Relative Permeability and Capillary Pressure Controls on CO_2 Migration and Brine Displacement

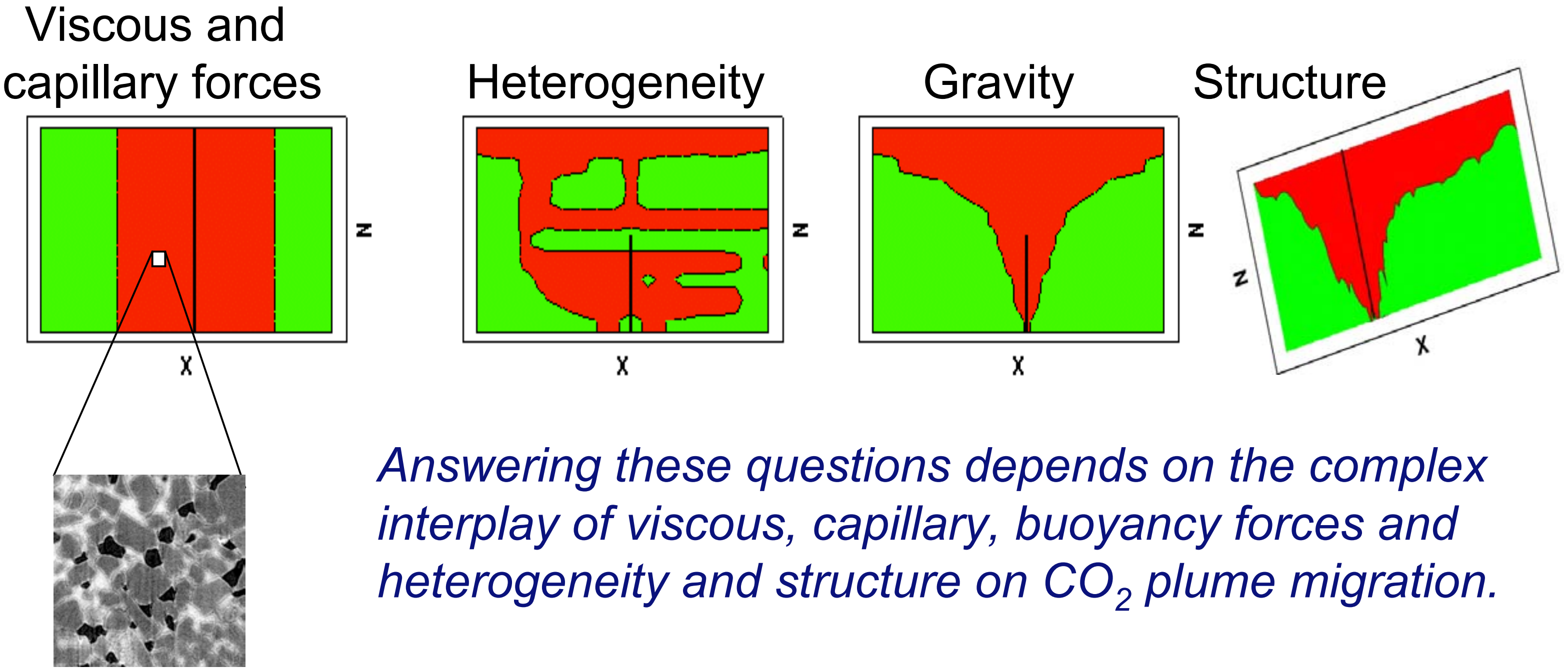
Sally M. Benson[1]
Ljuba Miljkovic[2], Liviu Tomutsa[2] and Christine Doughty[2]
[1]Energy Resources Engineering Dept., Stanford University
[2]Earth Sciences Division, Lawrence Berkeley National Laboratory

Acknowledgements

- Funded by DOE Fossil Energy through the Zero Emissions Research and Technology Program (ZERT)
- Outstanding co-authors from Lawrence Berkeley National Laboratory
  - Ljuba Miljkovic
  - Liviu Tomutsa
  - Christine Doughty

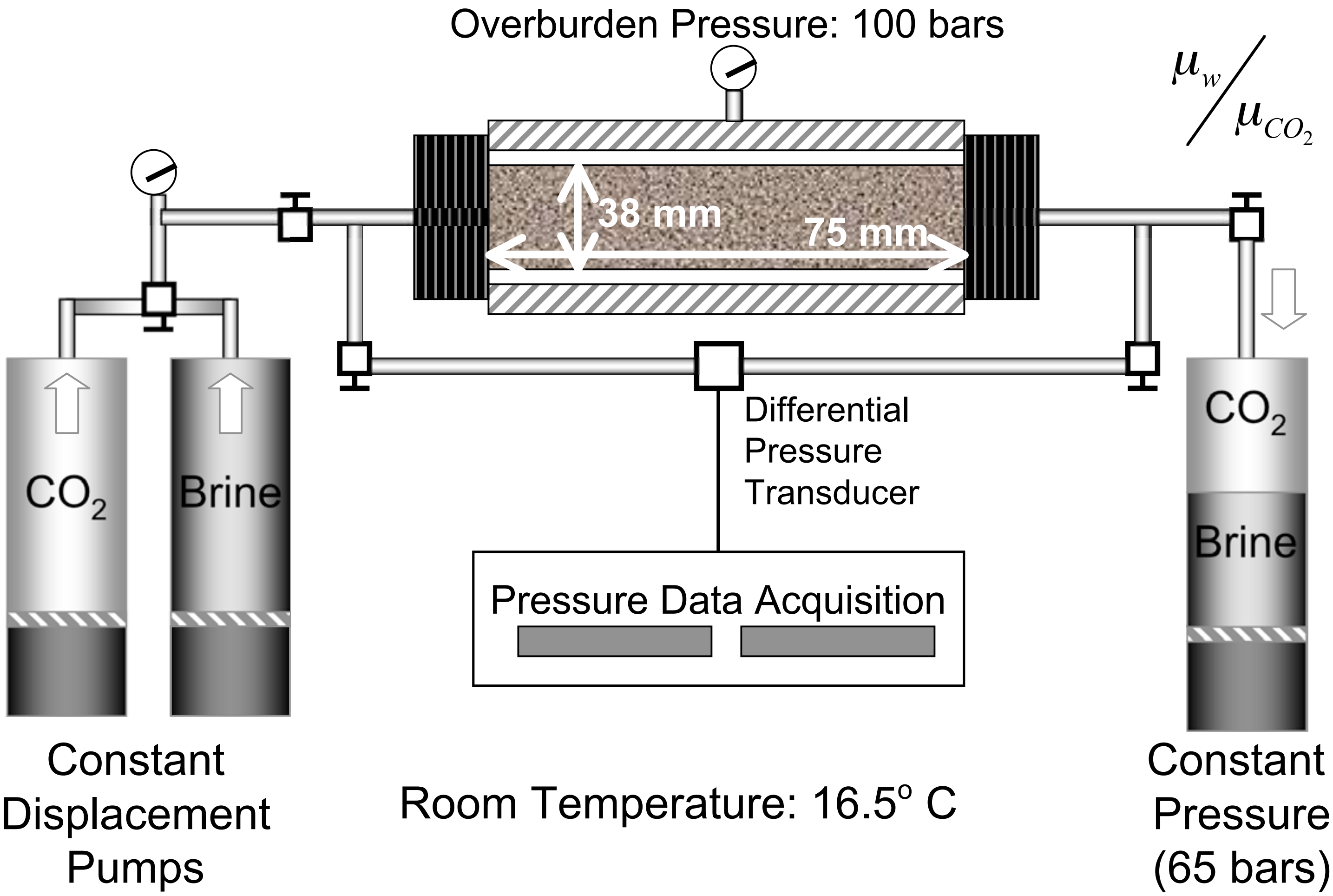
Some Key Issues for CO_2 Storage in Deep Saline Aquifers

- What fraction of the pore space can be filled with CO_2?
- How big will the CO_2 plume be?
- How much CO_2 will be dissolved?
- How much will capillary trapping immobilize CO_2?
- Can accurate models be developed to predict CO_2 fate and transport?



Answering these questions depends on the complex interplay of viscous, capillary, buoyancy forces and heterogeneity and structure on CO_2 plume migration.

