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Error Analysis of Sub-Core Scale Permeability Distributions for Modeling Multi-Phase Flow Experiments

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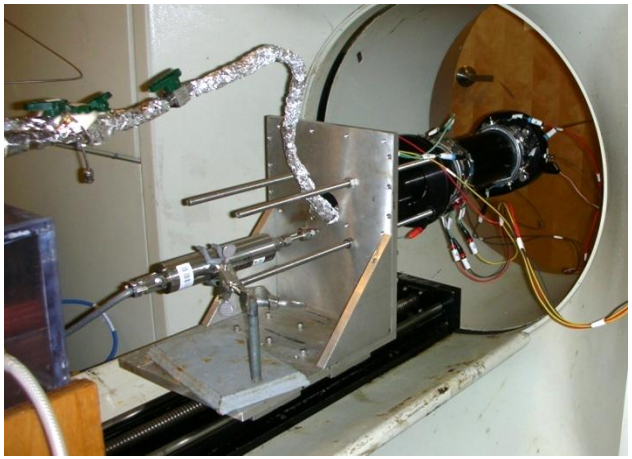
Science and technology for a low GHG emission world.

Motivation

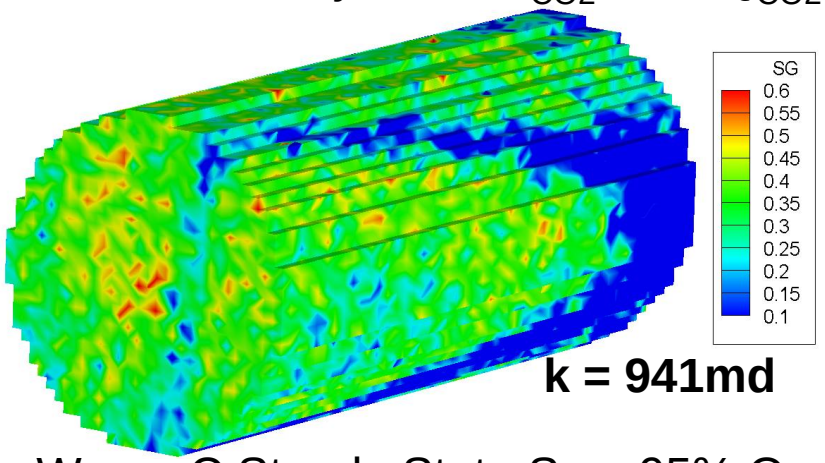
- What are we doing?
  - Conduct CO_2-brine core flooding experiments at reservoir conditions
  - Conduct simulations of the CO_2-brine core flooding experiments
  - Match experimental results
  - Develop predictive capabilities
- Validation
  - Show that the simulations predict sub-core scale saturation
  - Show that it is accurate to an acceptable tolerance
  - Show that the permeability grid is unique

Experiments

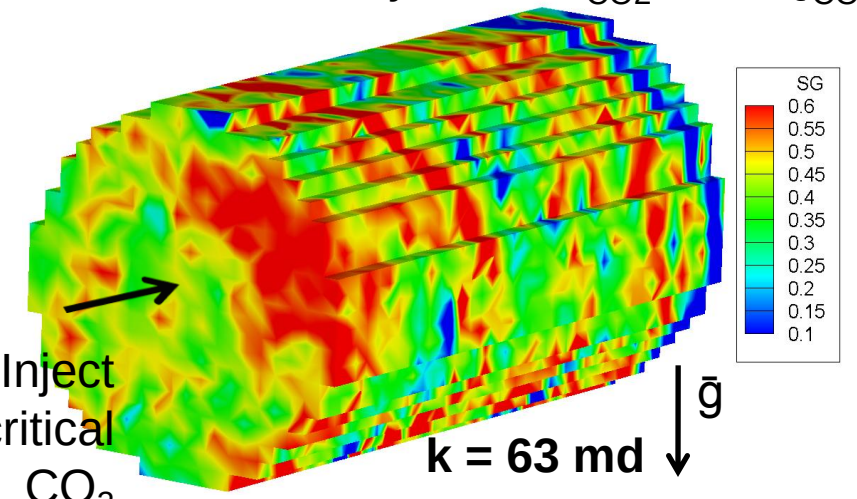
- Experiments
- Simulation Input
- Permeability
- Simulation Results



