Multiphase Flow of CO_2 and Brine: Fundamental Concepts to Optimization

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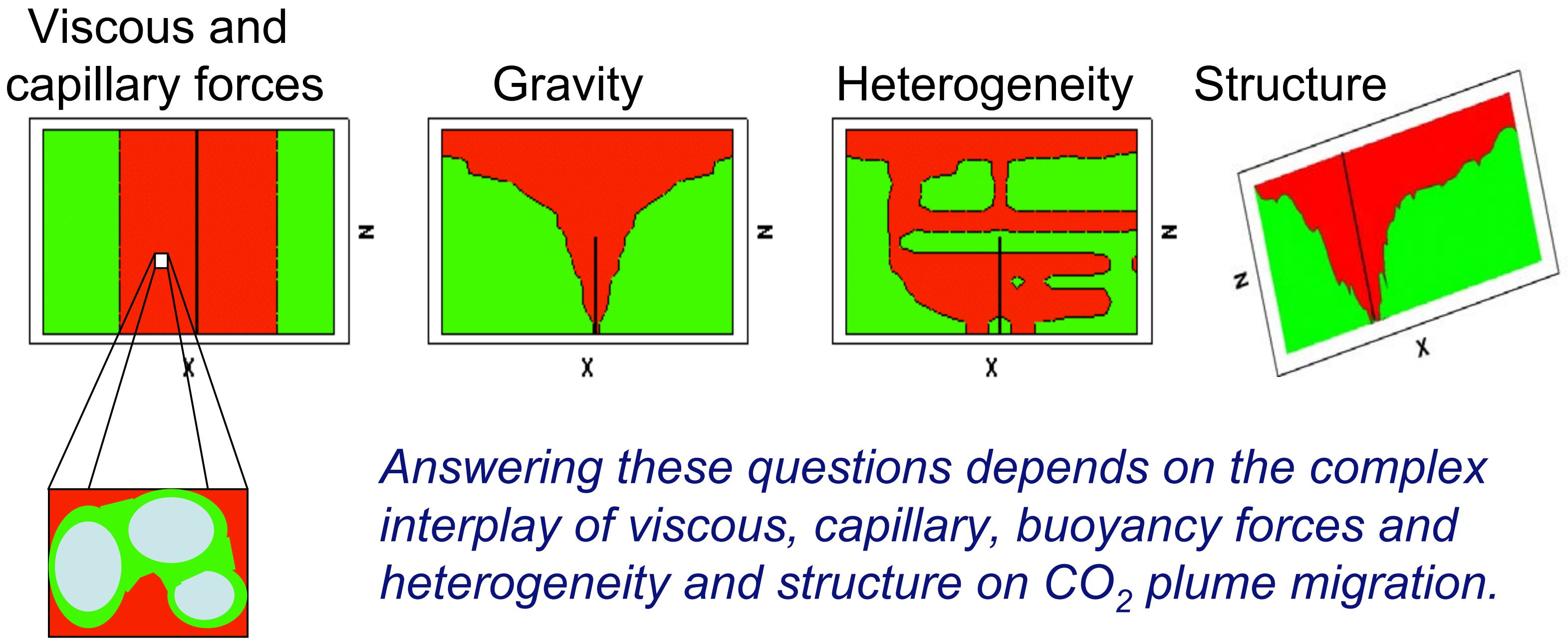
Key Issues for CO_2 Storage in Deep Geological Formations

- How big will the CO_2 plume be?
- What fraction of the pore space can be filled with CO_2?
- How much CO_2 will be dissolved?
- How much will capillary trapping immobilize CO_2?
- How fast could CO_2 leak up a fault zone?

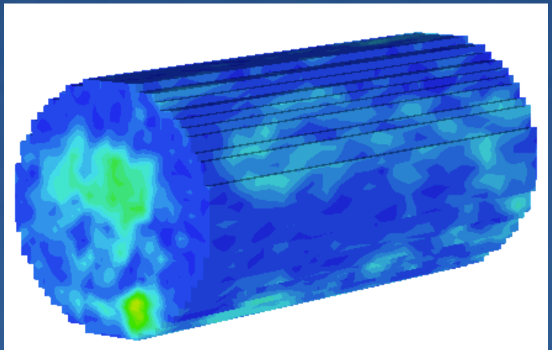


Answering these questions depends on the complex interplay of viscous, capillary, buoyancy forces and heterogeneity and structure on CO_2 plume migration.

Courtesy of Christine Doughty, LBNL

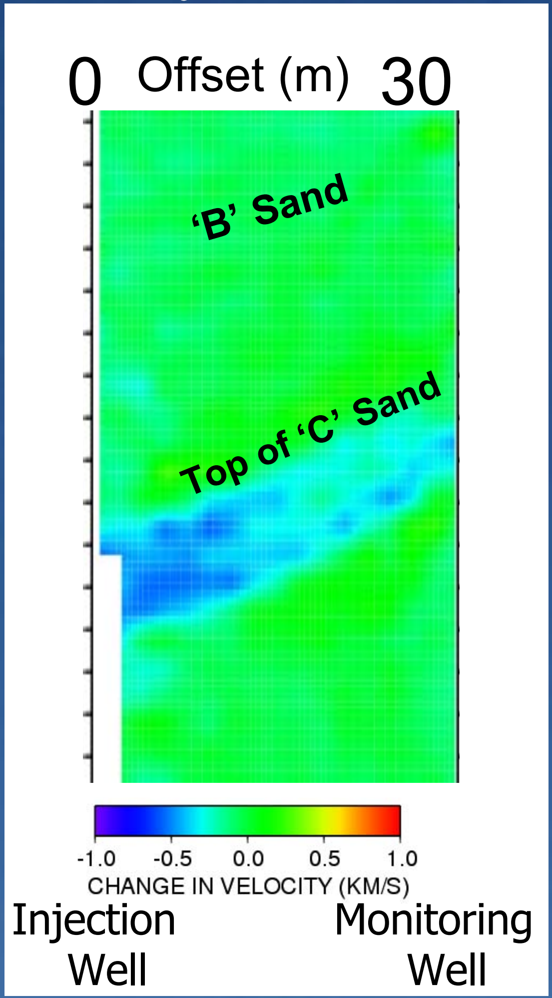
Complex Behavior at Every Scale

X-ray Tomogram
(L. Tomutsa, LBNL)