Core-flood Set-Up for Relative Permeability Measurements



Overburden Pressure: 100 bars

$$\mu_w / \mu_{CO_2} = 14.3$$

Differential Pressure Transducer

Pressure Data Acquisition

Constant Displacement Pumps

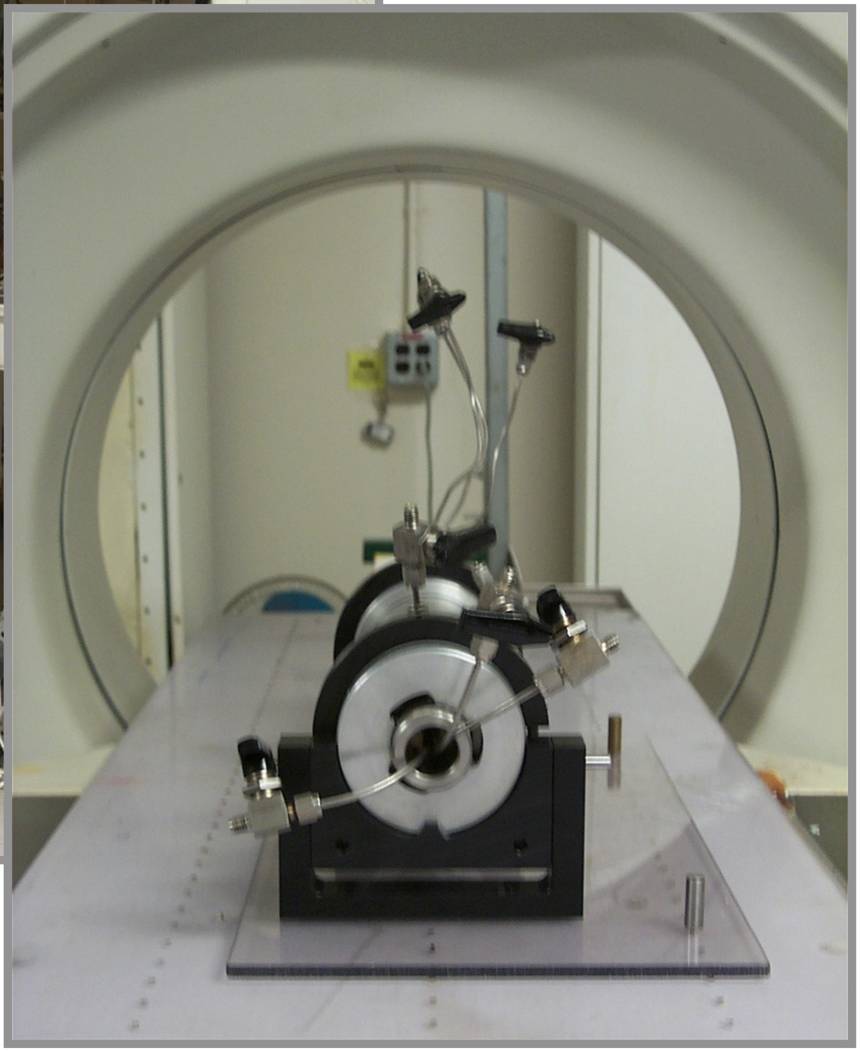
Room Temperature: 16.5° C

Constant Pressure (65 bars)

*Brine composition: CO$_2$ saturated brine with 0.5 molar potassium iodide

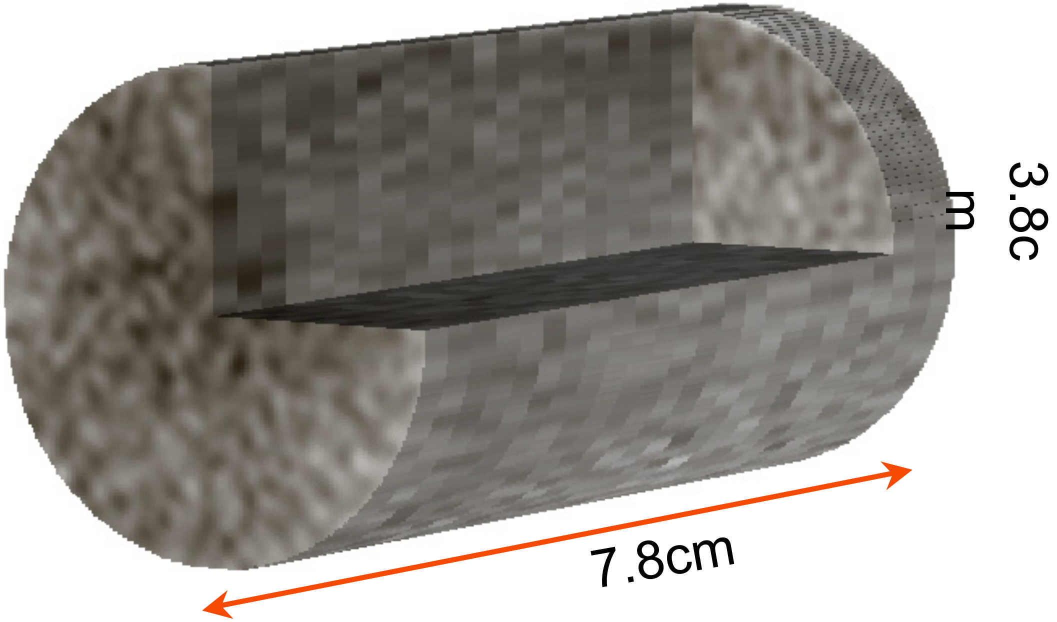
Core-Scale Imaging of CO_2 Distributions