Berea Steady-State S_{CO2} 90% Q_{CO2}

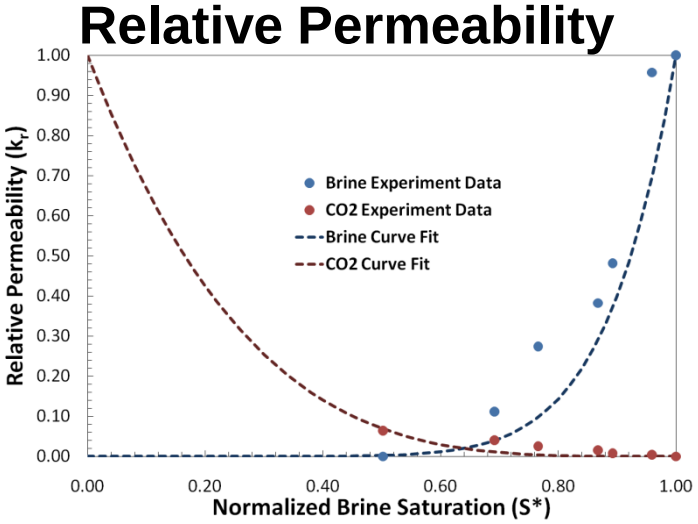


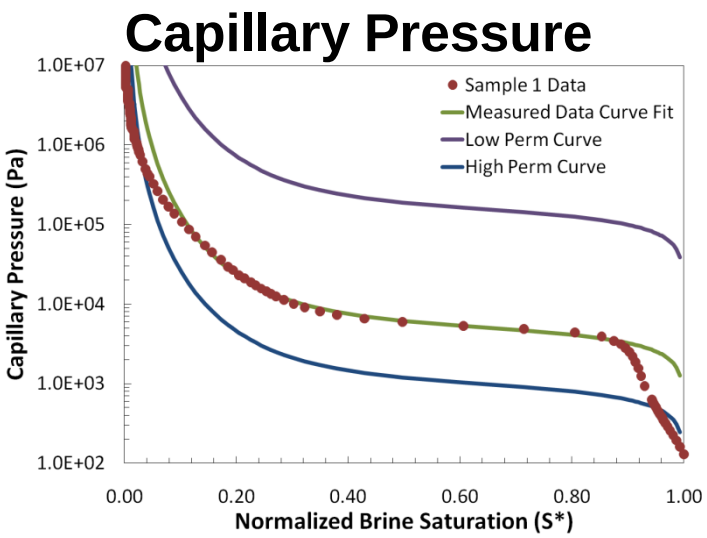
Waare C Steady-State S_{CO2} 95% Q_{CO2}



Simulation Procedure

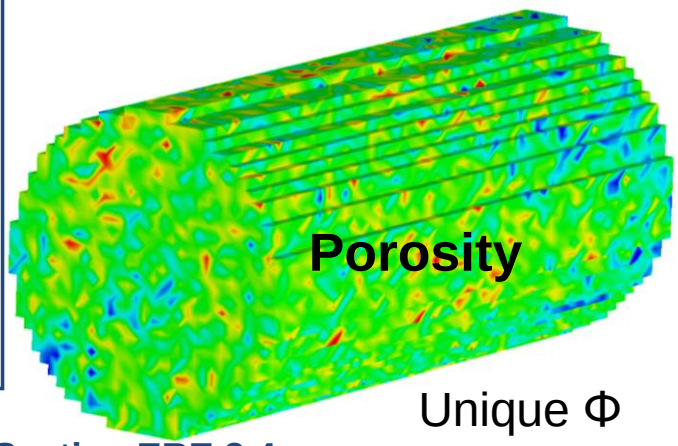
- Experiments
- Simulation Input
- Permeability
- Simulation Results