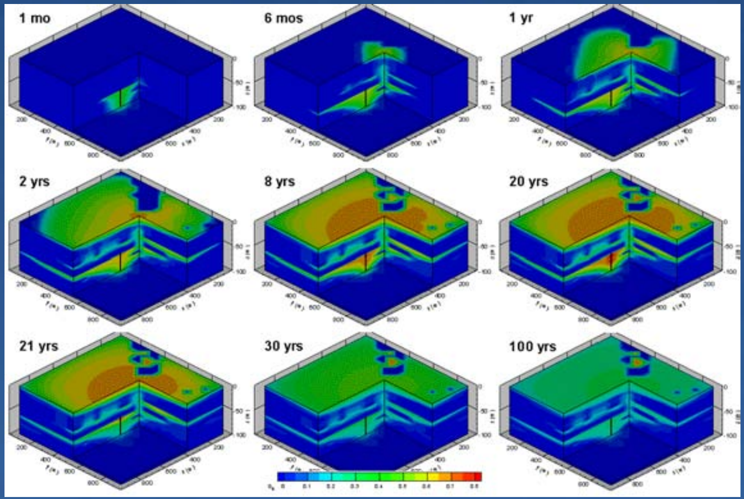
Core Scale

Seismic Tomogram
Daley et al., 2007



Frio Pilot Test

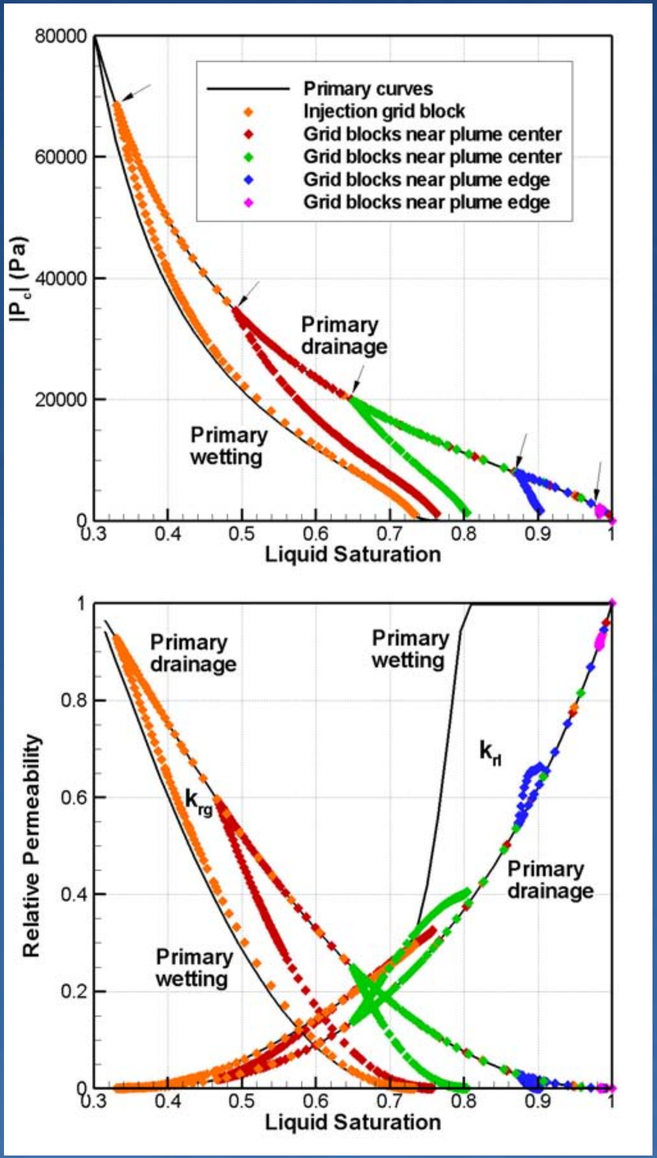
TOUGH2 Simulation
C. Doughty, LBNL



Reservoir Scale

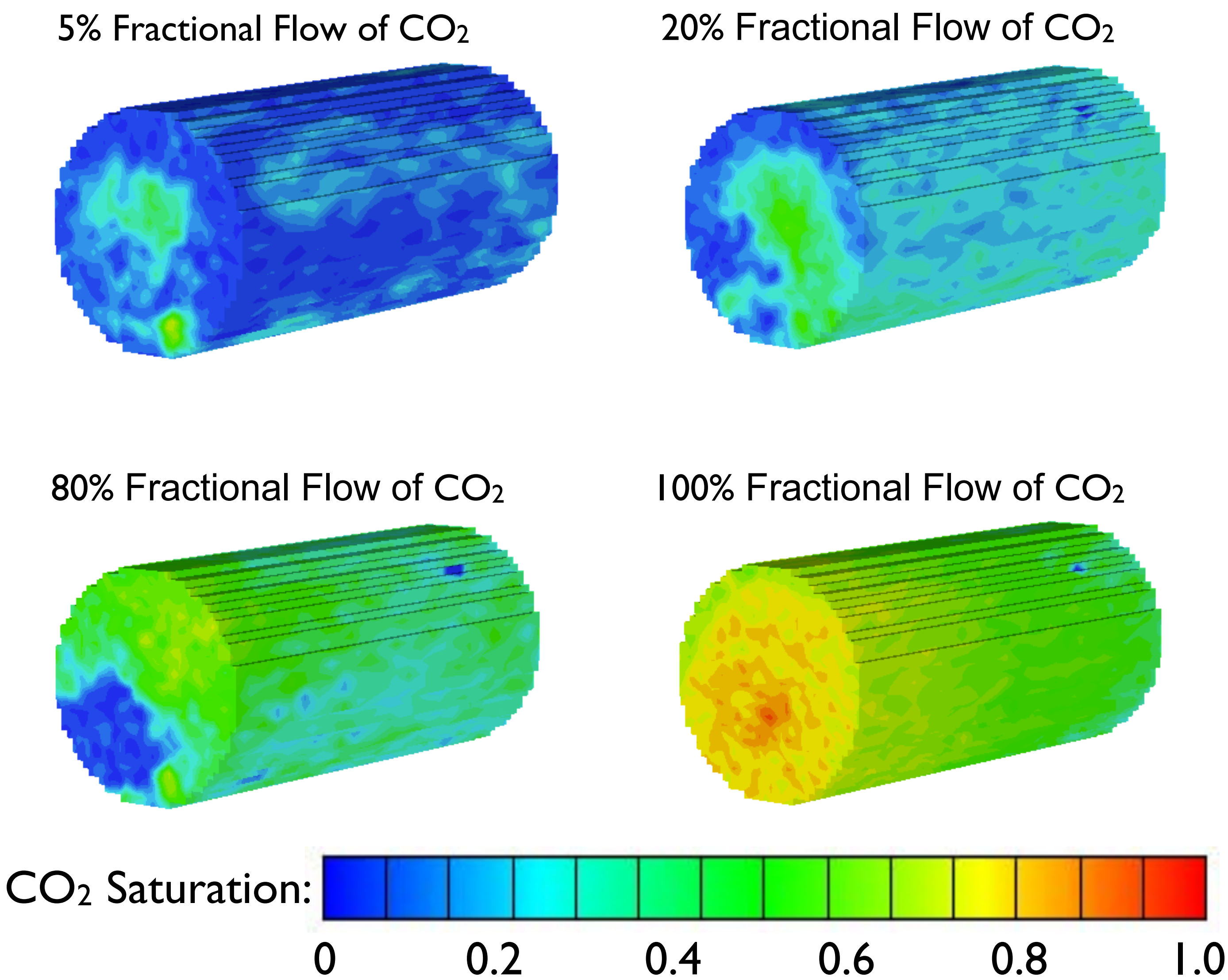
Simulation with TOUGH2

- Two-phase system
  - Native brine is wetting phase
  - Injected supercritical CO_2 is non-wetting phase
- Fluid flow modeled with multi-phase extension of Darcy's law
- Hysteretic relative permeability and capillary pressure functions describe interaction between phases
- CO_2 partially dissolves in brine according to Henry's Law
- Isothermal simulations