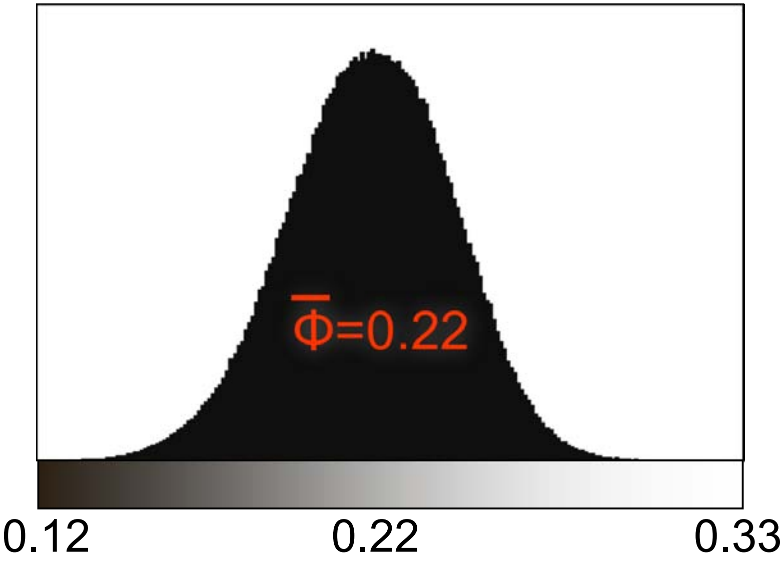
High Pressure Pumps

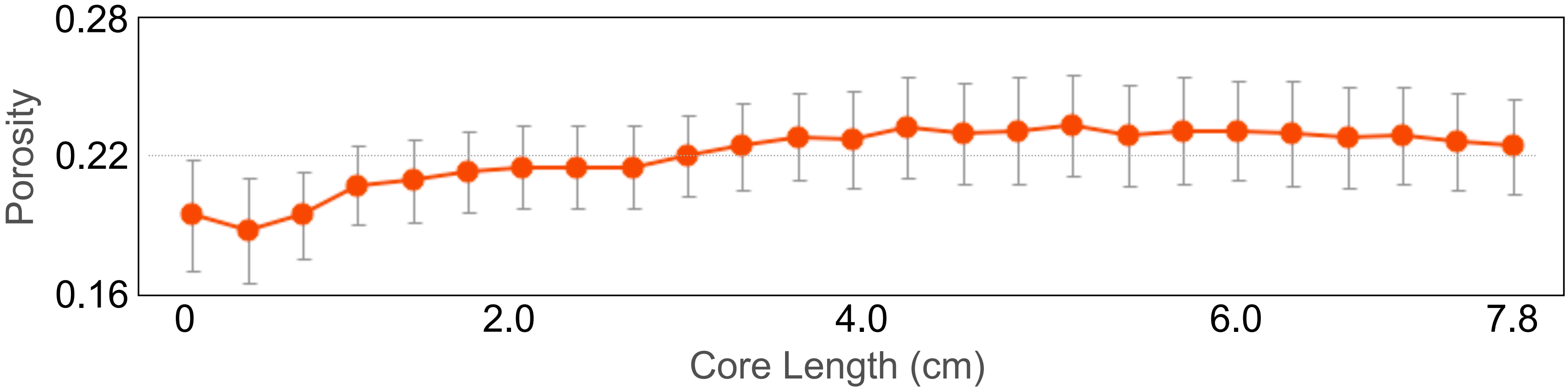


Core Holder
In Scanner

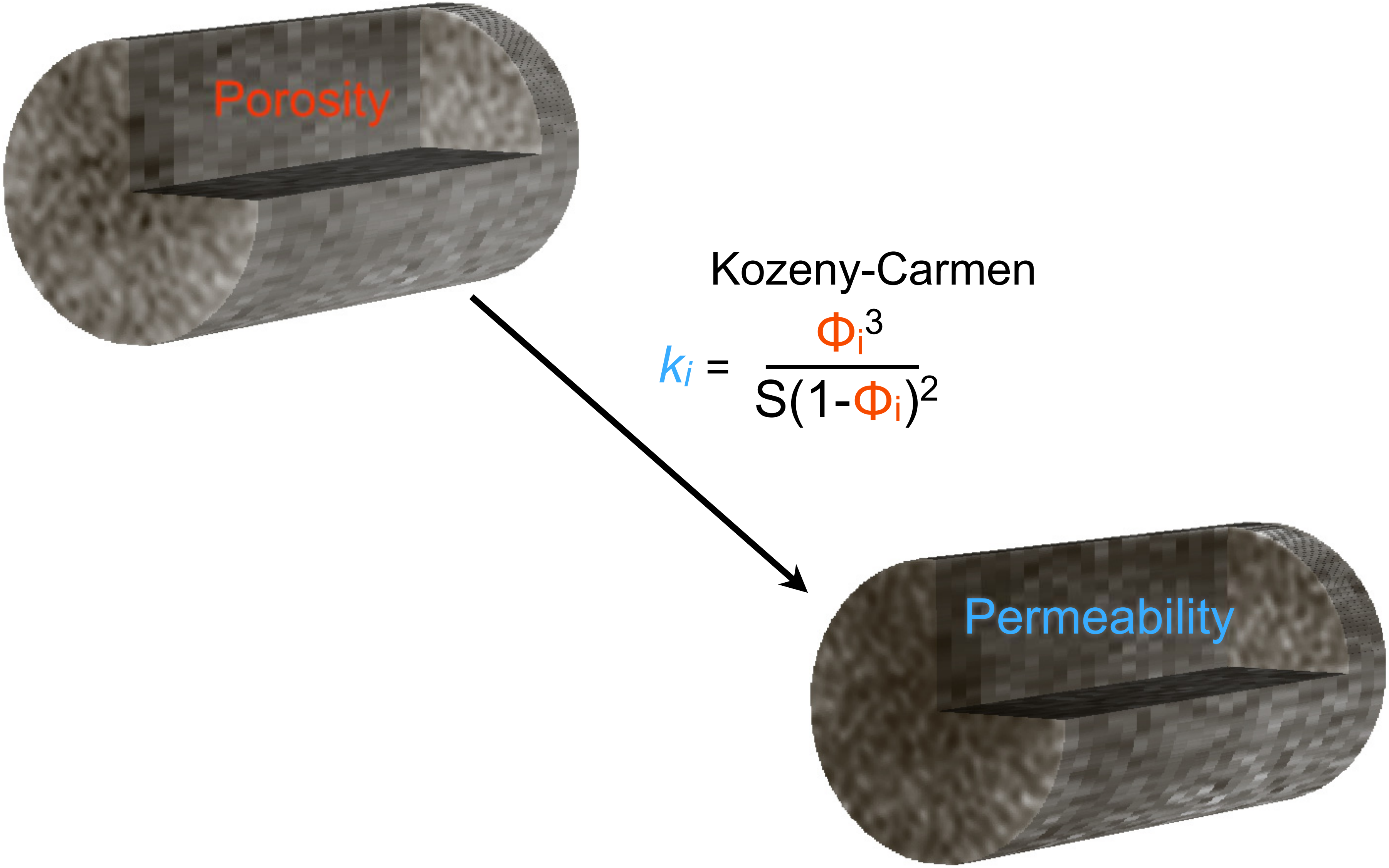
CT Scans Measure Core Porosity







Calculation of Permeability



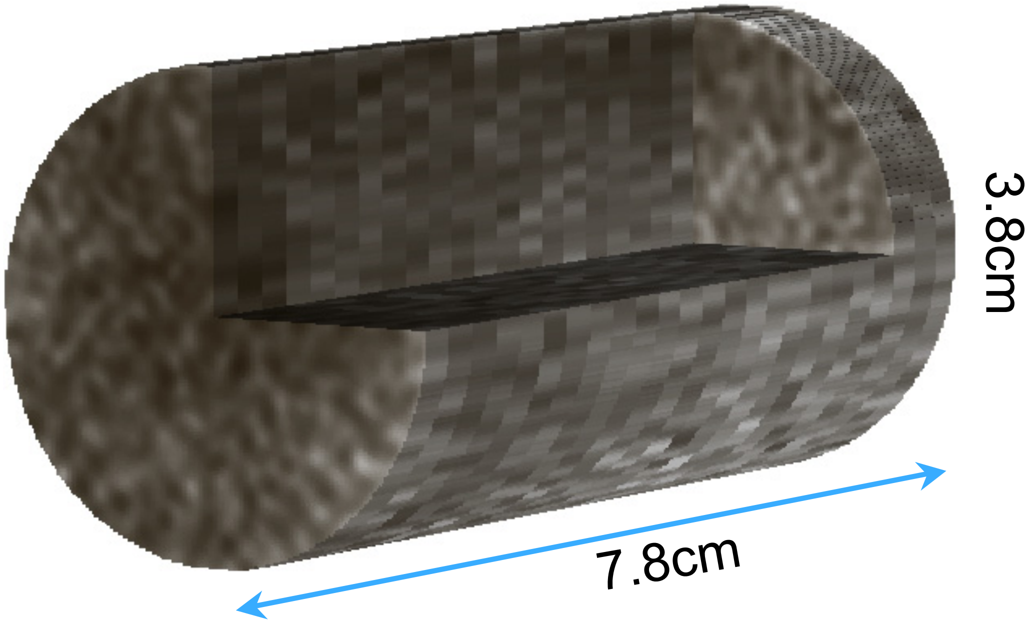
Porosity

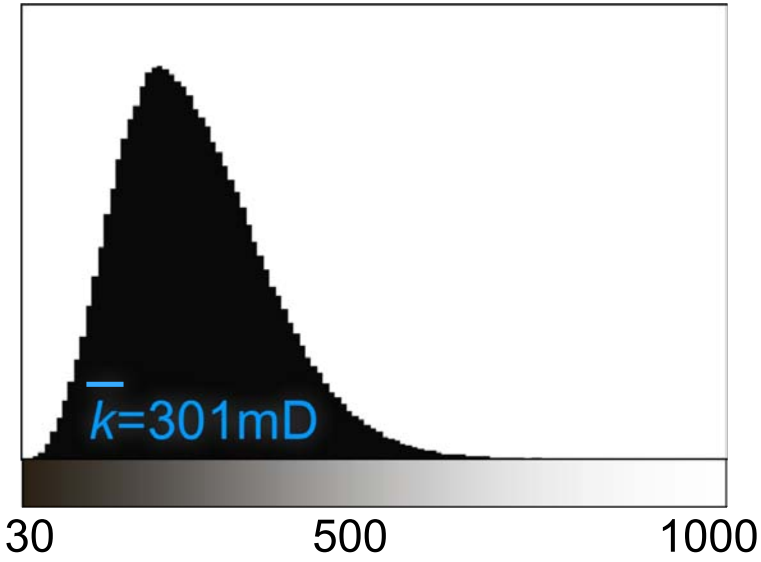
Kozeny-Carmen

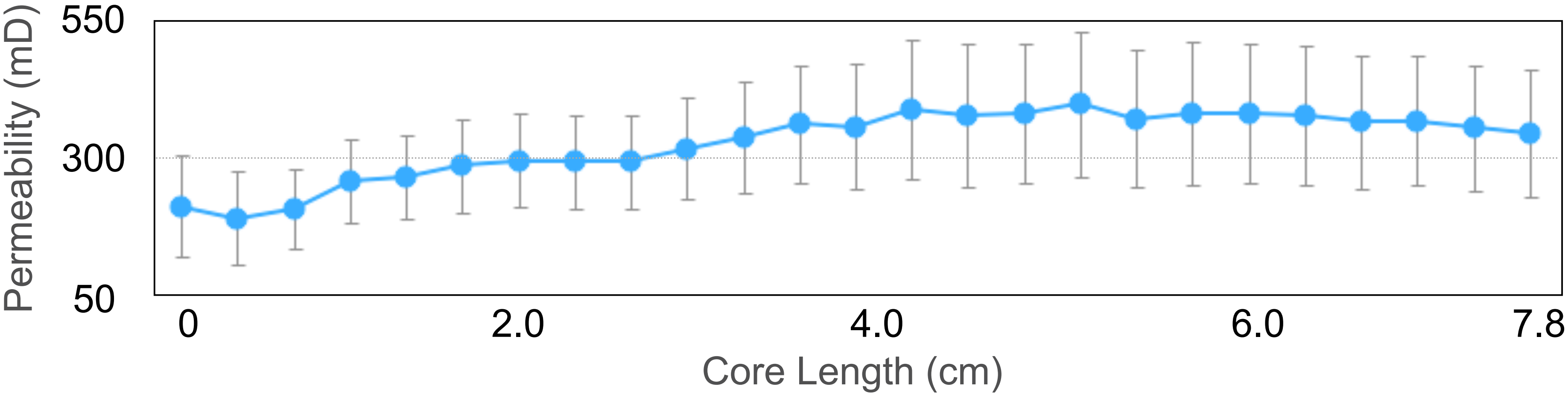
$$k_i = \frac{\Phi_i^3}{S(1-\Phi_i)^2}$$

