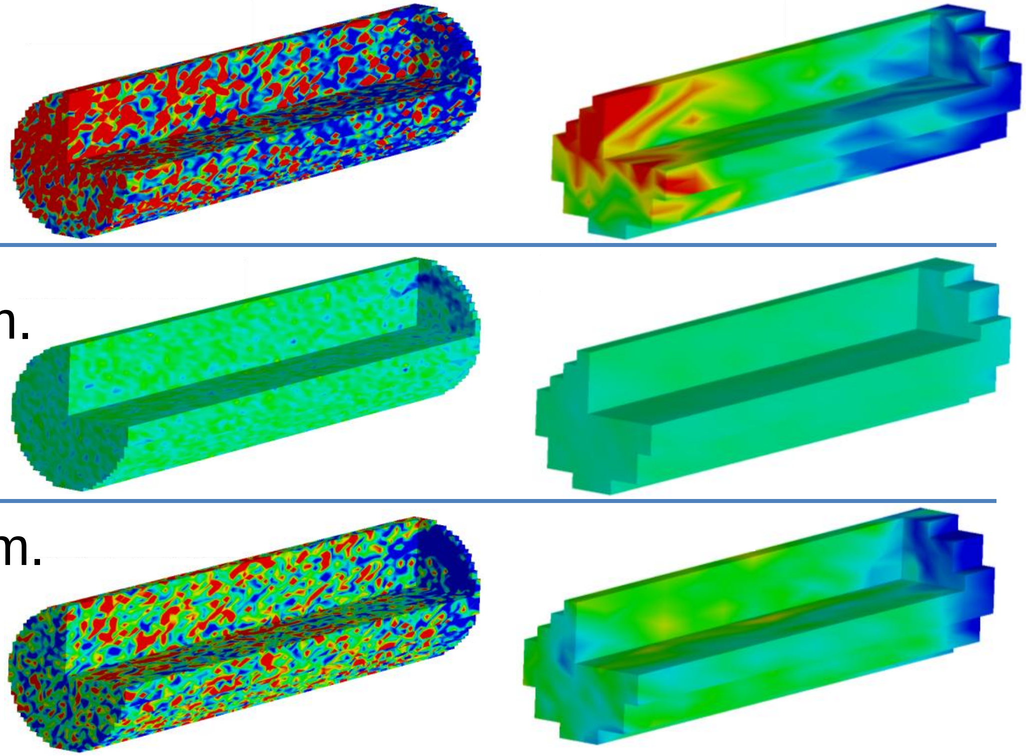
Porosity-Method Low Contrast Perm.

$$k_i = c_o \frac{\phi_i^{1.42}}{(1-\phi_i)^2}$$

Porosity-Method High Contrast Perm.

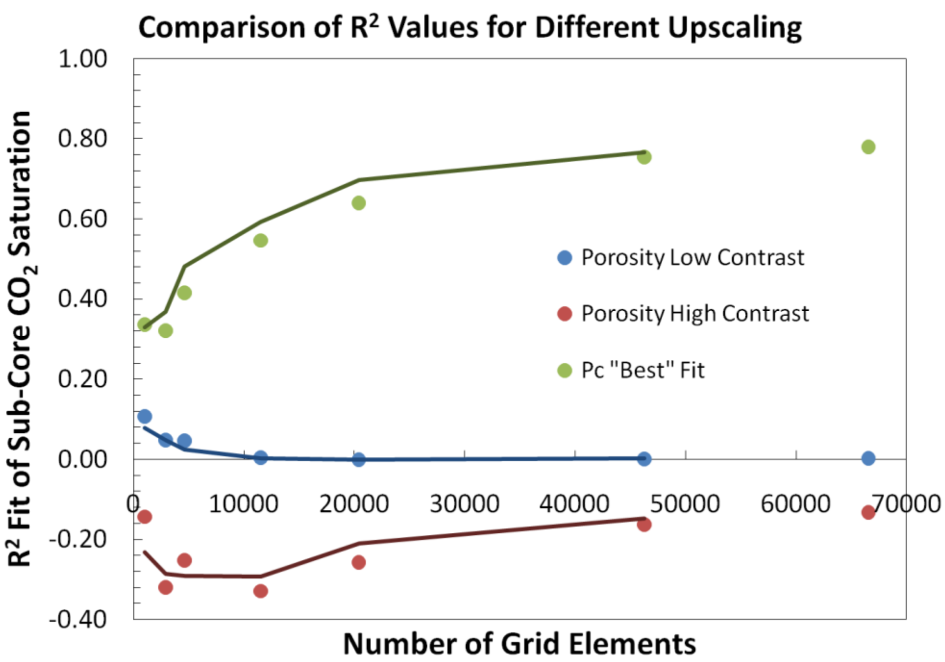
$$k_i = c_o\left(6.2\phi_i + 1493\phi_i^2 + 58(10\phi_i)^{10}\right)$$