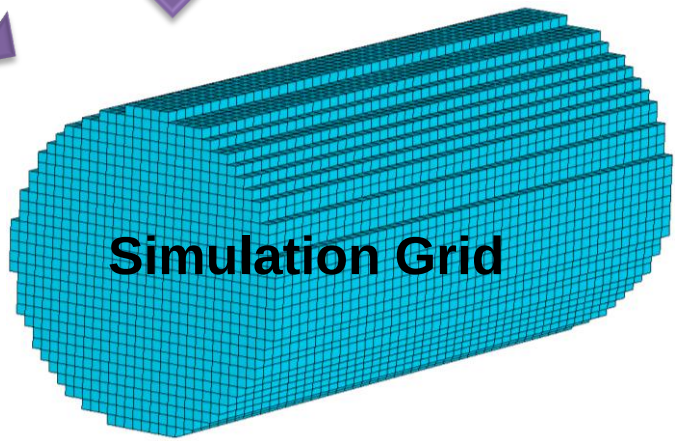


Core-Average

Unique Curves



Unique Φ



Permeability

- Experiments
- Simulation Input
- Permeability
- Simulation Results

Cap. Pressure Method

Porosity

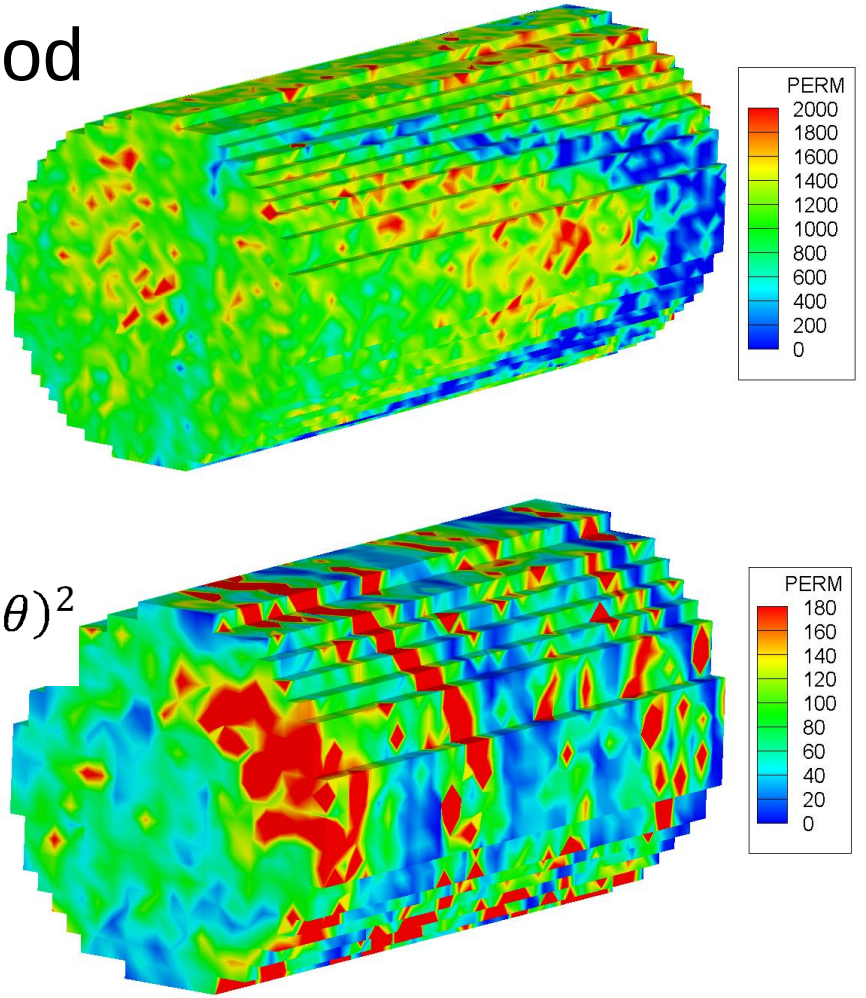
Saturation

Capillary Pressure

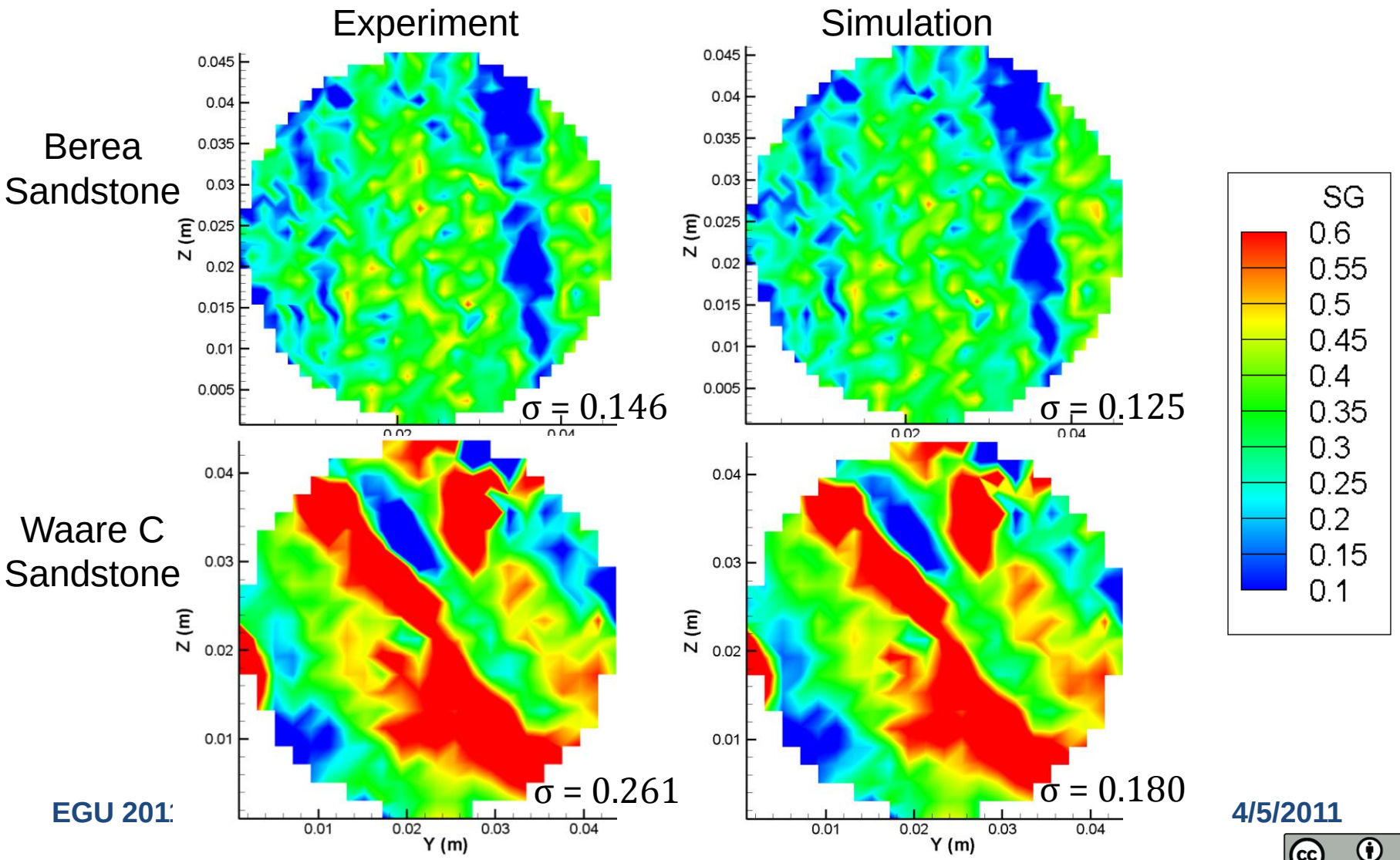
$$P_c = \sigma \cos(\theta) \sqrt{\frac{\phi}{k}} J(S_w)$$

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

Krause, M., Perrin, J.-C. and Benson S.M. 2011. Modeling Permeability Distributions in a Sandstone Core for History Matching Coreflood Experiments. SPE Journal, Published Online 7 January 2011.



Simulation Comparison with Exp.