Permeability

Core Permeability Distribution





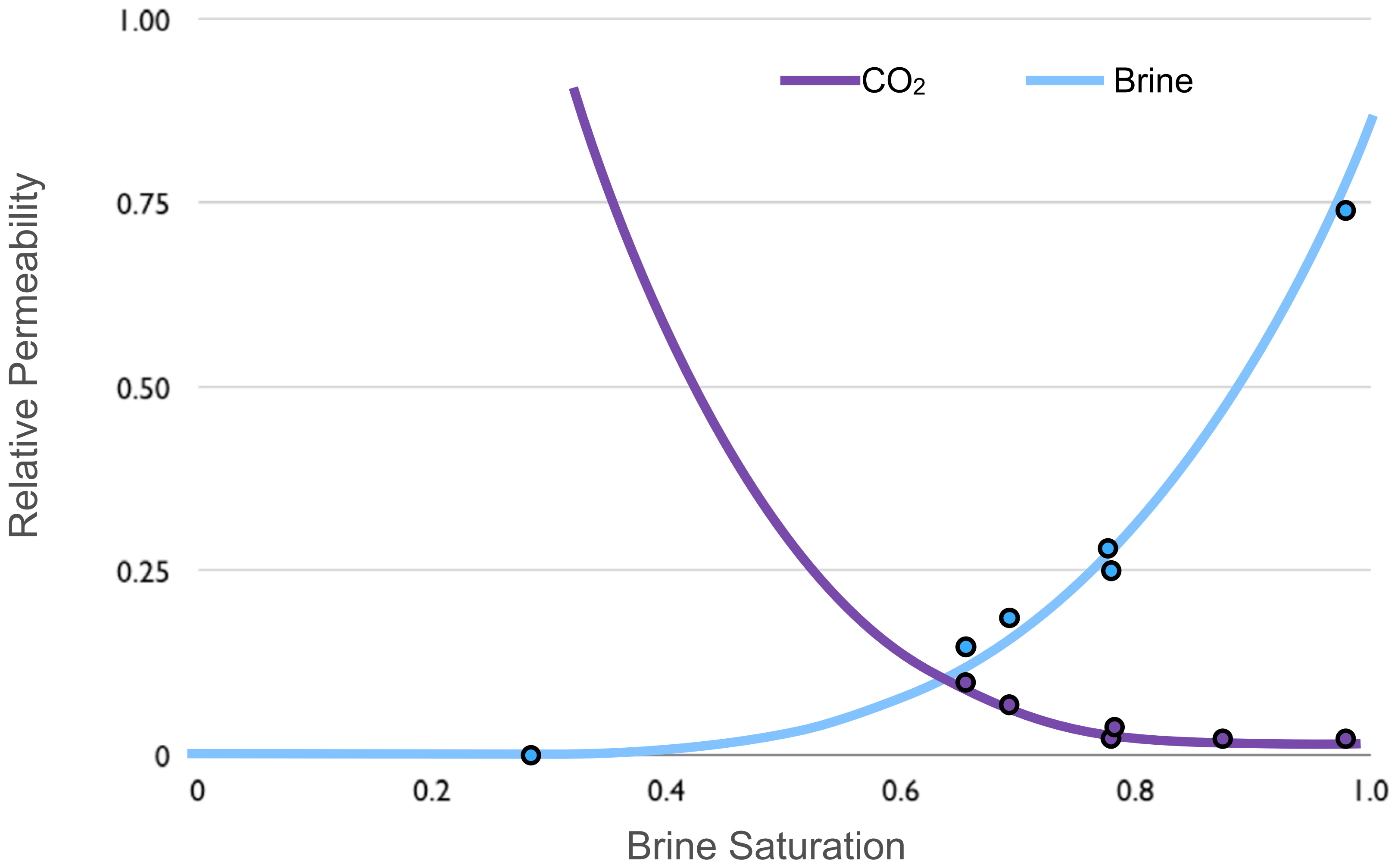


Laboratory Injections of Various CO_2-Brine Proportions

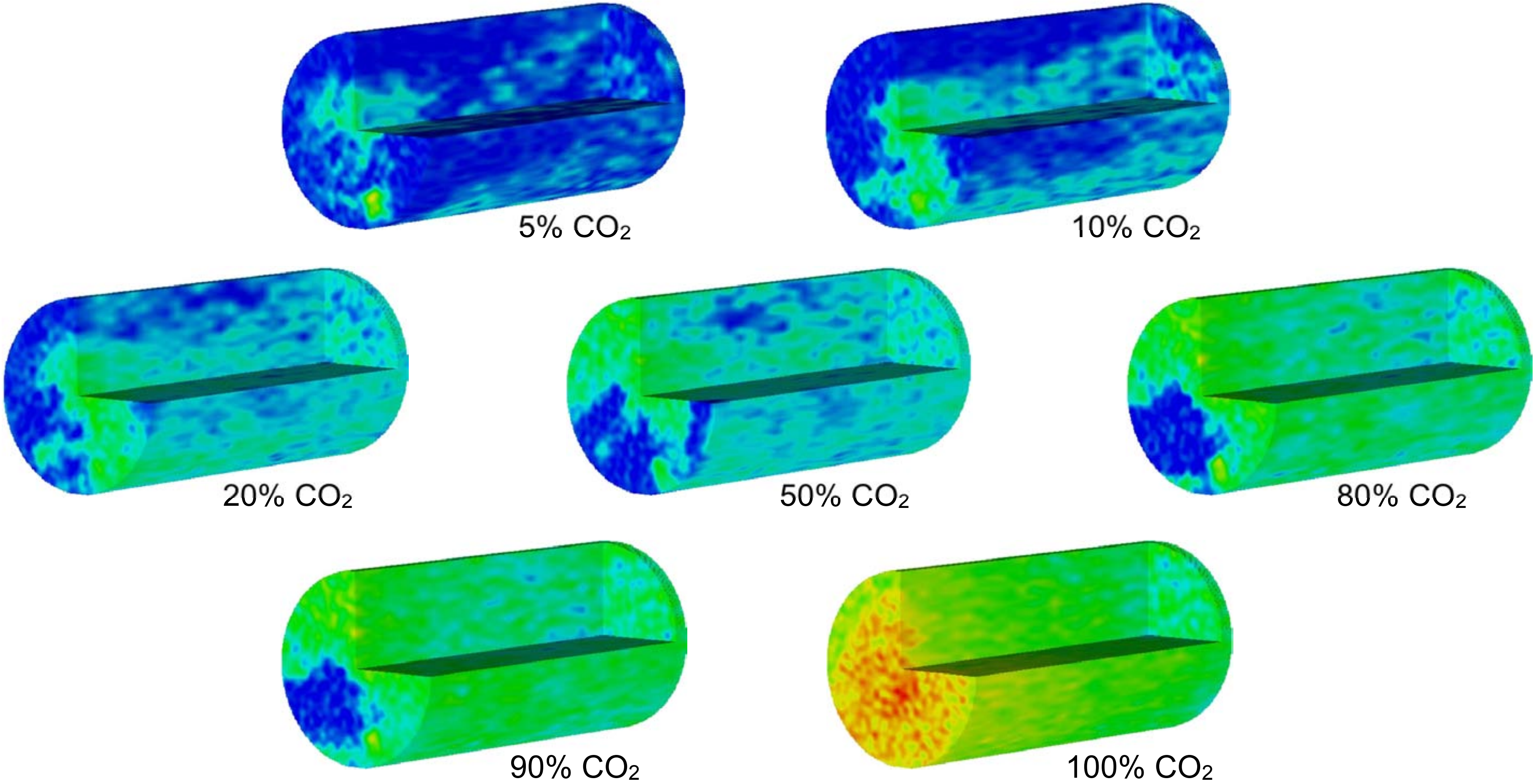
- Experimental Setup:
  - 5%, 10%, 20%, 50%, 80%, 90%, 100% CO_2 injections
  - 3mL/min constant flow-rate
  - 6.89MPa constant back-pressure
  - 16 ±2°C lab temperature
  - Brine contains dissolved CO_2
  - CO_2 contains dissolved water

- Measure CO_2 Saturation with CT Scanner
  - Digitally reconstruct image

Relative Permeability Curves



Small-scale CO_2 Saturation Variations



5% CO_2

10% CO_2

20% CO_2

50% CO_2

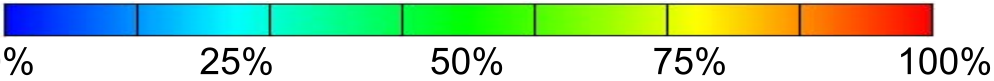
80% CO_2

90% CO_2

100% CO_2

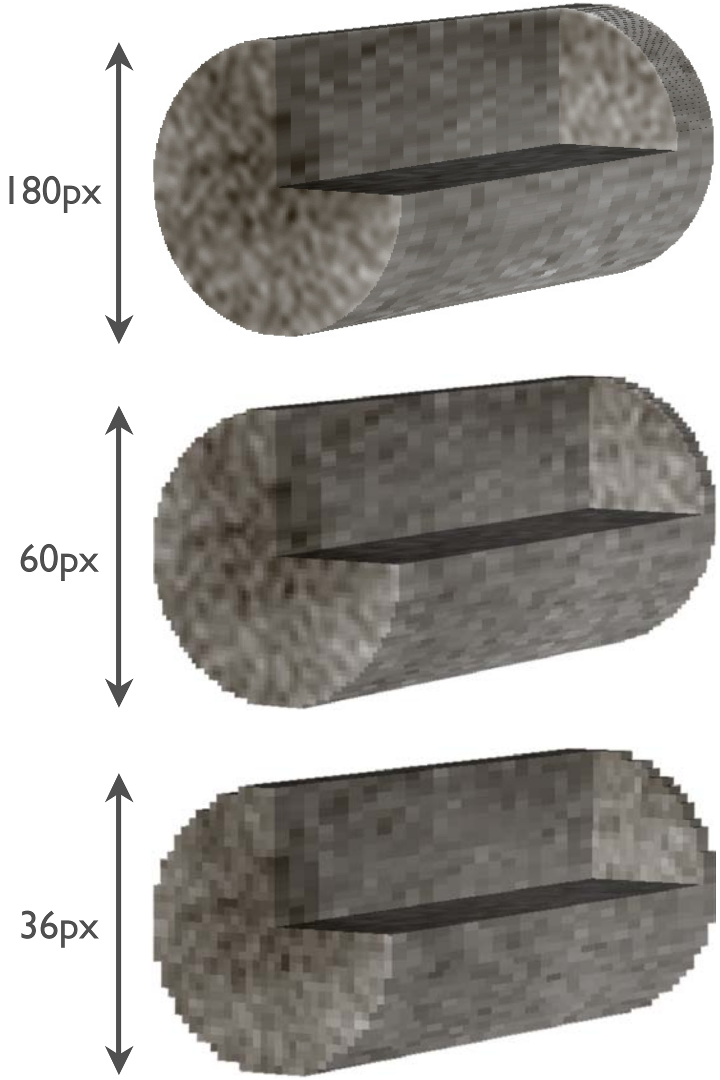
Sub-corescale saturation variations generally overlooked in relative permeability measurements.

