Simulation of Multi-phase Flow Experiments

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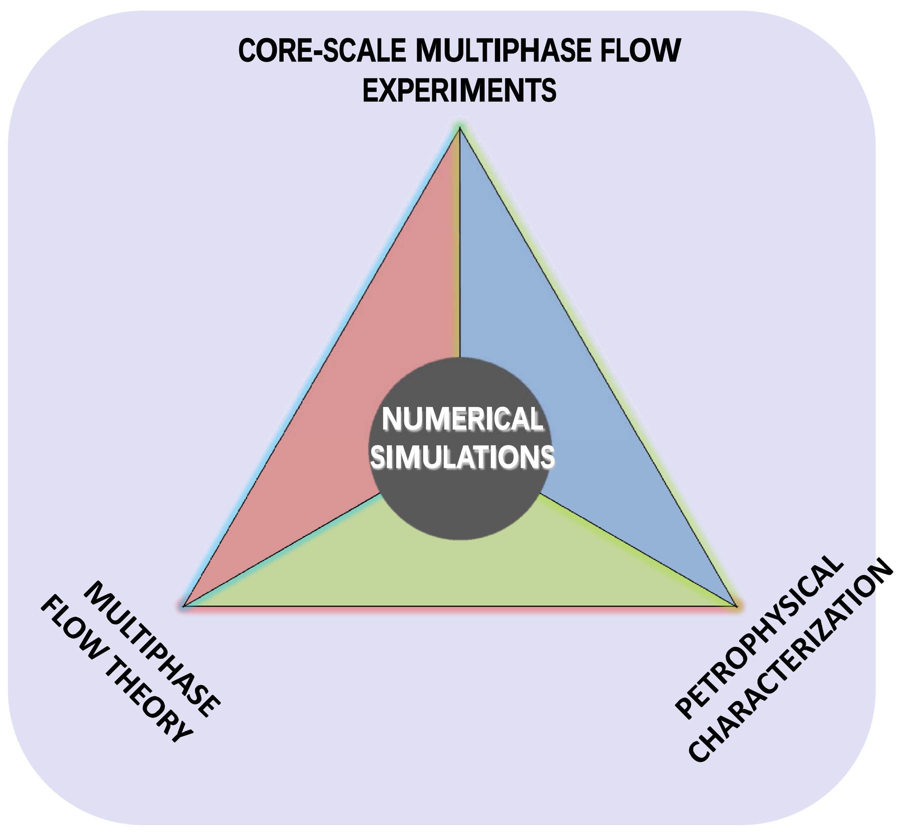
Motivation



THE SEQUESTRATION LAB
The goal of the Sequestration Lab is to develop the ability to predict the spatial and temporal distribution of CO_2 saturation and trapping through an improved understanding of the pore and core scale physics over the life cycle of a sequestration project.

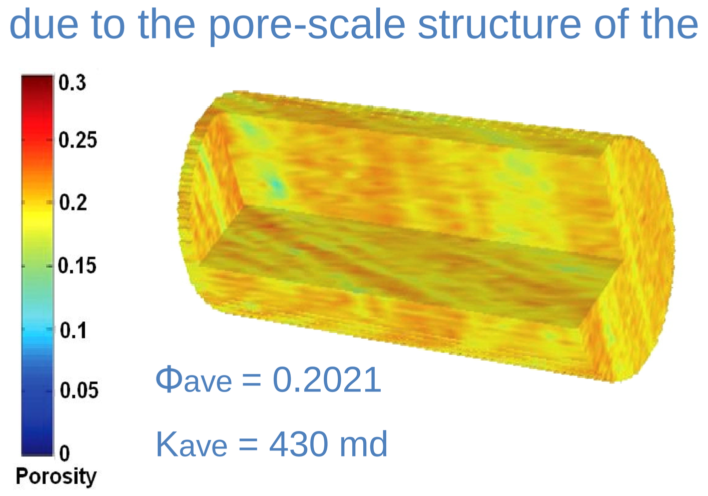
Focus of this work

- Model the behavior of brine displacement by injected CO_2 in a series of core-scale laboratory experiments.
- Better understand the fundamental physics of sub-core scale multi-phase flow
- Tough2 MP* was used for numerical simulation (*: developed by Karsten Pruess)

Sub-core Scale Petrophysical Characterization

Porosity Map Of The Core

Raw data is from X-Ray CT Scanning. The spatial variation of porosity is due to the pore-scale structure of the rock sample.