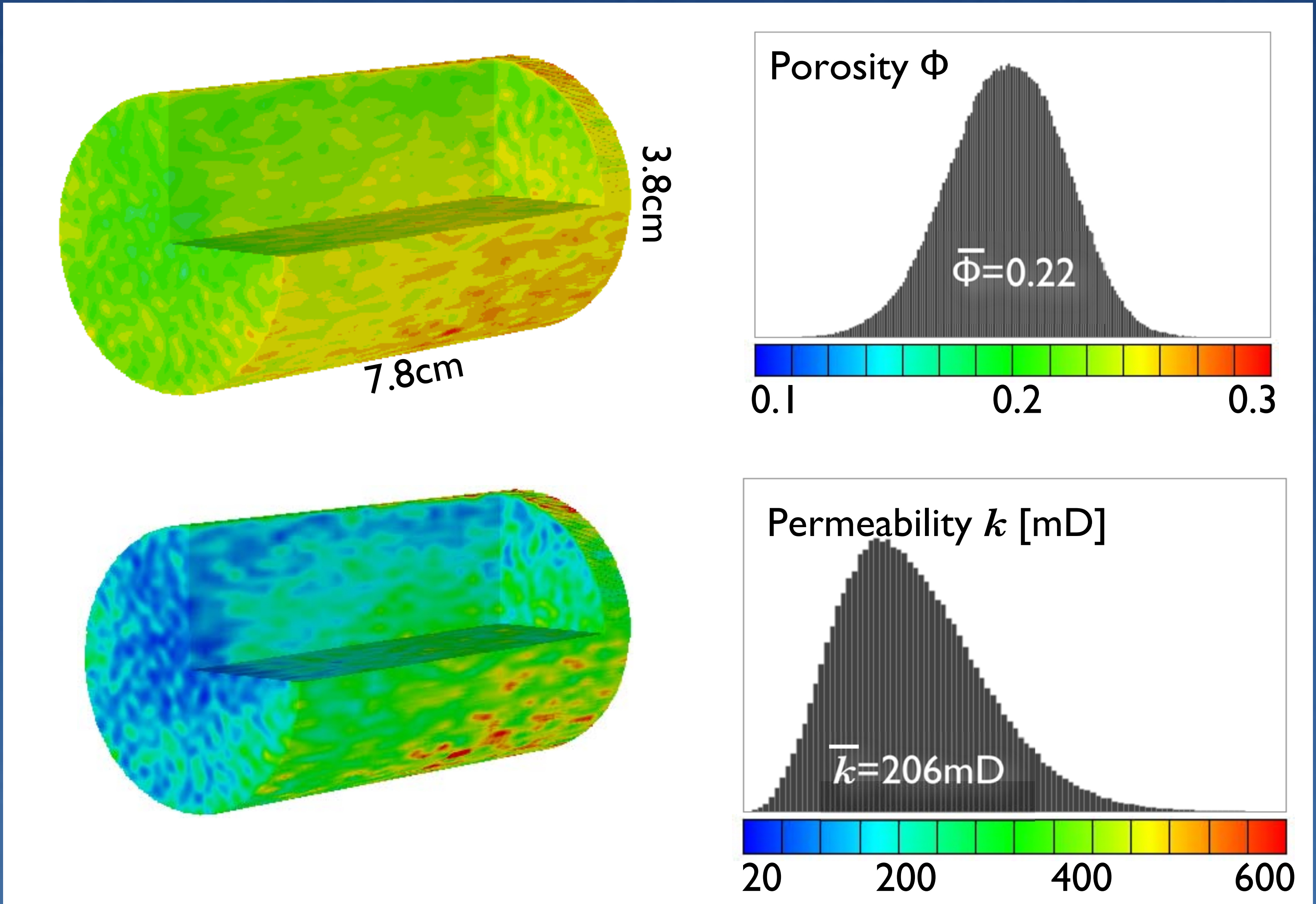


Hysteretic Capillary Pressure and Relative Permeability Curves Used by TOUGH2

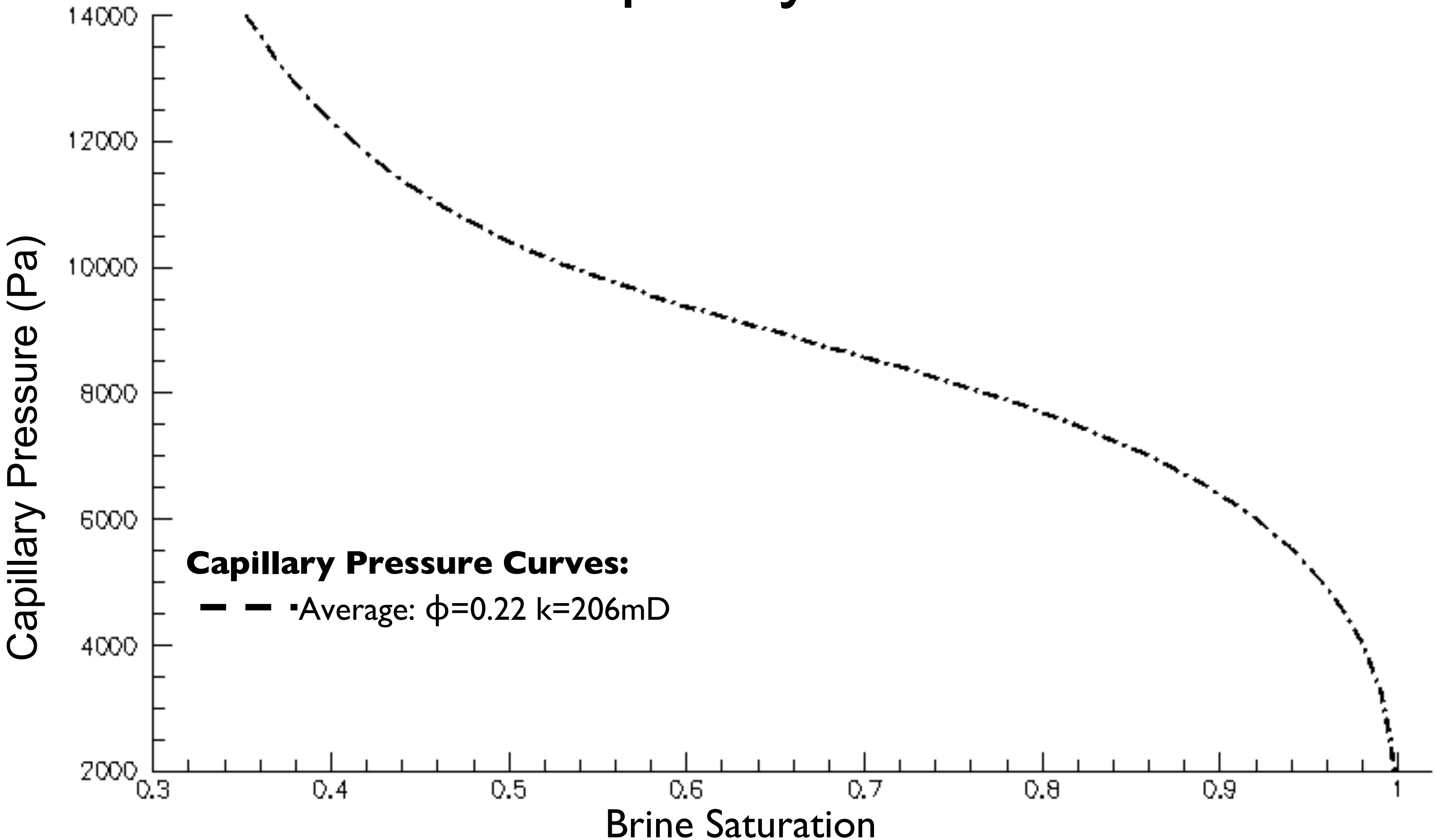
Core Flood Experiments



Berea Sandstone Core

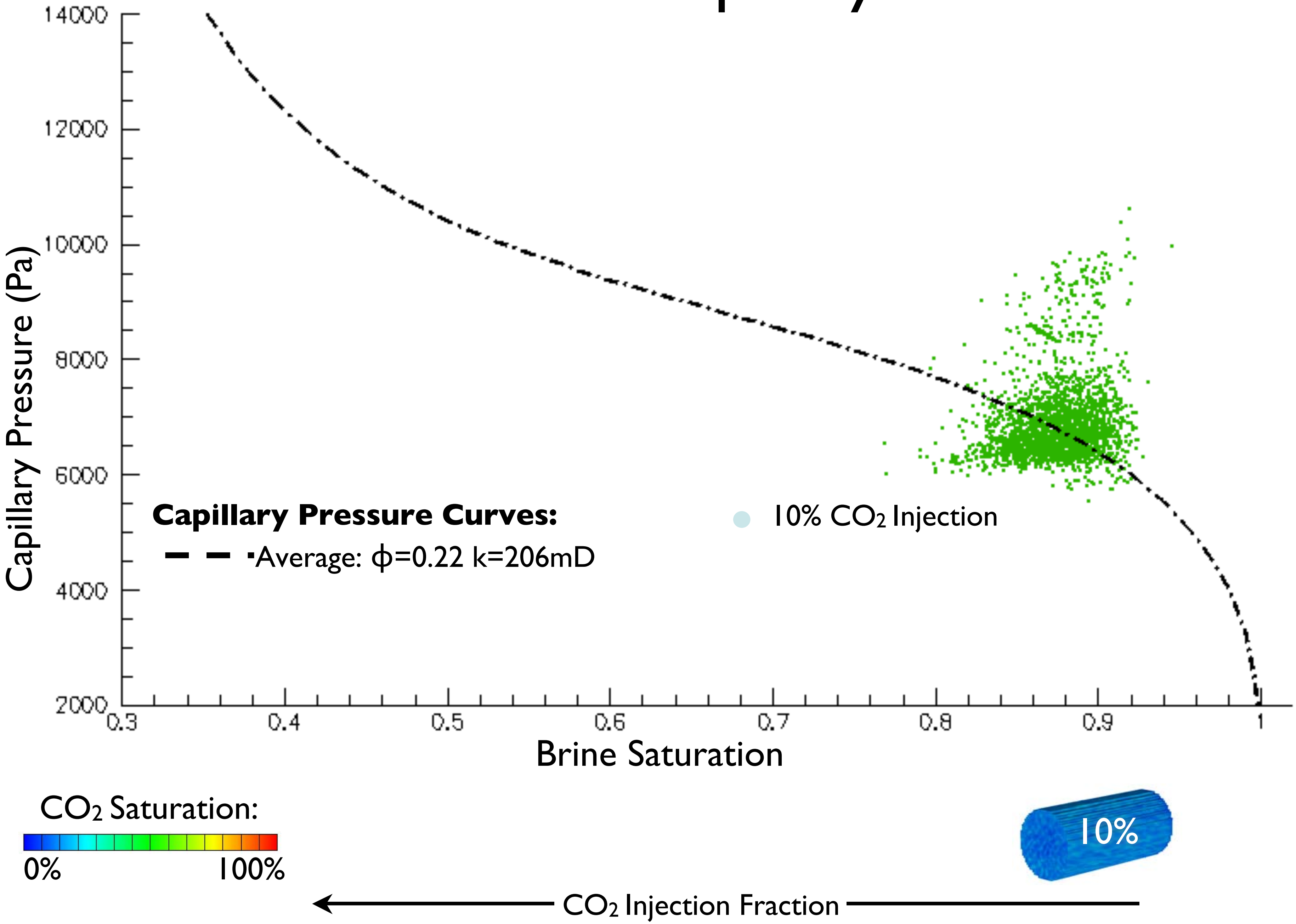


Measured Capillary Pressure Curve