Comparison of Grid Size Results

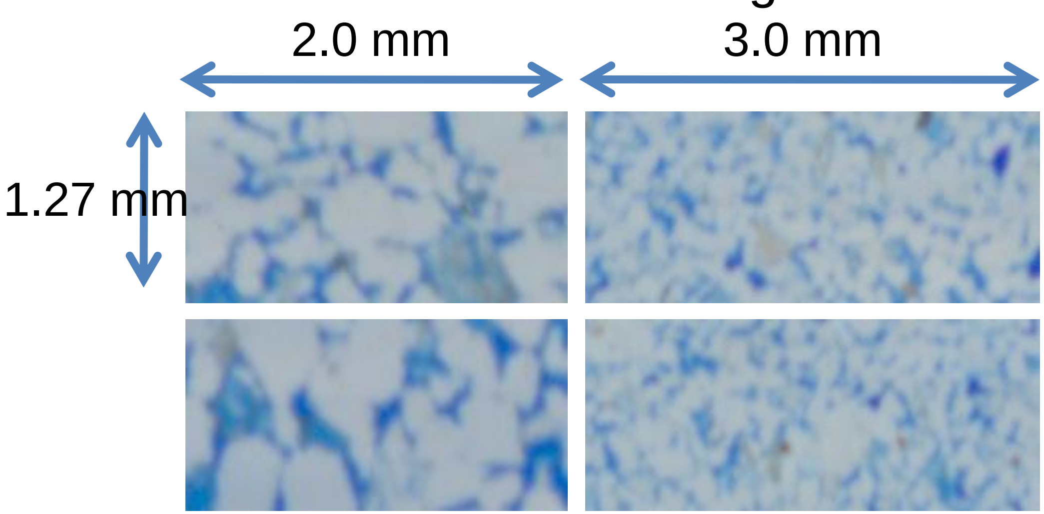
- P_c-method results are most accurate at all grid resolutions
- P_c-method results are most accurate at fine resolution
- Low contrast porosity-method increases in accuracy at low grid resolution
- High contrast porosity-method does not increase in accuracy at low grid resolution



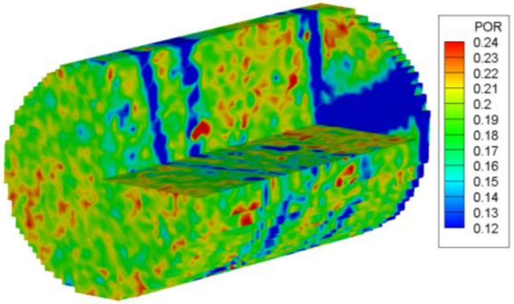
What About More Heterogeneity?

- Otway Basin Pilot Project core
- Very heterogeneous sandstone
- Test the limits of the method and core flooding simulations