Φ_{ave} = 0.2021

K_{ave} = 430 md

Capillary Pressure

$$P_{c,i} = \sigma \sqrt{\frac{\phi_i}{k_i}} * J(S)$$

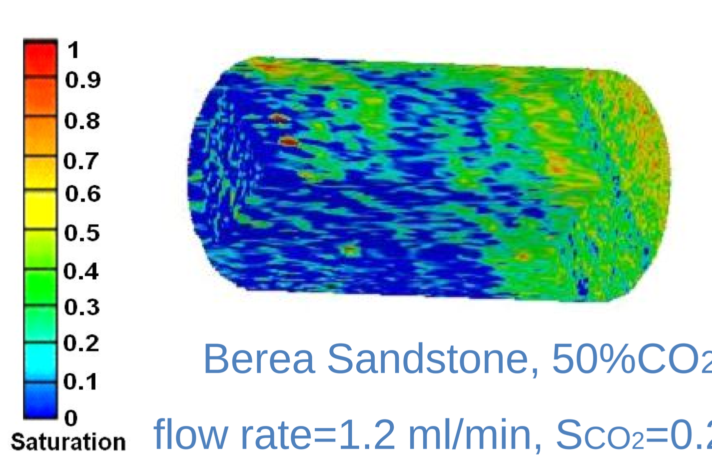
$$J(S) = A\left(\frac{1}{S_*^{\lambda_1}} - 1\right) + B\left(1 - S_*^{\lambda_2}\right)^{1/\lambda_2}$$

$$S_* = \frac{S - S_P}{1 - S_P}$$

A=0.040061, B=0.992531,
λ_1=2.183, λ_2=1.077,
S_p=0.010036, σ=0.02247

CO_2 Saturation Measurement

(see poster by Perrin and Benson)



Berea Sandstone, 50%CO_2,
flow rate=1.2 ml/min, S_{CO_2}=0.209

Relative permeability relation

$$k_{r,CO_2} = \left(\frac{1 - S_{br}}{1 - S_{br,r}}\right)^{n_{CO_2}}$$

$$k_{r,br} = \left(\frac{S_{br} - S_{br,r}}{1 - S_{br,r}}\right)^{n_{br}}$$

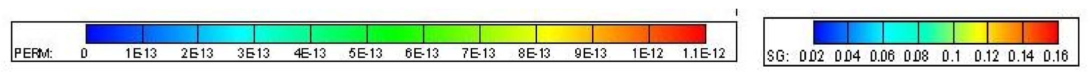
$n_{br} = 1.9$, $n_{CO_2} = 2.5$, $S_{br,r} = 0.57$

Resolution Of Simulation And Measurement

Measurement: # of pixels in y, z, x directions: 159, 159, 31
Simulation: # of grid blocks in y, z, x directions: 53, 53, 31

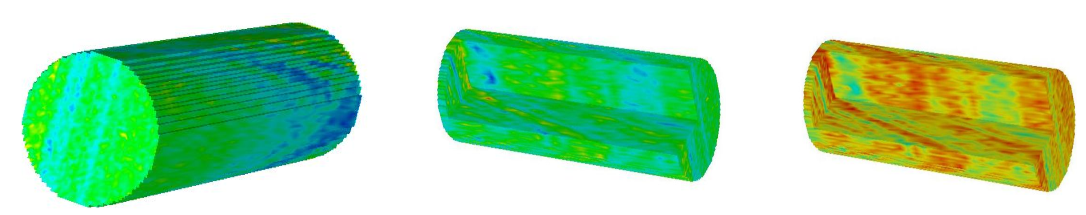
Numerical Simulations Using Different Permeability Distributions