$$P_c = \sigma \sqrt{\frac{\phi}{k}} J^*(s) \; where \; J^*(\mathrm{s}) = \mathrm{A}\left(\mathrm{s}^{*-\lambda_1} - 1\right) + B\left(1 - \mathrm{s}^{*\lambda_2}\right)^{1/\lambda_2} \; and \; s^* = \frac{s - s_J}{1 - s_J}$$

Simulated Capillary Pressure



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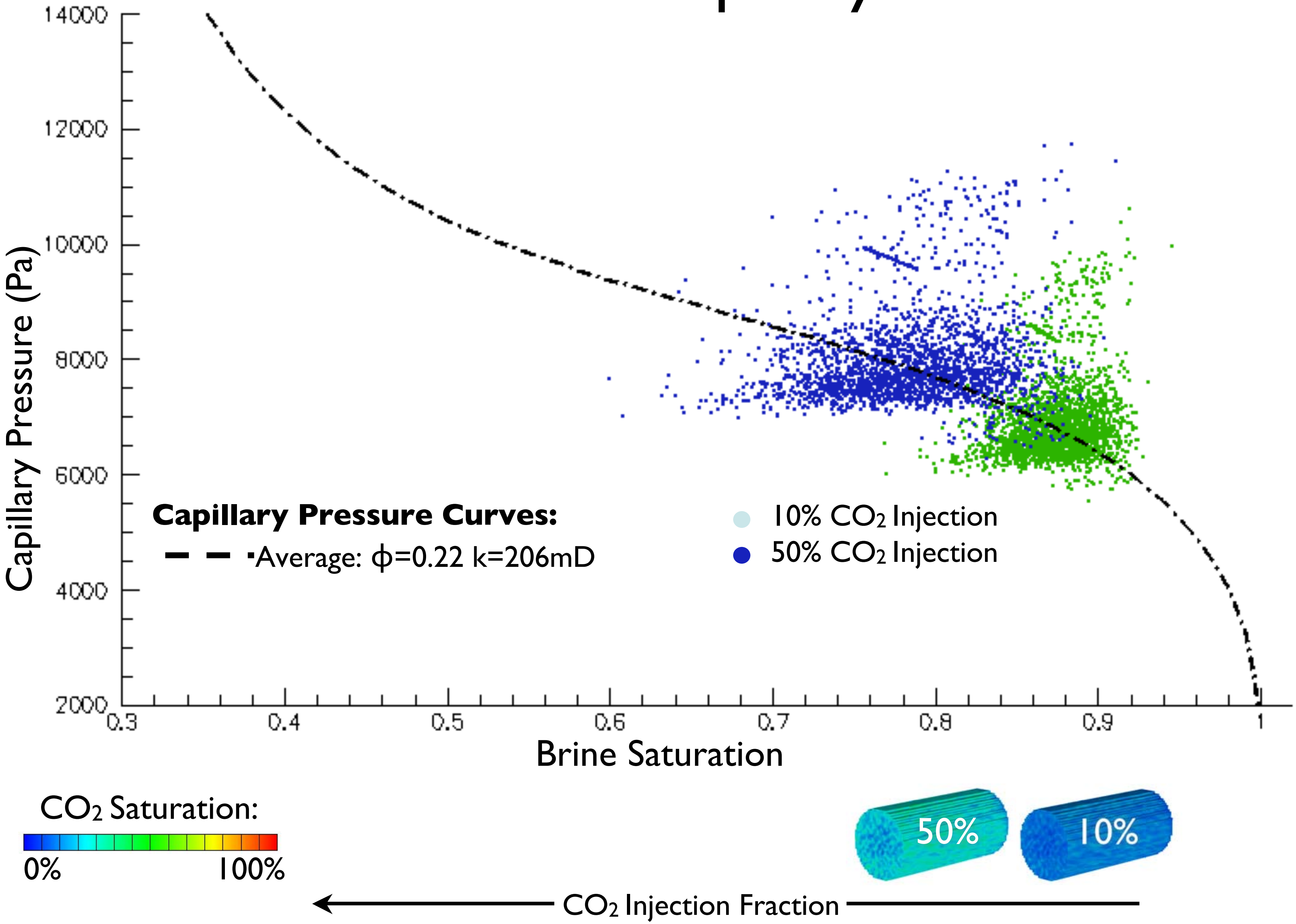