CO_2 Saturation:



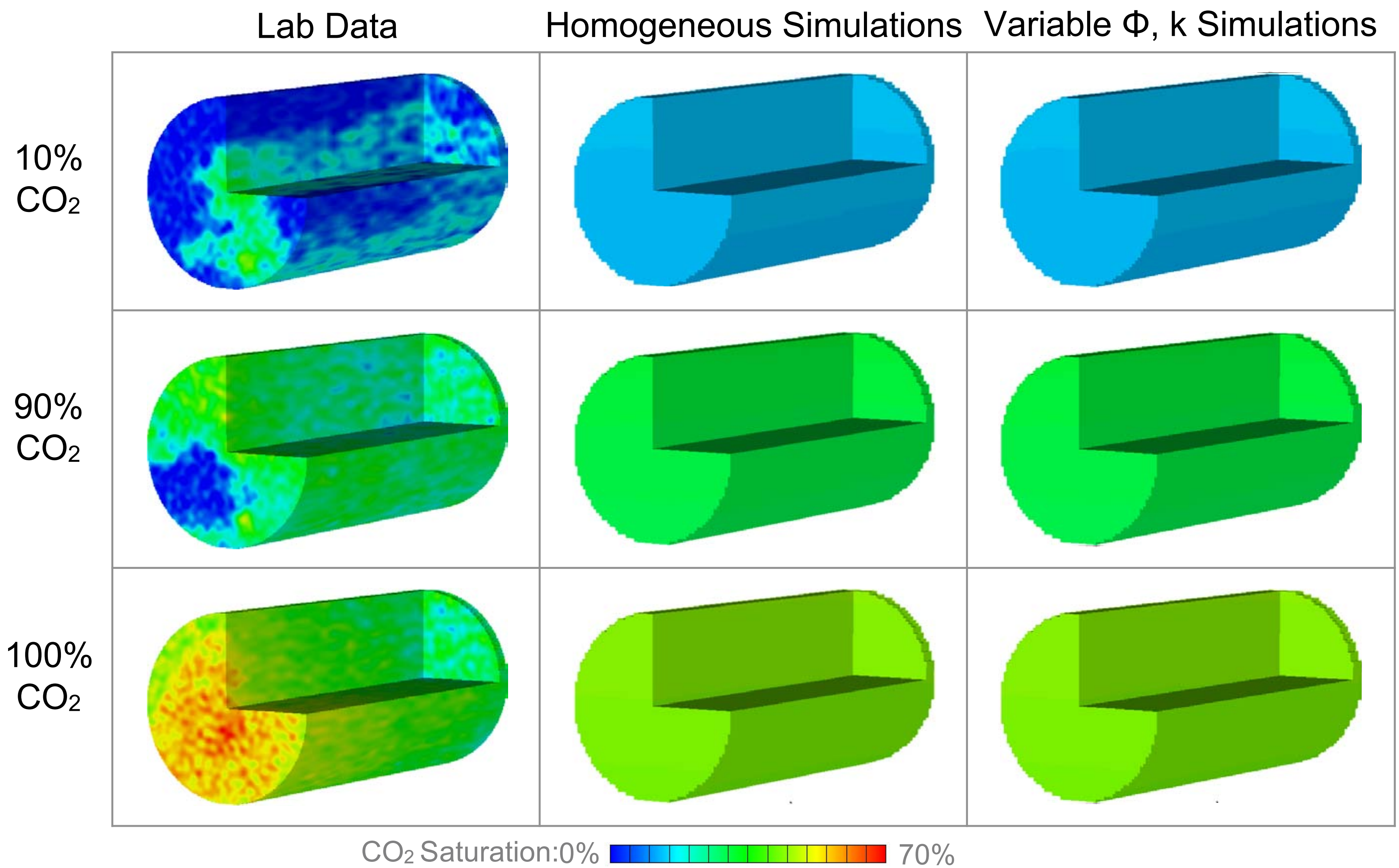
Simulated Injection of Various CO_2-Brine Proportions

- Simulation Cases
  - 10%, 90%, 100% CO_2 injections
  - 3mL/min constant flow-rate
  - 6.89MPa constant back-pressure
  - 16°C constant temperature
  - Brine contains dissolved CO_2
  - CO_2 contains dissolved water
- Core Characterization
  - Porosity/permeability “map” coarsened
  - Relative permeability/capillary pressure
    curves matched to experimental curves
- TOUGH2 (Pruess, LBNL)