1st column: Different permeability relationships to the porosity
2nd column: Corresponding permeability map of whole core
3rd column: Cross-sectional view of permeability maps
4th column: Cross-sectional view of saturation of CO_2 at steady state



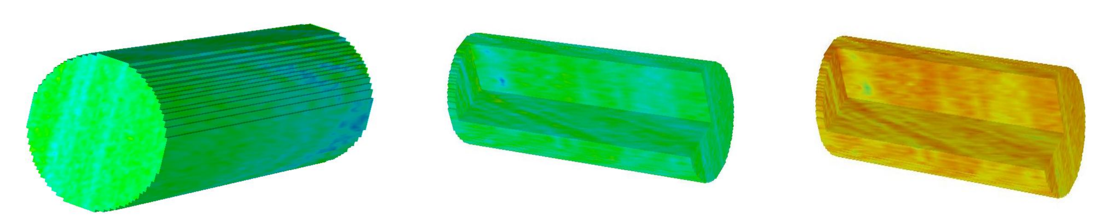
Model a : Kozeny-Carman Equation

$$k_a = \frac{1}{3.28\times10^6}\frac{\phi^3}{(1-\phi)^2}$$



Model b : Krause's Modified K-C Equation

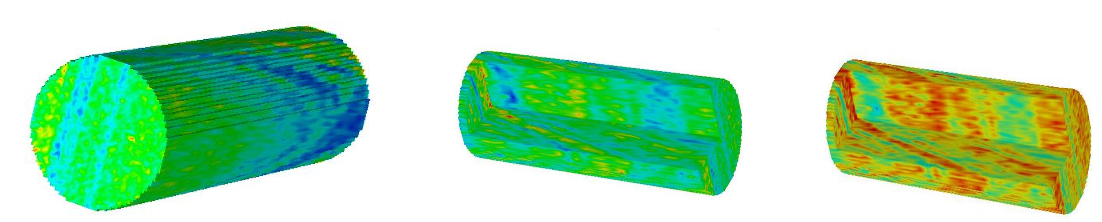
$$k_b = \frac{1865}{(0.3283\times\phi^{0.77})^2}\frac{\phi^3}{(1-\phi)^2}$$



- From result of Krause's thin section analysis. Surprisingly, it has less contrast map of permeability

Model c :

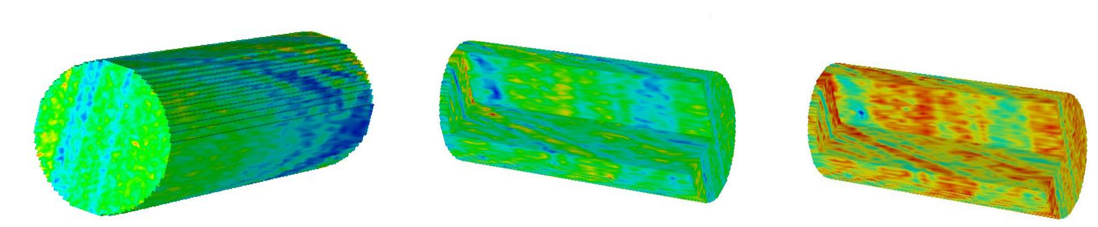
$$k_c = \frac{1865}{(0.3283\times\phi^{0.25})^2}\frac{\phi^{4.5}}{(1-\phi)^2}$$



- Keep the form of Krause's modified K-C equation but with different power

Model d :

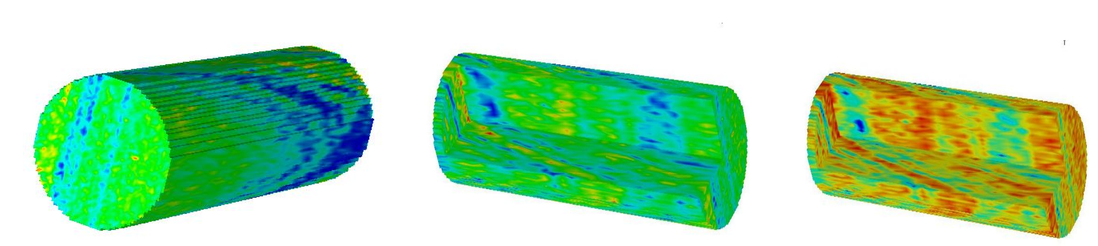
$$k_d = a\times\phi^4 + b$$
$$a = 2653770,\ b = -539.841$$