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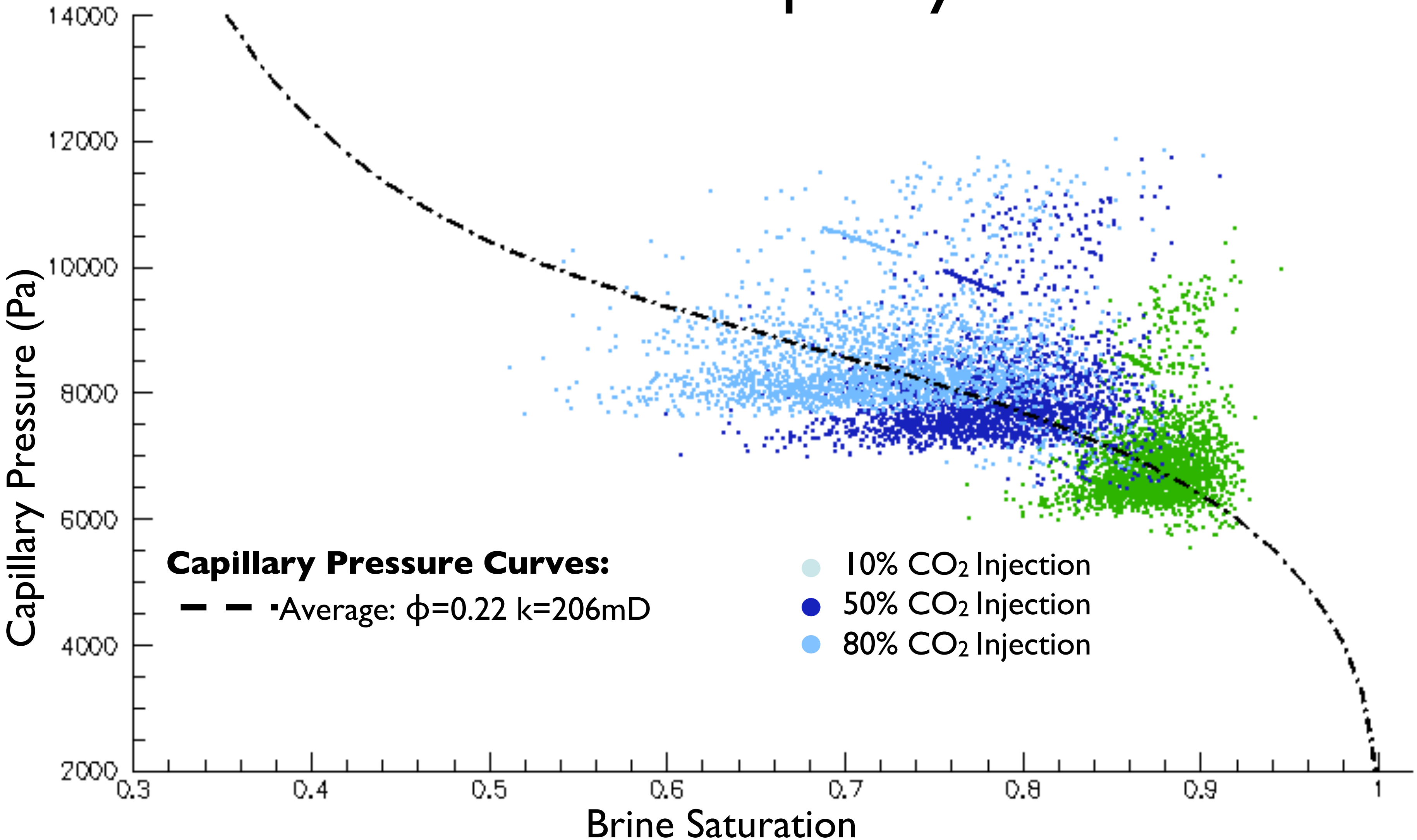