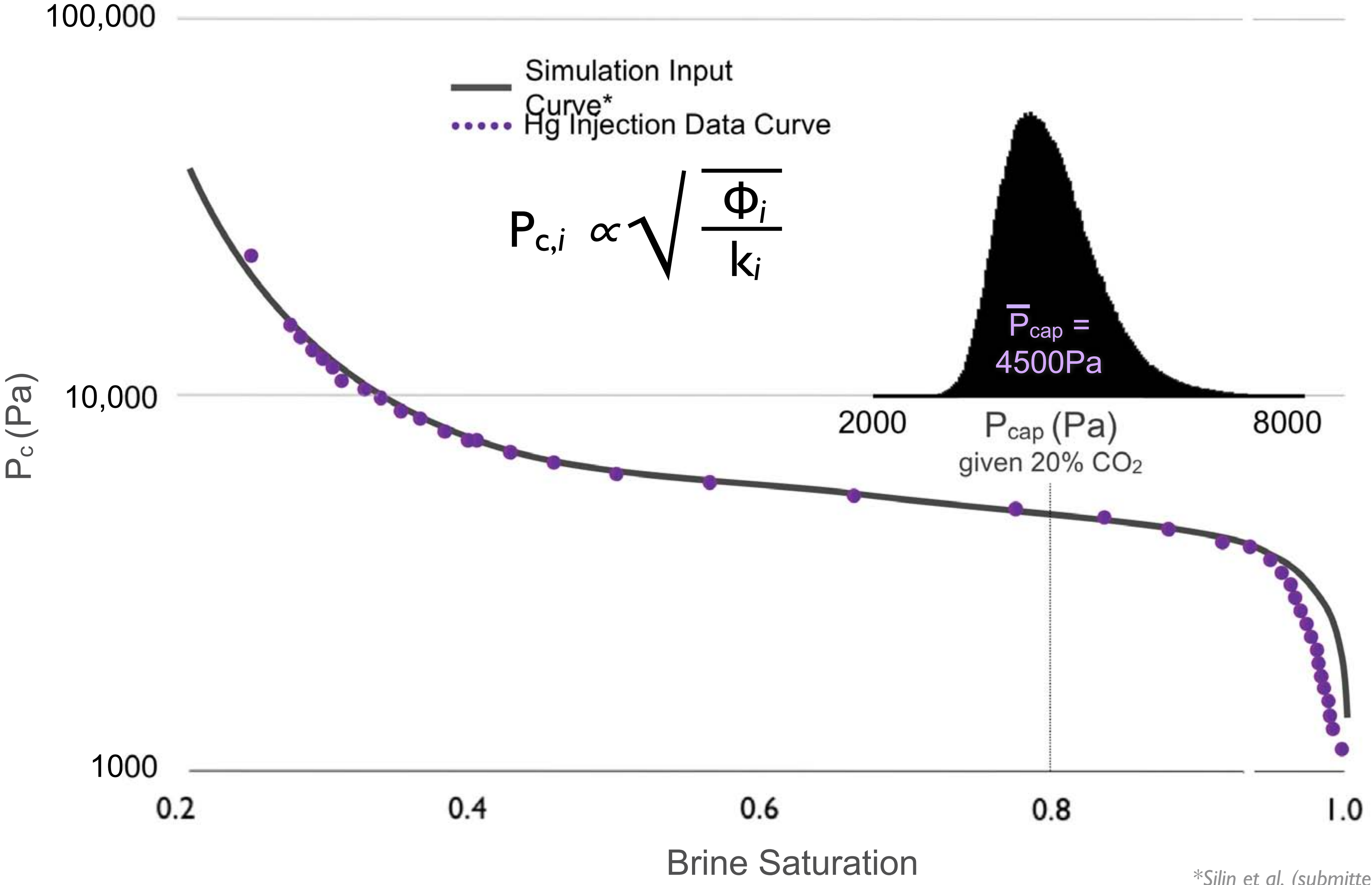


Simulated CO_2 Saturations

Constant P_c Produces Homogeneous CO_2 Saturations



Fitting Capillary Pressure Curve

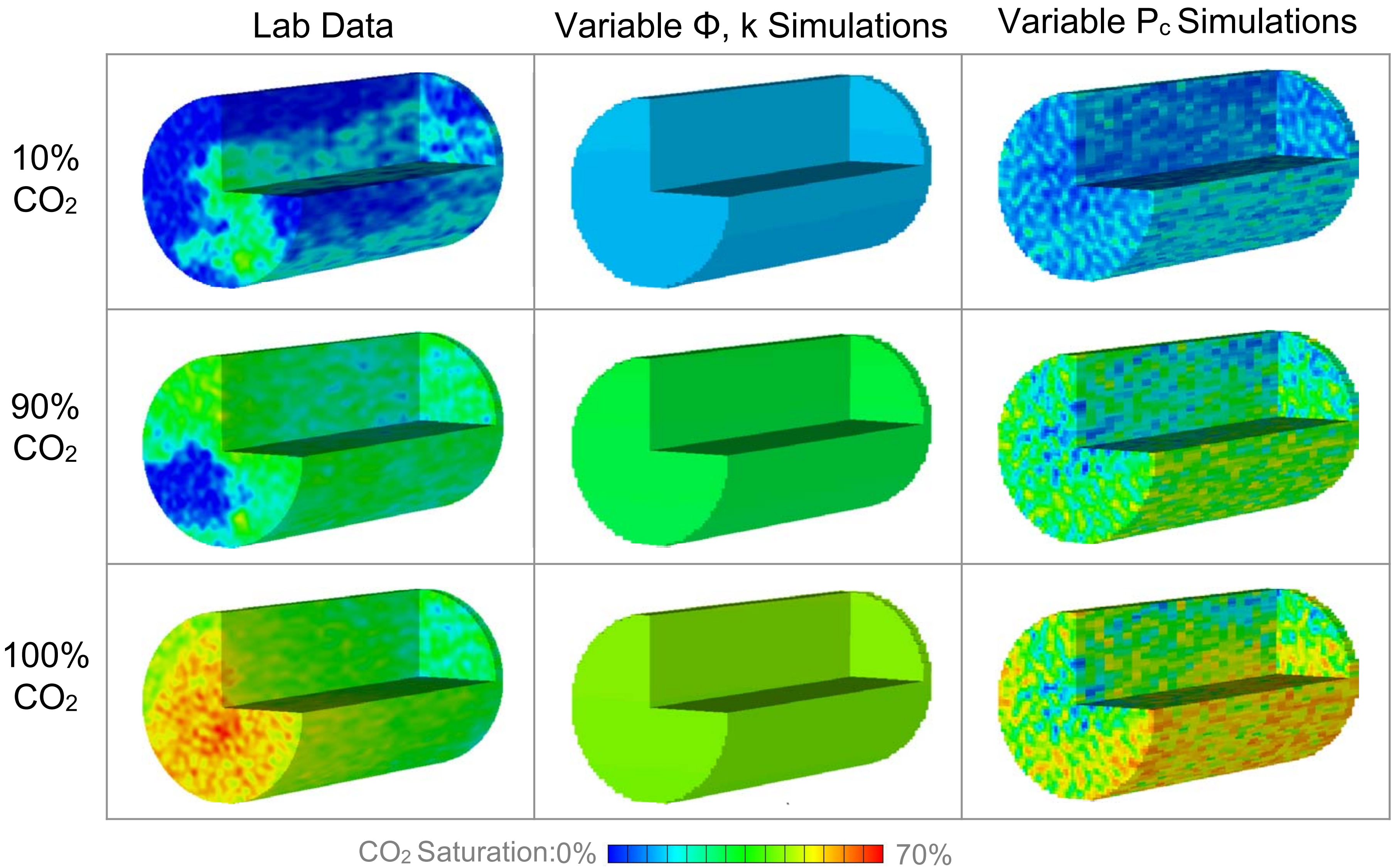


$$P_{c,i} \propto \sqrt{\frac{\Phi_i}{k_i}}$$

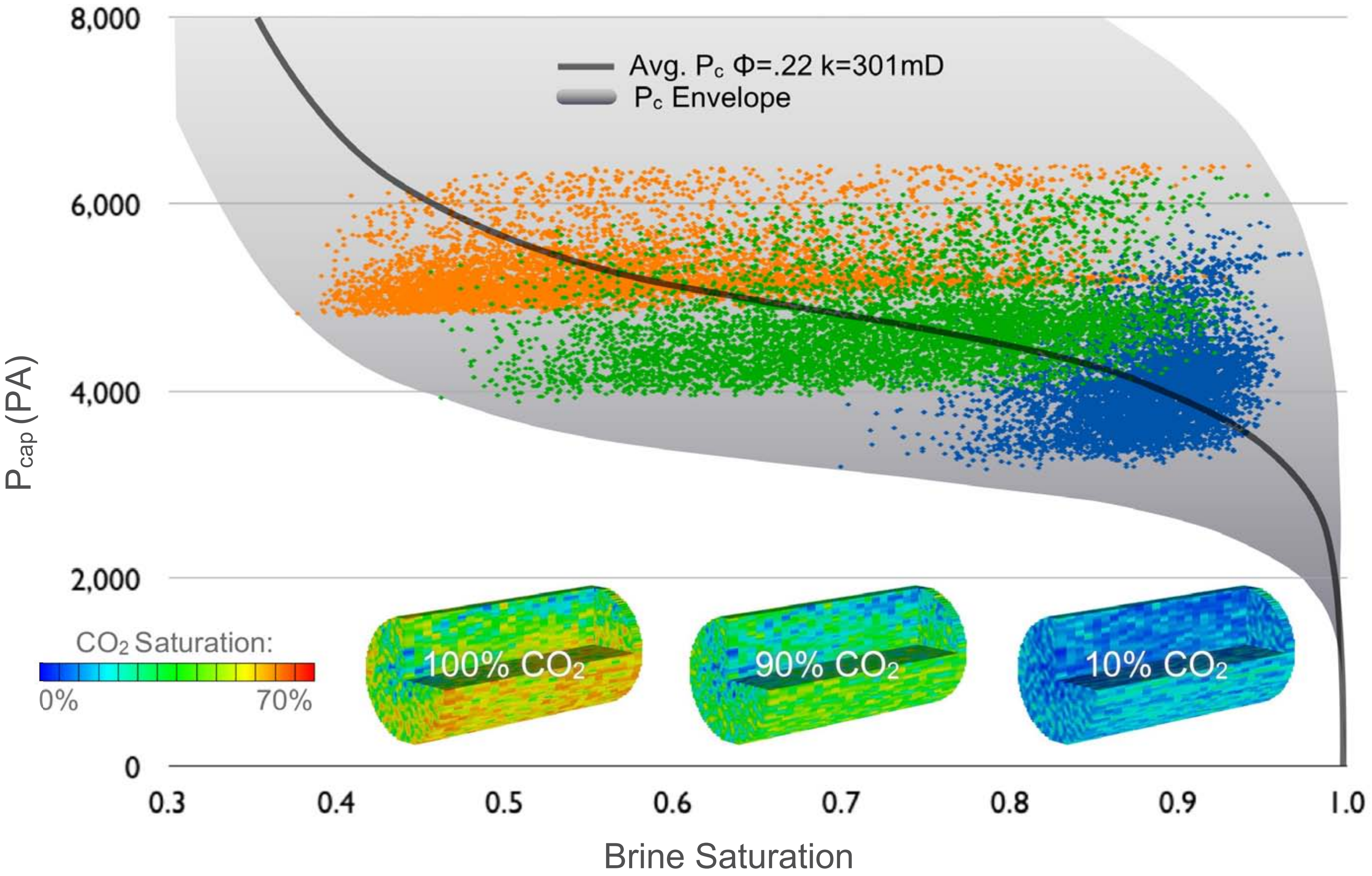
*Silin et al. (submitted, 2007)

Simulated CO_2 Saturations

Variable P_c Produces Small-scale CO_2 Saturation Variations



Capillary Pressure Curve



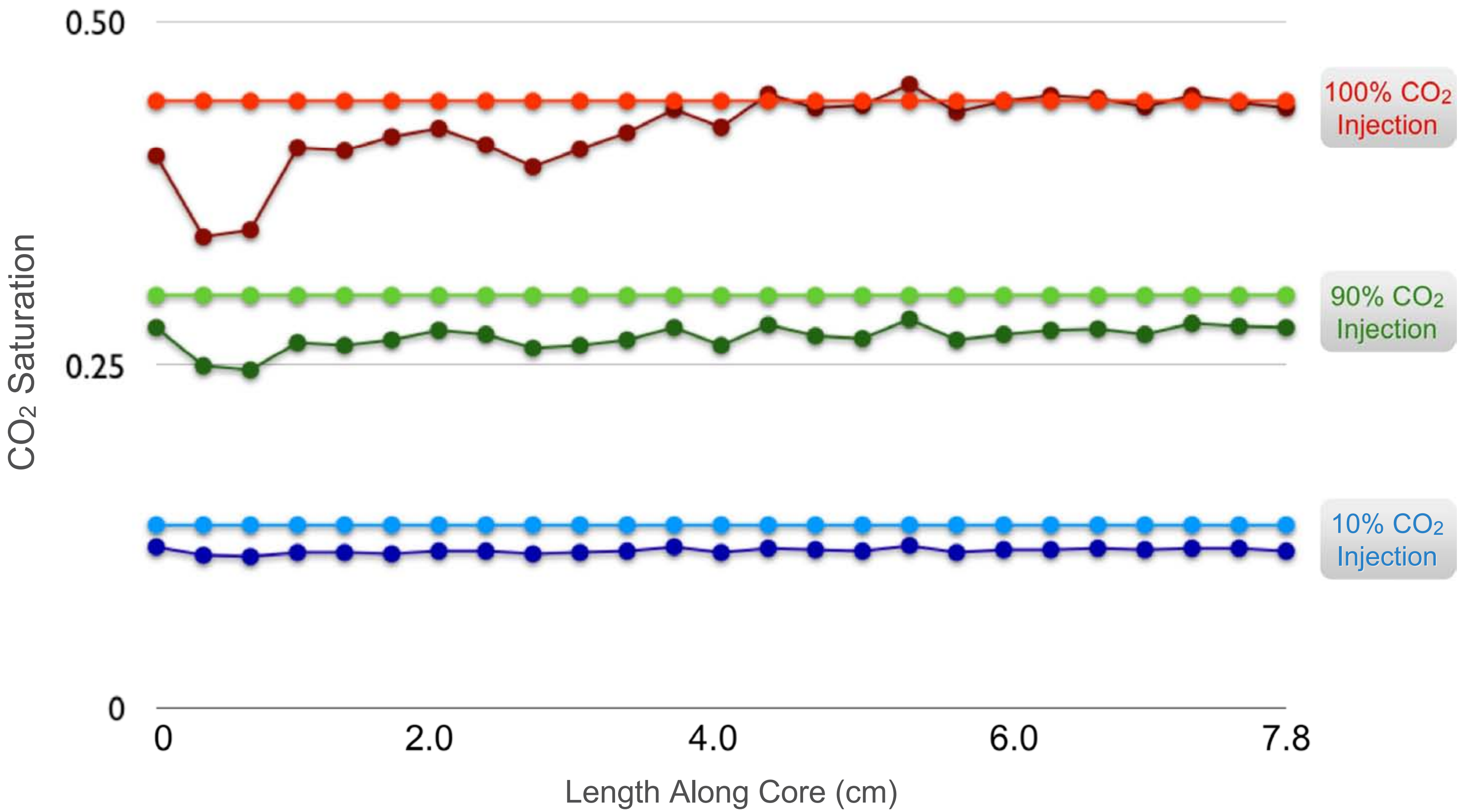
Why should we care?