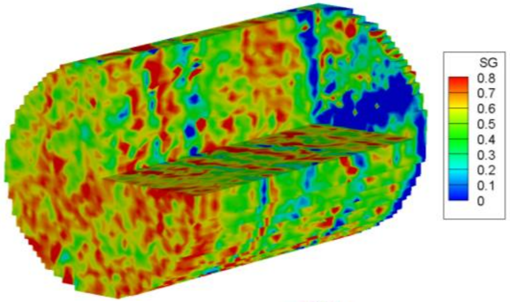
Thin Section Images



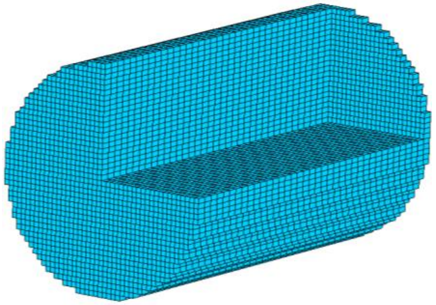
Porosity Image



Sat. at 100% CO_2 Injection

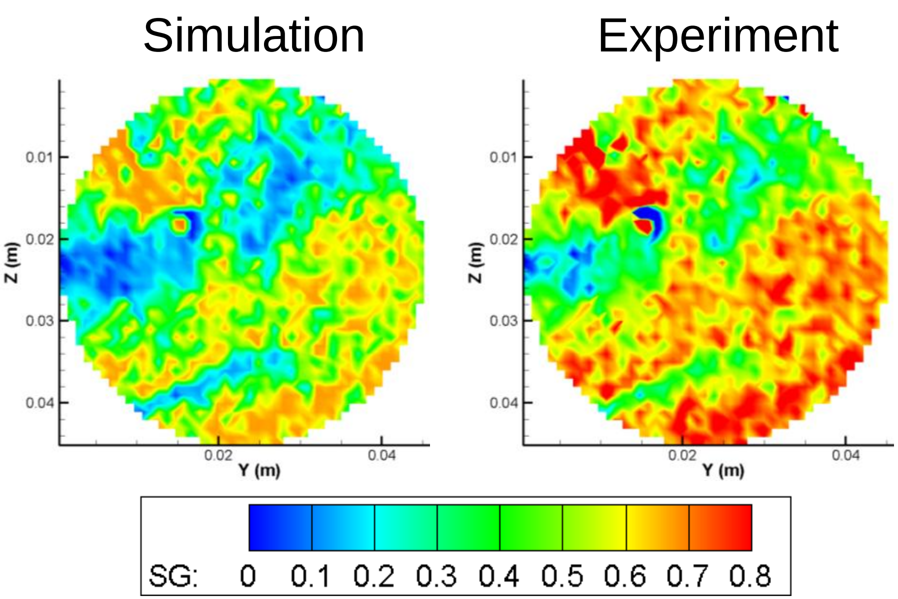


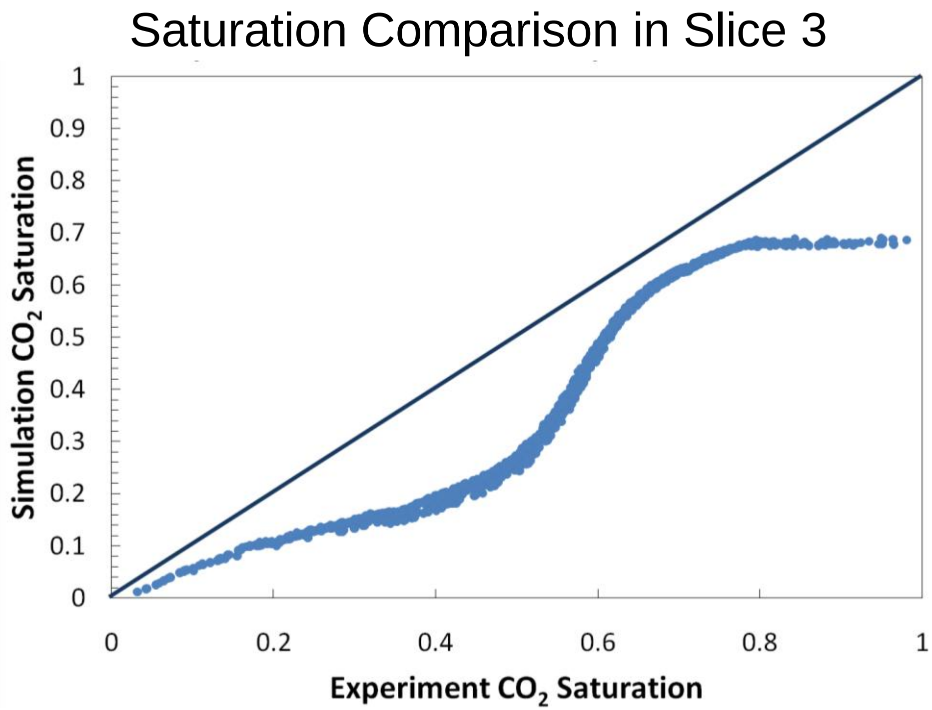
Simulation Grid



What about Heterogeneity?

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





Conclusions & Future Work

- P_c-based permeability methods are more accurate than simple porosity-based methods
- P_c-based permeability distributions have high accuracy across a range of grid resolution
- Porosity-based method results do not approach P_c-based method results as the grid coarsens
- Method is still robust for highly heterogeneous cores
- Improvement at high saturation is still required

Future Work and Questions

- Future Work
  - Introduce variable relative permeability curves
  - Verify our solutions are correct for different flow scenarios
  - Study integration of sub-core and core scale knowledge to reservoir-scale problems

- Acknowledgements
  - Jean-Christophe Perrin for conducting the experiments
  - GCEP for sponsoring the work

Supplemental Data

Property	Homogeneous Berea	Heterogeneous Otway
Pressure	12.41 MPa	12.41 MPa
Temperature	50C	63C
Salinity	6500 ppm NaCl	6500 ppm NaCl
Injection Rate	3 ml/min	3 ml/min
Grid Element Size	1.27mm x 1.27mm x 3mm	1mm x 1mm x 2mm
ϕ_{core}	18.49%	18.04%
Core Average Permeability	85 md	62.3 md
Length	20.2 cm	7.5 cm
Core Diameter	5.08 cm	5.08 cm