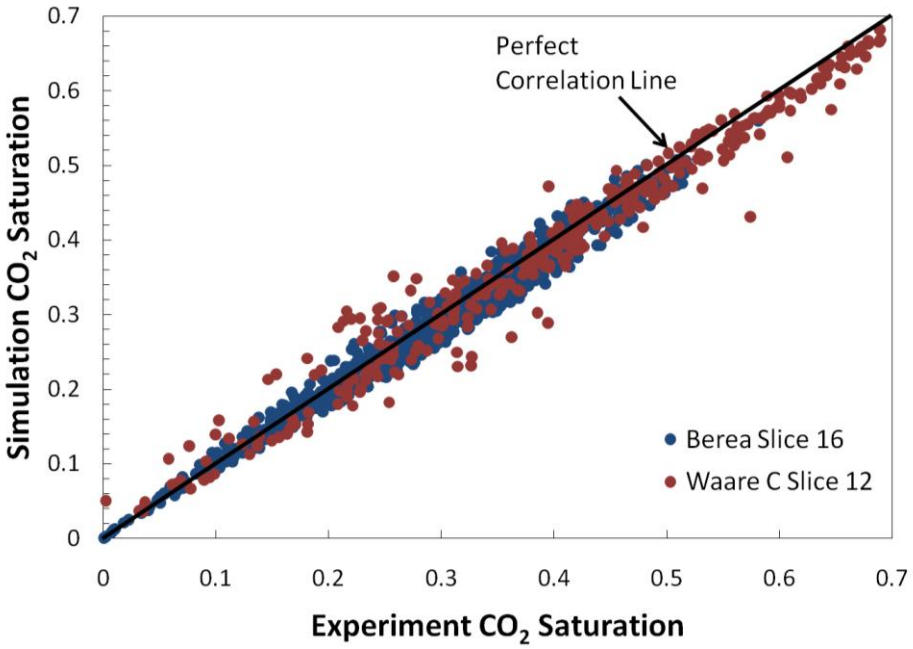
Simulation Comparison with Exp.

Conclusions:

- Very accurate replication of experimental measurement
- Excellent match in sub-core scale predication, as well as core average values

Error Comparison			
	CO_2 Sat R^2	S_{CO2} Error (%)	ΔP Error (%)
Berea	0.909	0.5	3.1
Waare C	0.727	7.9	7.8