Why Should We Care?

Average CO_2 saturation is:

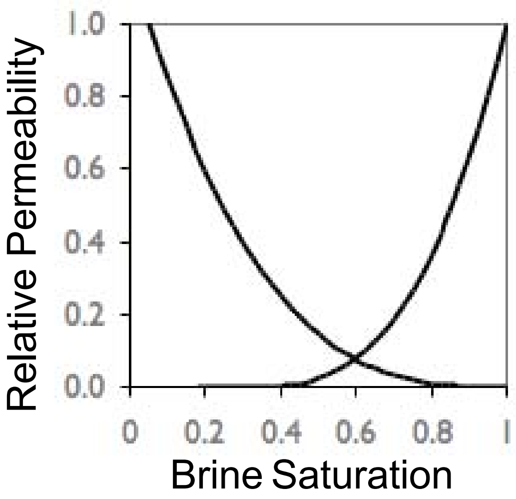
- Decreased by sub-corescale heterogeneity
- Flow-rate dependent
- Affected by simulation grid resolution

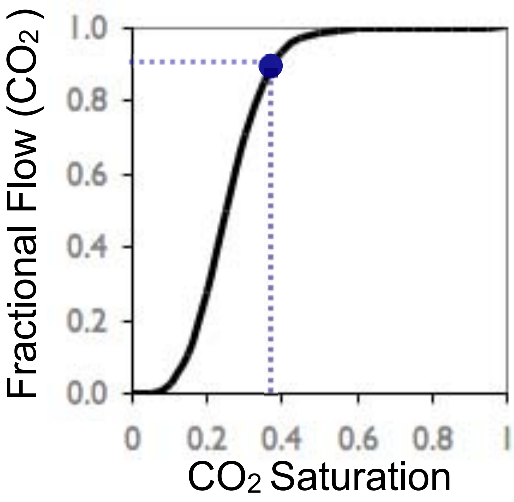
Subcore-scale Heterogeneity Decreases CO_2 Saturation