- Try other form of permeability relationship: k is proportional to the power 4th of porosity
- have very similar result as Model c, almost identical

Model e :

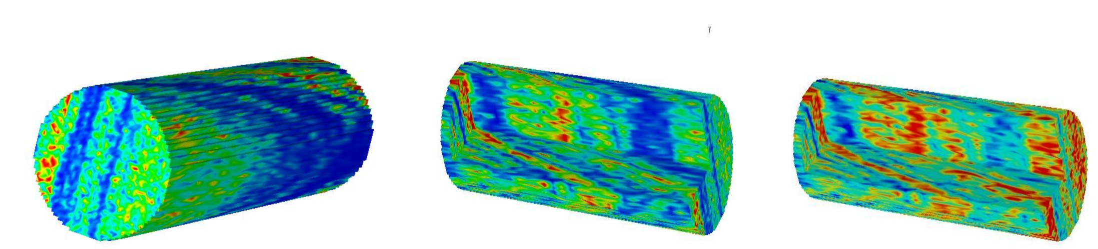
$$k_e = \begin{cases} 1 & \text{if } \phi \le 0.14 \\ 10 & \text{if } 0.14 < \phi \le 0.15 \\ 30 & \text{if } 0.15 < \phi \le 0.16 \\ 50 & \text{if } 0.16 < \phi \le 0.17 \\ a\times\phi^4 + b & \text{elsewhere} \end{cases}$$



- Modified Model d to get more contrast permeability map

Model f : Best Model

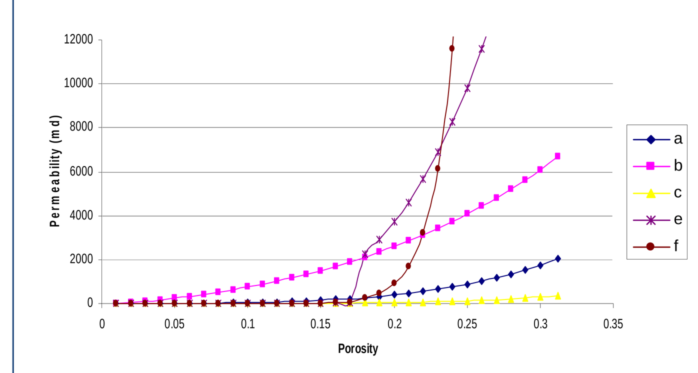
$$k_f = \begin{cases} 1 & \text{if } \phi \le 0.14 \\ 10 & \text{if } 0.14 < \phi \le 0.15 \\ 30 & \text{if } 0.15 < \phi \le 0.16 \\ 50 & \text{if } 0.16 < \phi \le 0.17 \\ e^{m\times\phi^4 + n} & \text{elsewhere} \end{cases}$$
$$m = 64,\ n = -6$$



- Try log k is proportional to the power 4th of porosity.=> extreme contrast permeability map we have