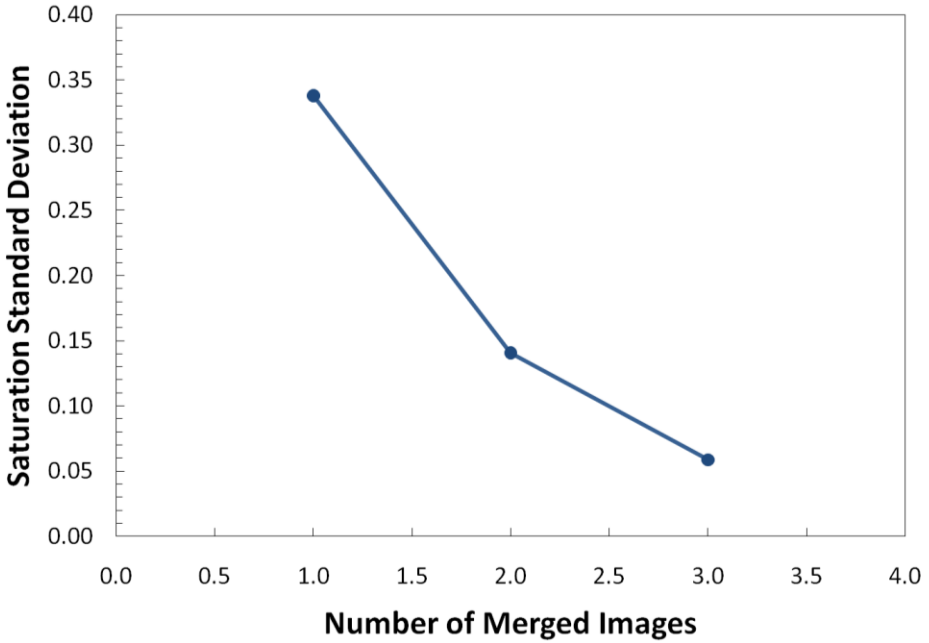
Saturation Comparison



Error Analysis

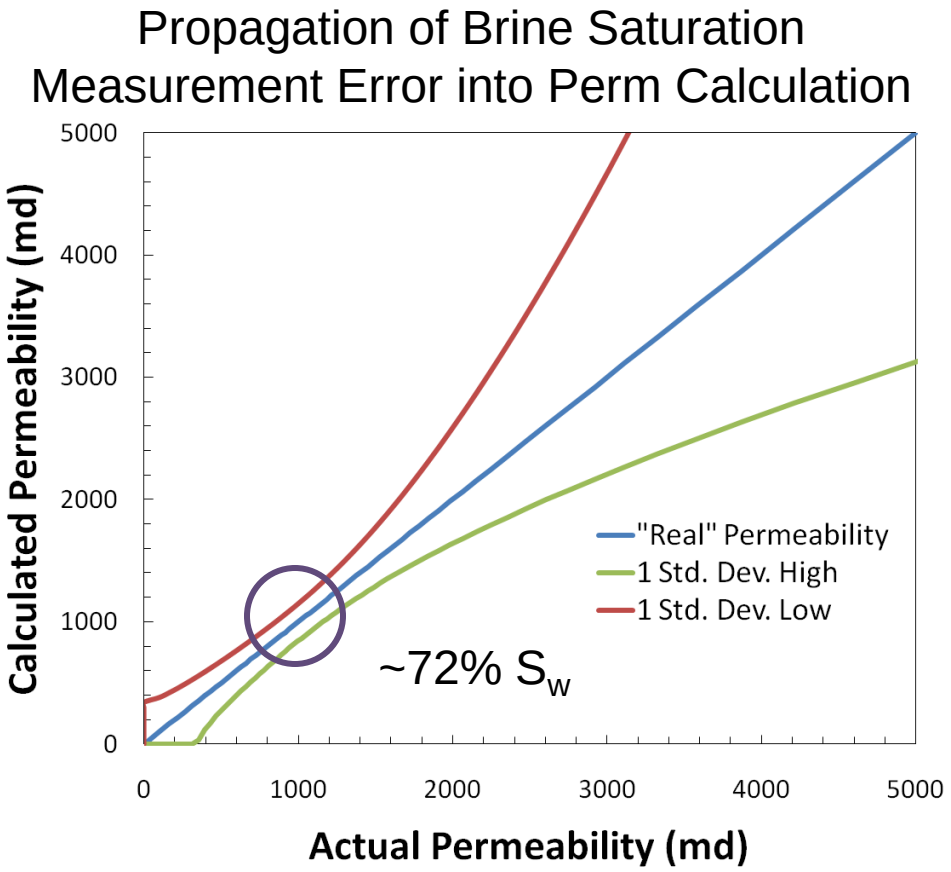
- Want to use these cores for prediction
- Reduce error in CT measurement by merging multiple scans
- Optimal number of scans is 2-4 depending on scan times and cooling capability

Error in 90% Fractional Flow Saturation Measurements



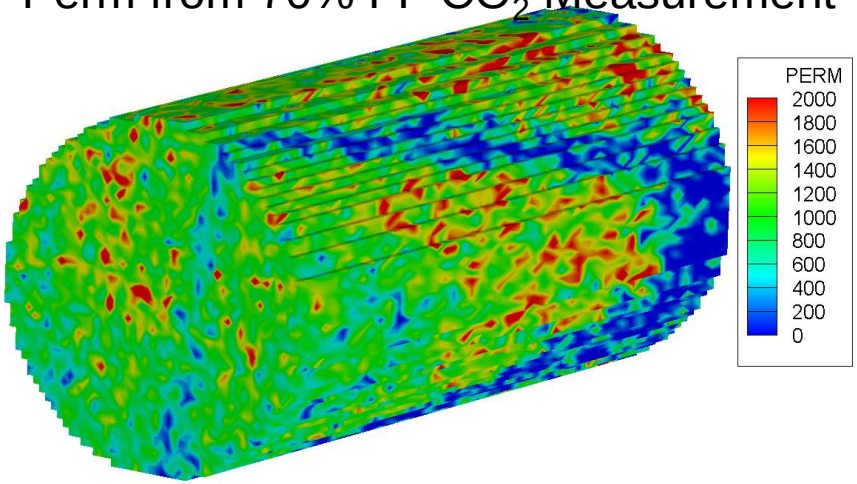
Accuracy of Permeability Grids

- Error propagation is a nonlinear function of saturation
- Error has a significant effect on permeability calculations at high CO_2 saturations
- Implies there is an optimal saturation for calculating permeability