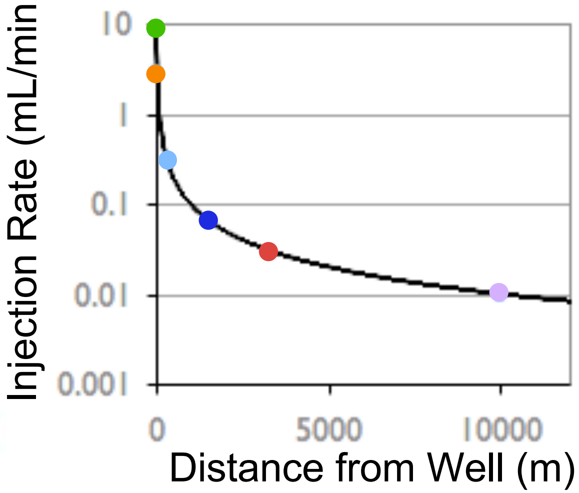


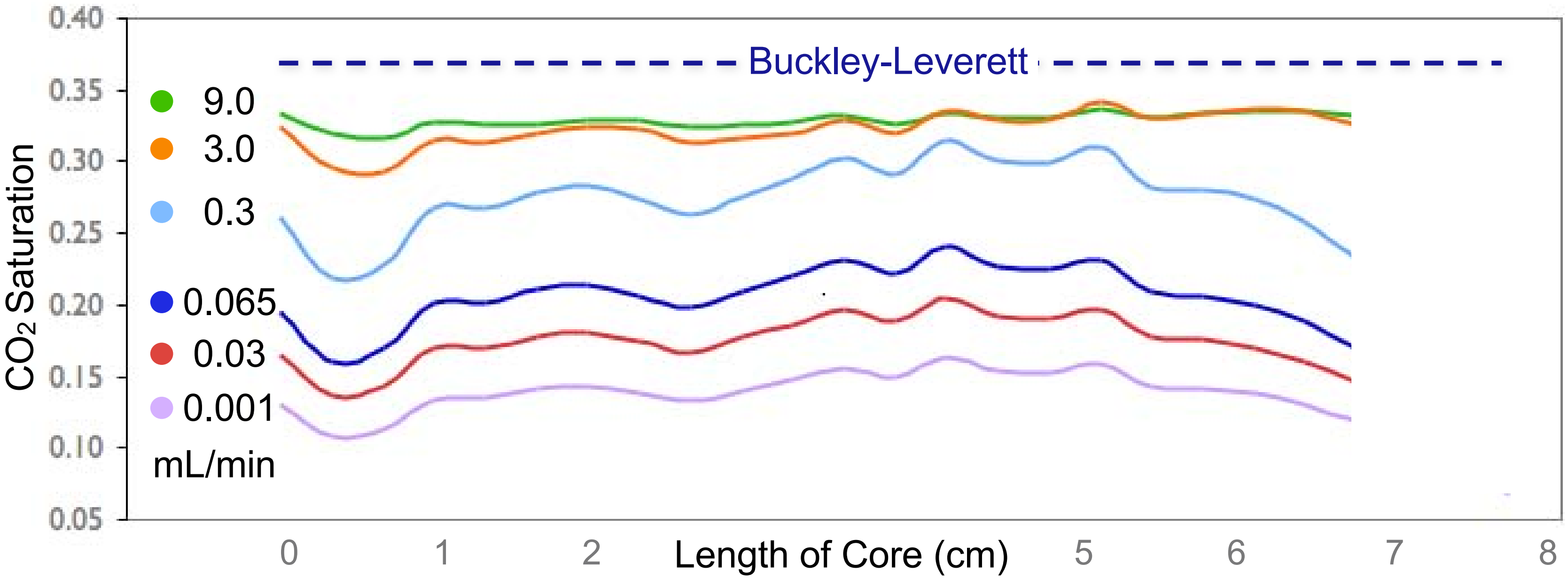
Effects of Flow Rate on CO_2 Saturation

90% CO_2 Injection Simulation

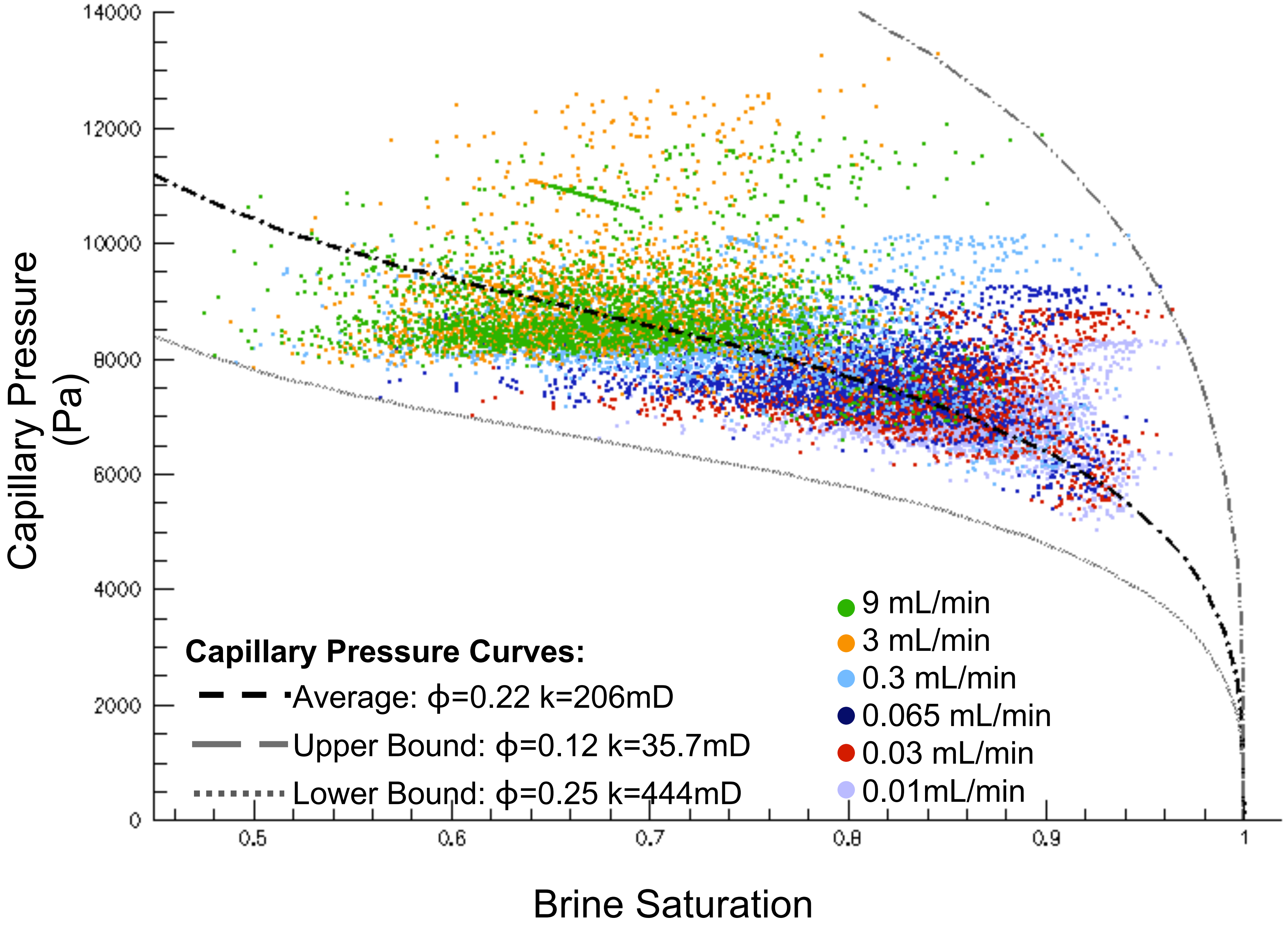






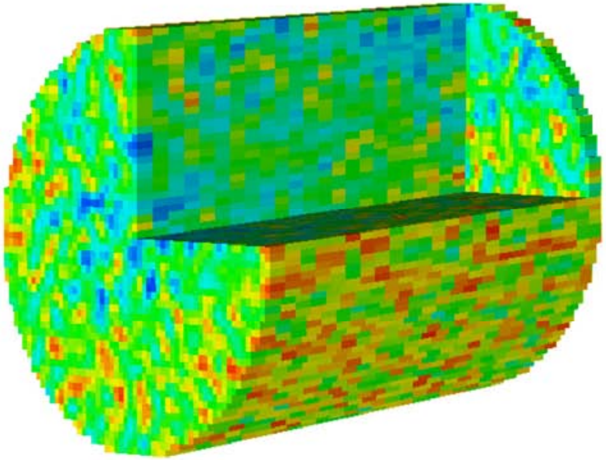


Capillary Pressure Distribution at Different Flow Rates

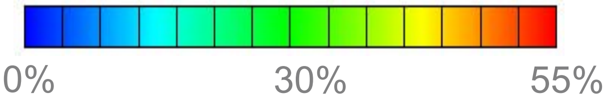


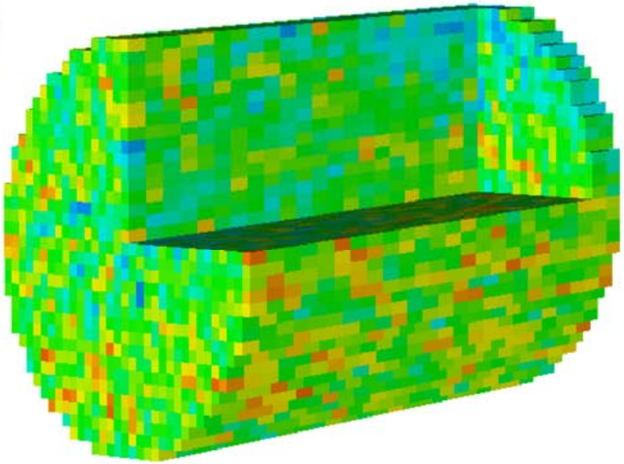
90% CO_2, 10% Brine Injection

Variable Simulation Resolutions

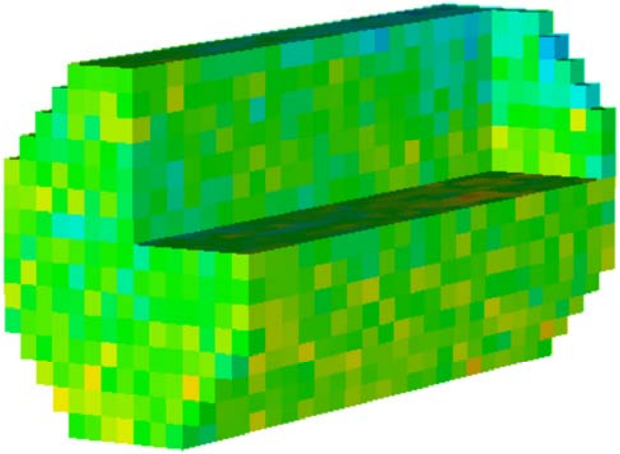


Grid Size: 0.6×0.6×3mm
Grid Count: 67,350



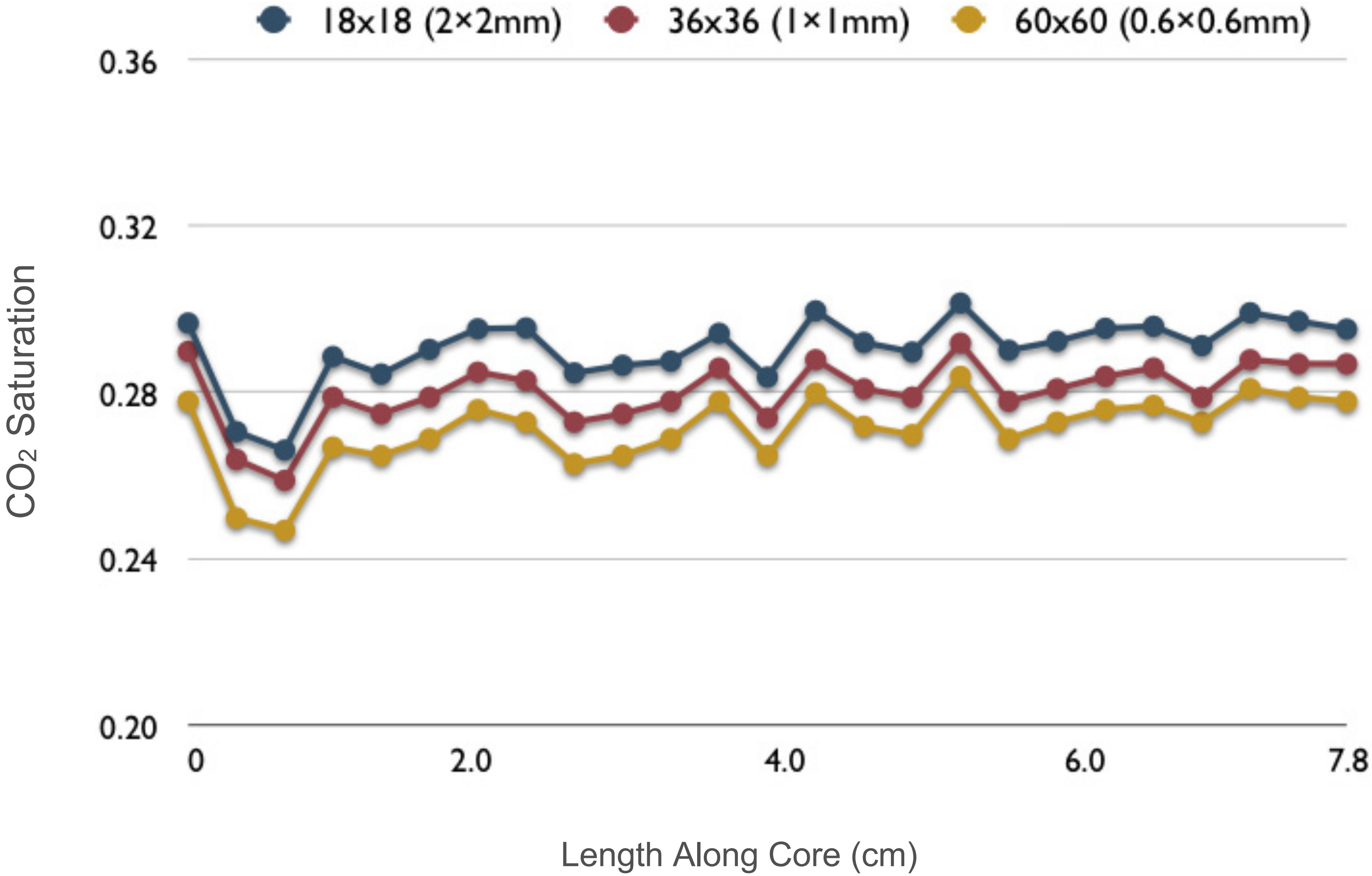


Grid Size: 1×1×3mm
Grid Count: 23,400



Grid Size: 2×2×3mm
Grid Count: 5,400

Finer Simulation Grids Decrease CO_2 Saturation



Conclusions

- Core-scale multi-phase flow experiments reveal strong influence of sub core-scale heterogeneity
- Spatial variations in capillary pressure behavior control CO_2 saturations
- CO_2 saturation:
  - Decreases due to bypass of low porosity regions
  - Decreases at lower flow rates
  - Predictions depend on grid size
- Similar phenomena are expected at all spatial scales
- Fundamental research needed to improve model predictions
  - Fundamental process understanding based on lab and field experiments
  - Up-scaling strategies that accurately include the effects of sub-grid scale heterogeneity
  - Calibration and validation of predictive models