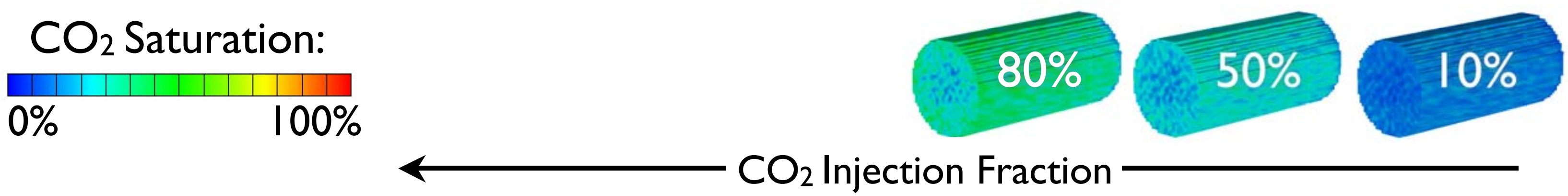
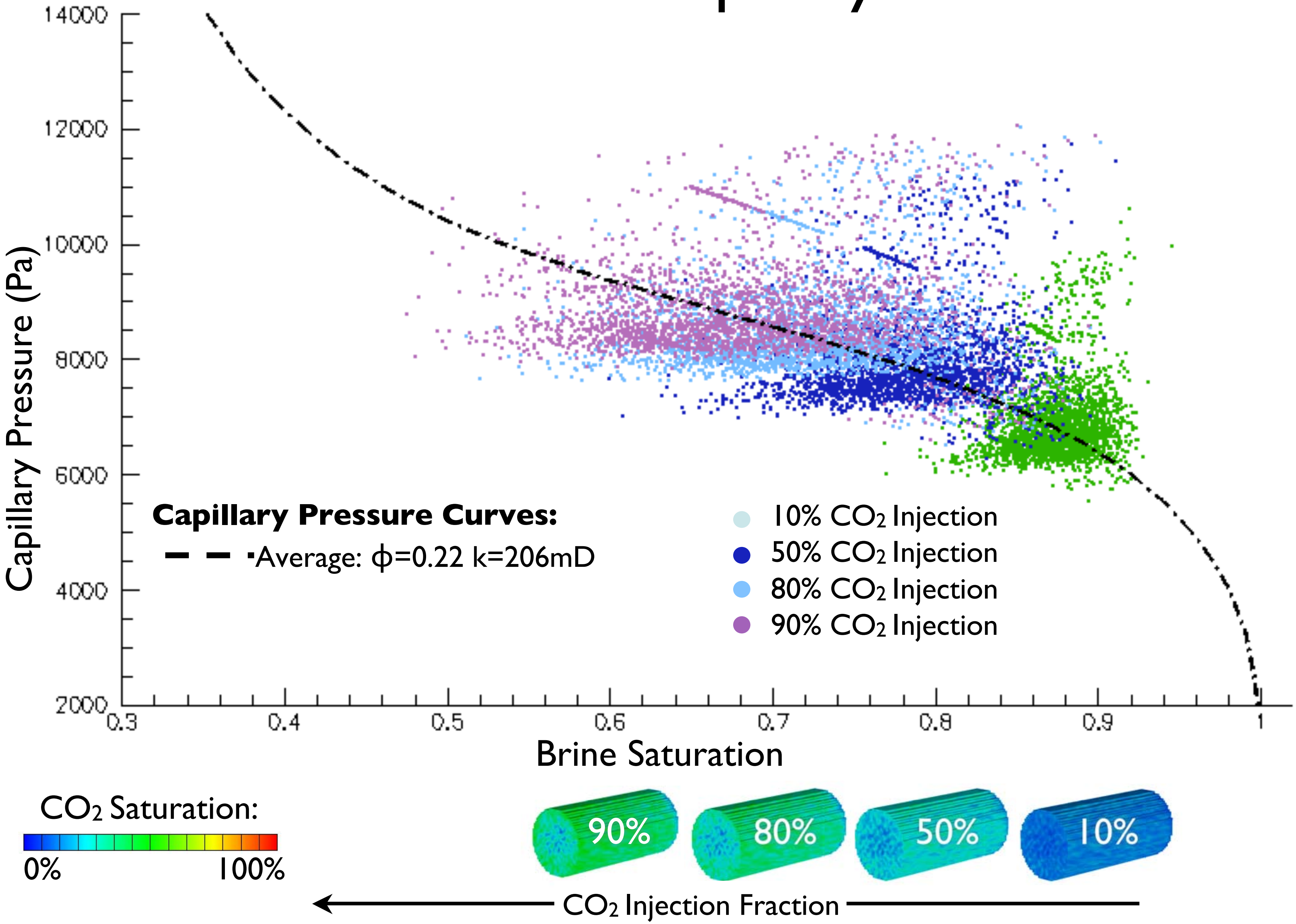
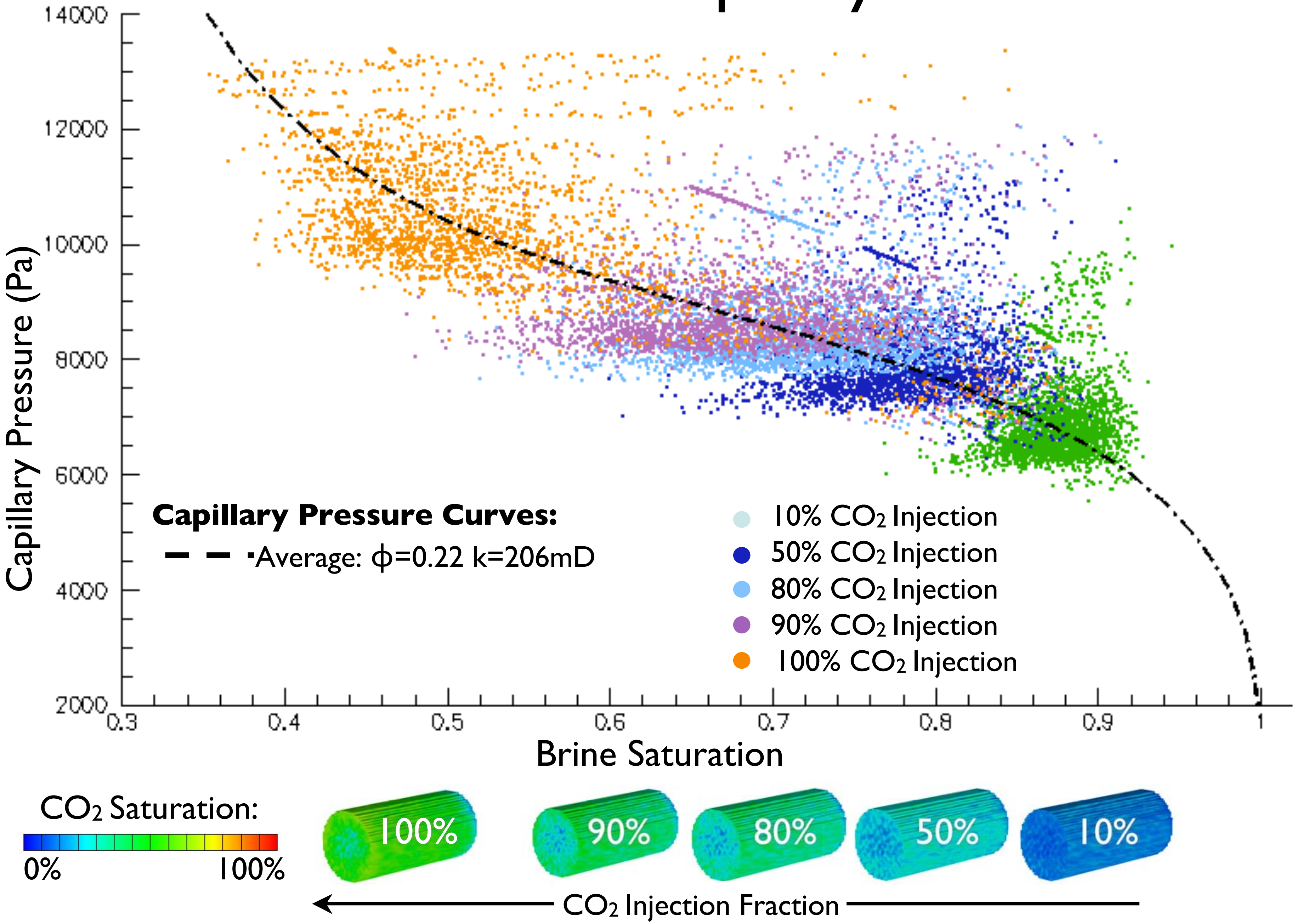