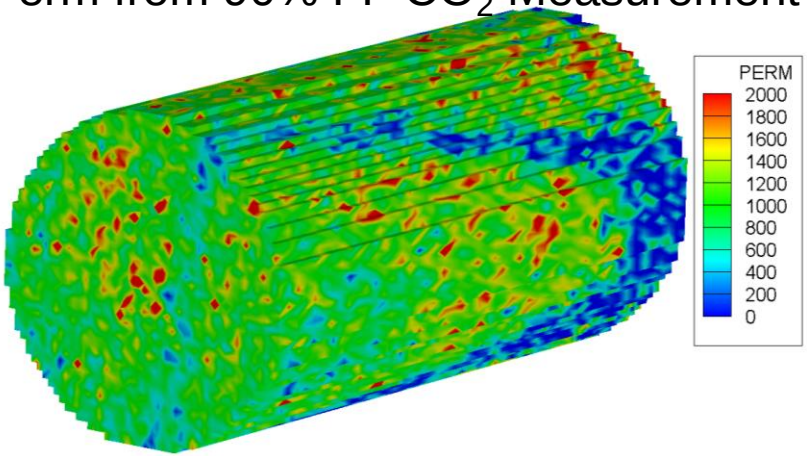


Unique Permeability Grid

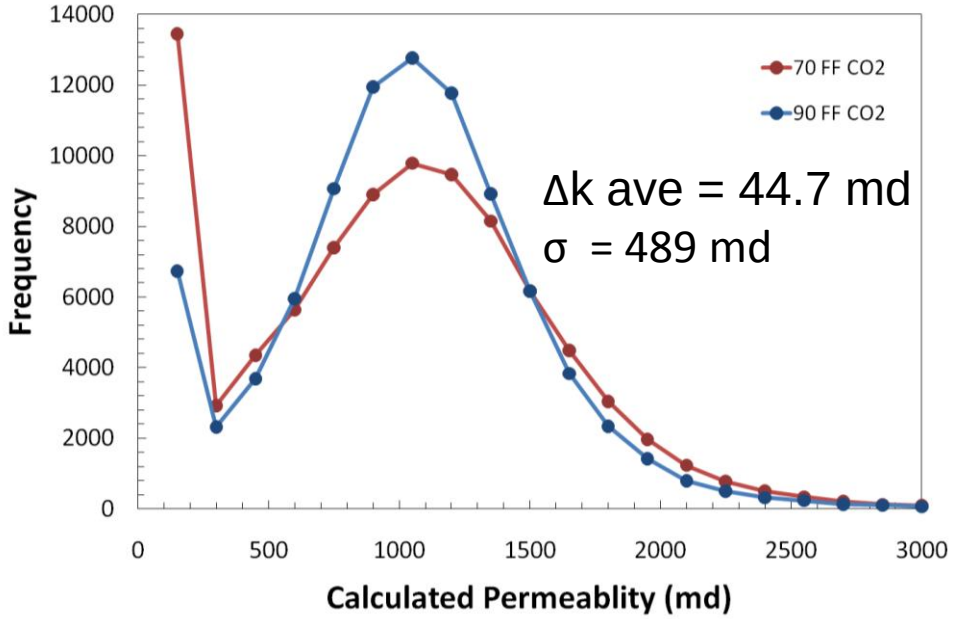
Perm from 70% FF CO_2 Measurement



Perm from 90% FF CO_2 Measurement



Comparison of Permeability Distributions for Two Fractional Flows

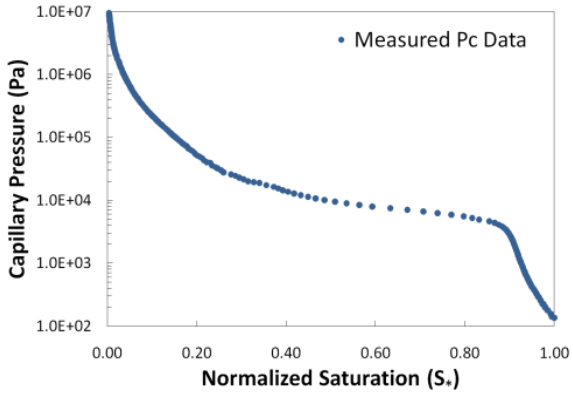


Grid	S_{CO2} Ave	Perm Error (md)	Perm Std. Dev. (md)
70	0.2063	1.4	254
90	0.2654	9.5	256

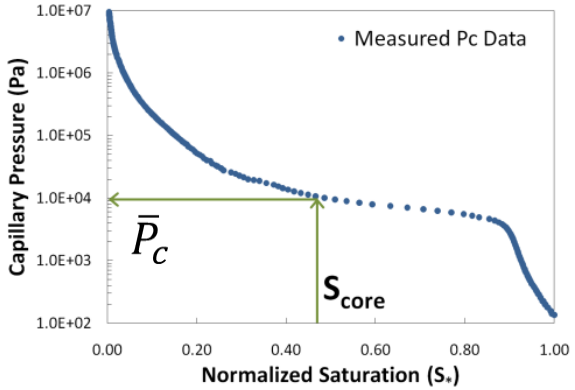
Conclusions

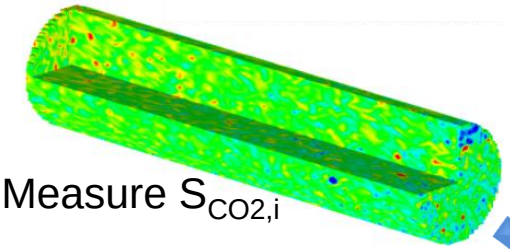
- The method works for predicting sub-core and core-scale properties
  - Predict pressure drops
  - Predict saturation distribution
- Error can be minimized by selecting appropriate experimental conditions and output
- Difference in permeability grids
  - Experimental error attributed to some fraction of the difference
  - Capillary entry pressure not exceeded is limiting factor