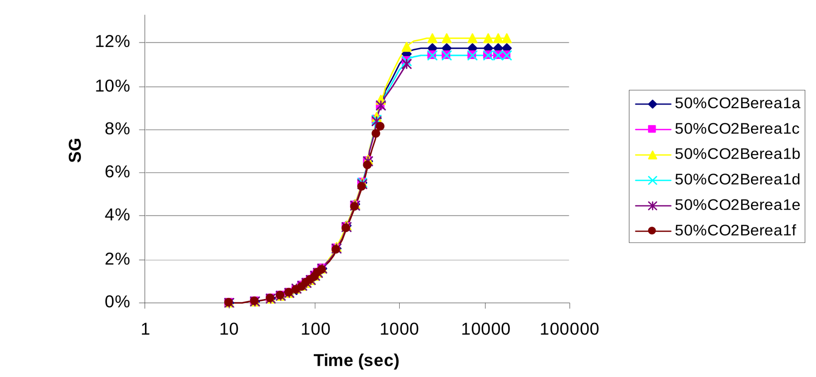
Results / Discussion

Permeability vs. Porosity



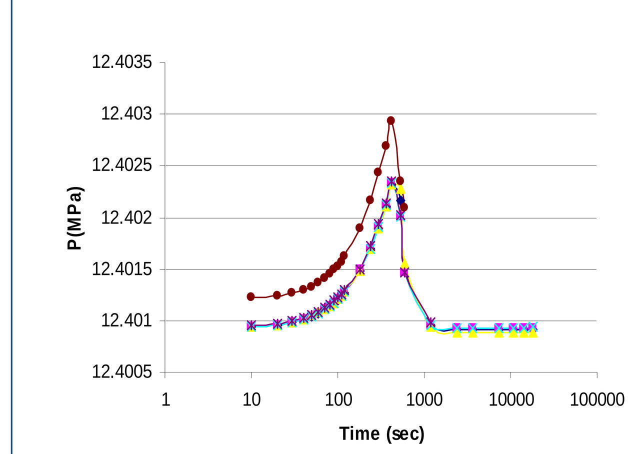
- Model b has the flattest curve.
- Model f has the sharpest curve.

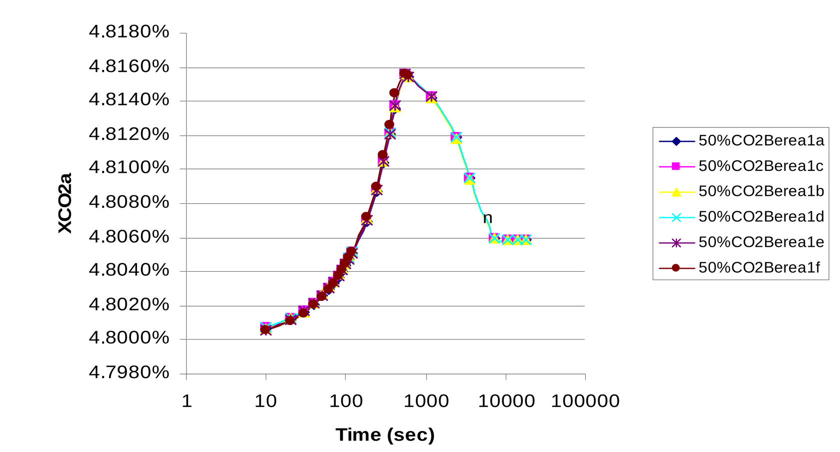
Compare Saturation of CO_2



- Average S_{CO_2} after steady state ≈ 0.12
- Lower than the experimental data (0.209)

Compare Pressure, and Mass Fraction of Dissolved CO_2 in Brine





Variation of pressure and mass fraction of dissolved CO_2 in brine are both very small

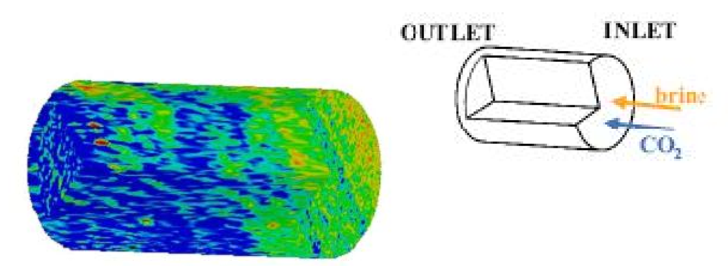
Results

Model with higher contrast permeability provide better results

Making progress for improving history matching of multiphase flow experiment with numerical simulation

Improvement still needed

- Bypass of part of core observed in lab experiments is not replicated with simulations
- Capillary pressure curve
- Permeability map



Conclusion

- Core-scale lab experiments were simulated to investigate cause of CO_2 saturation distribution
- Heterogeneities of porosity, permeability and saturation control the distribution of CO_2
- The more contrast of permeability map, the more precise results we can get.