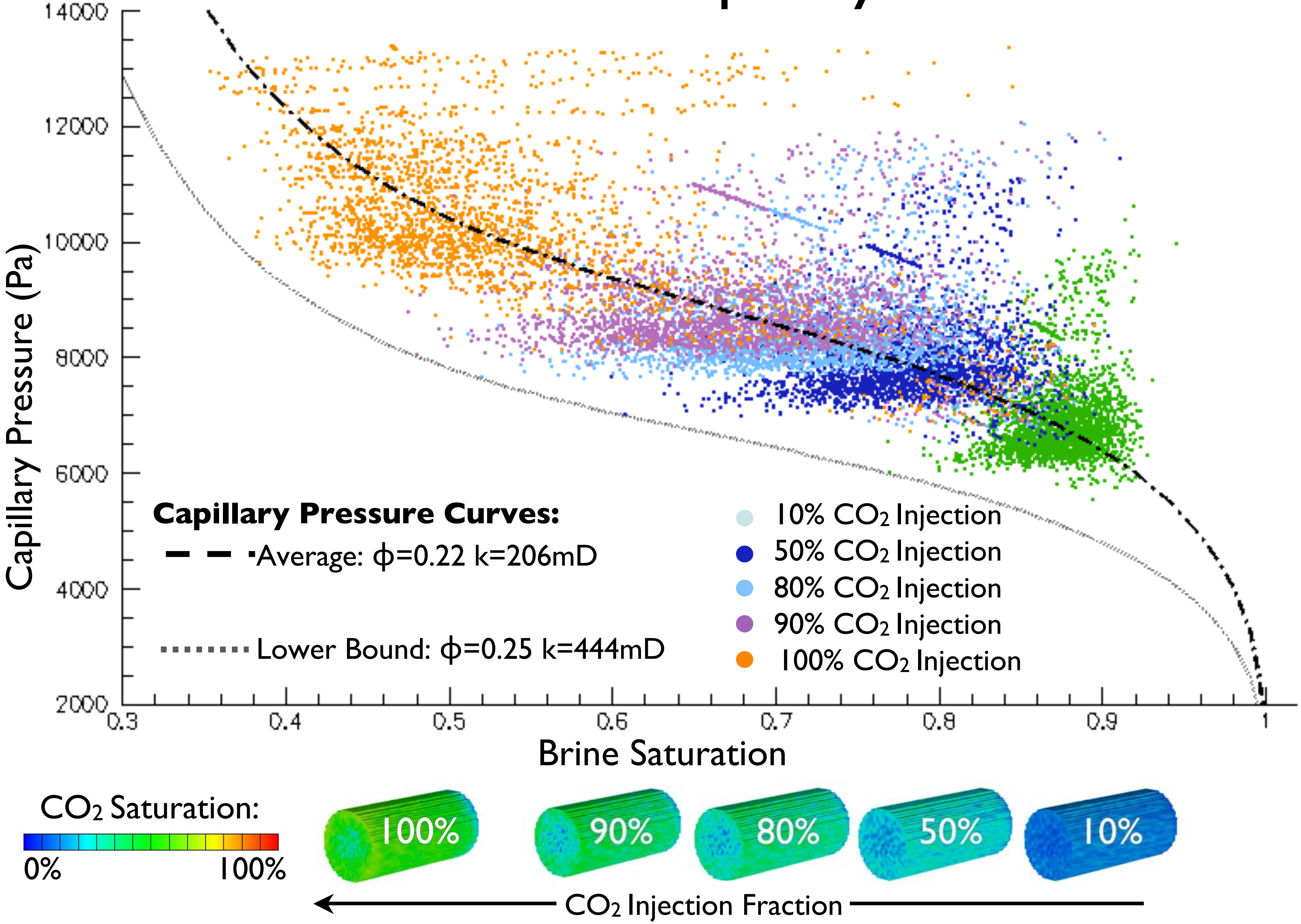
Simulated Capillary Pressure



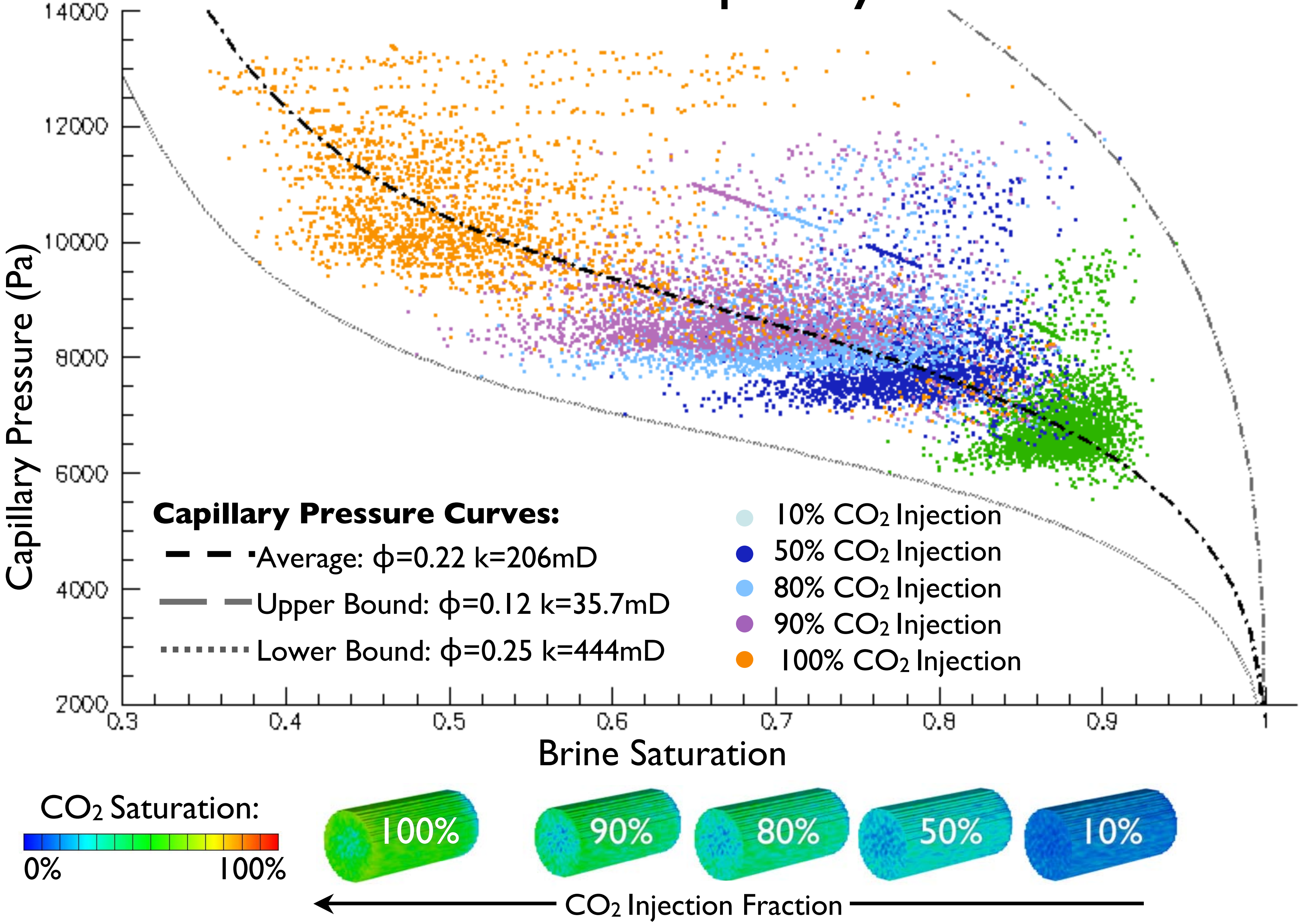
Simulated Capillary Pressure



Simulated Capillary Pressure

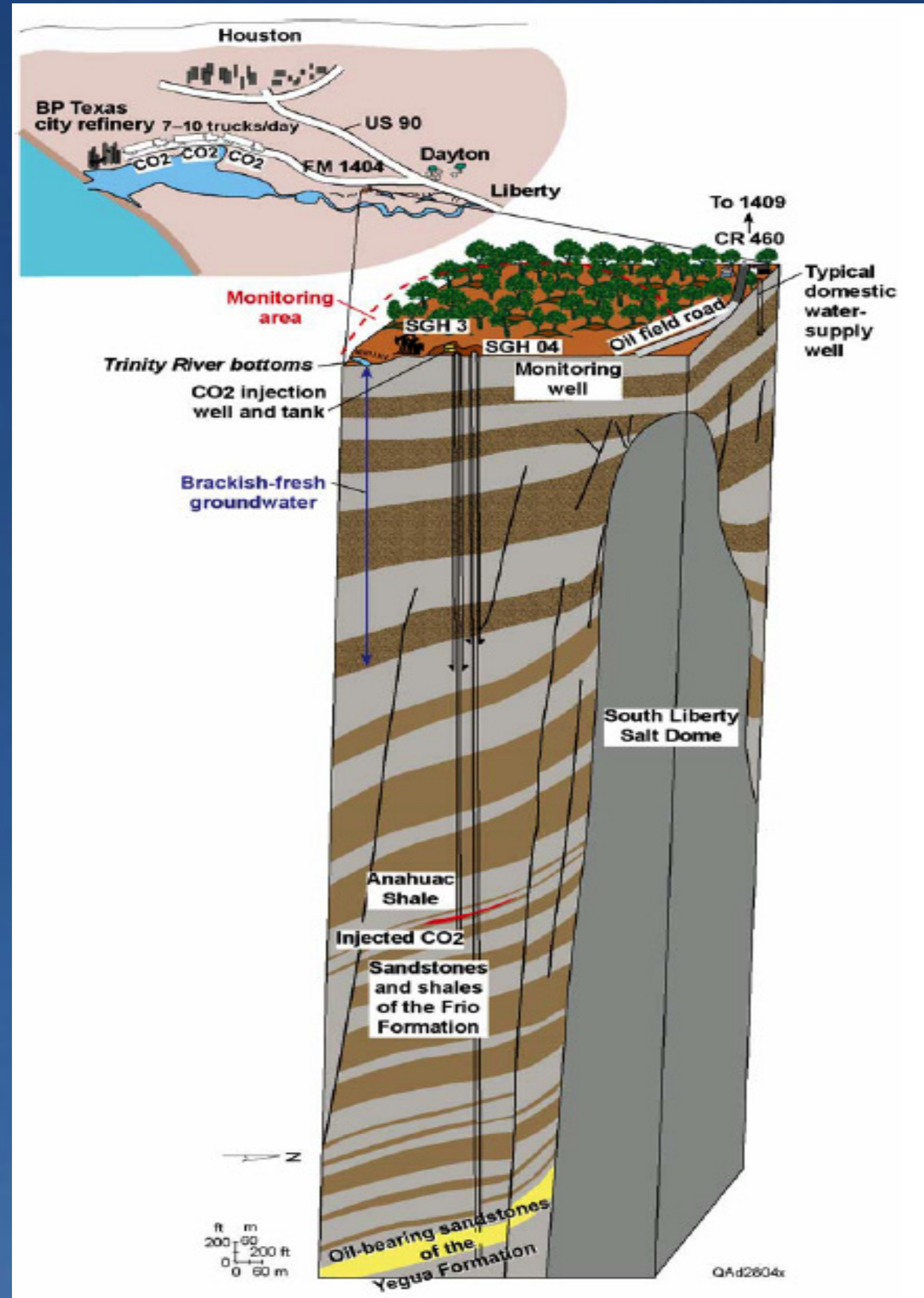


Simulated Capillary Pressure



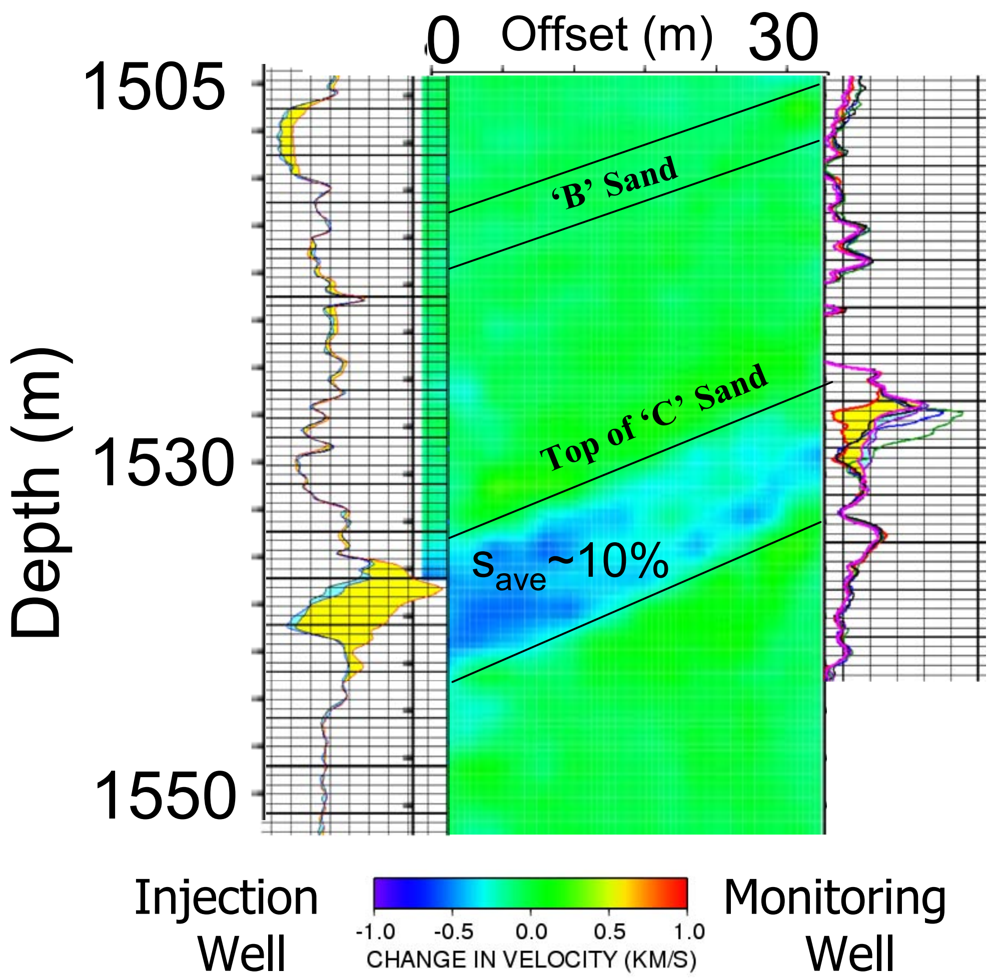
Frio Brine Pilot Test