- Permeability calculation still quite good

Measure P_c Curve

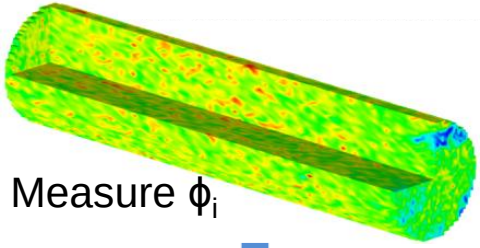


Calculate Core-Average P_c





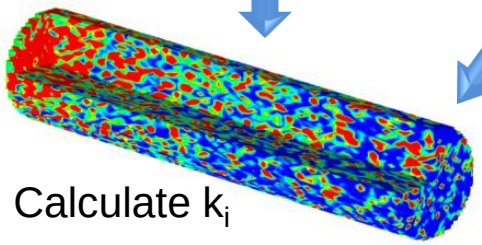
Measure $S_{CO2,i}$



Measure ϕ_i

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

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



Calculate k_i

$$k_i = c_o \phi_i \left[A\left(\frac{1}{S_{*,i}^{\lambda_1}} - 1\right) + B\left(1 - S_{*,i}^{\lambda_2}\right)^{1/\lambda_2} \right]^2 \left(\frac{\sigma \cos\theta}{\bar{P}_c}\right)^2$$

Supplemental Data

Property	Berea	Otway (Waare C Form.)
Pressure	12.41 MPa	12.41 MPa
Temperature	50C	63C
Salinity	0 ppm NaCl	6500 ppm NaCl
Injection Rate	3 ml/min	3 ml/min
Grid Element Size	1.5mm x 1.5mm x 2mm	2mm x 2mm x 3mm
ϕ_{core}	24.09%	18.11%
Core Permeability	941 md	62.3 md
Length	10.2 cm	7.5 cm
Core Diameter	5.08 cm	5.08 cm