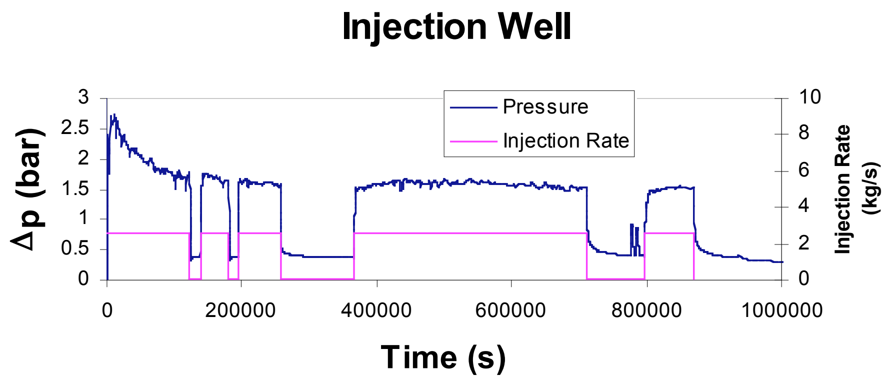
- 1,540 m deep
- Formation properties
  - Average permeability: 2.1 darcy
  - Average porosity: 33%
  - 5.5 m injection zone
- 10 day injection test @ 2.6 kg/s
- 1,600 tonnes CO_2 injection

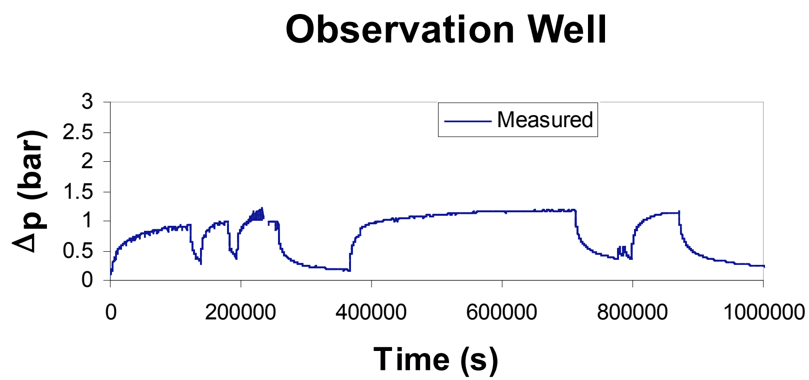


From S. Hovorka, TBEG

Frio Formation CO_2 Migration and Pressure Data

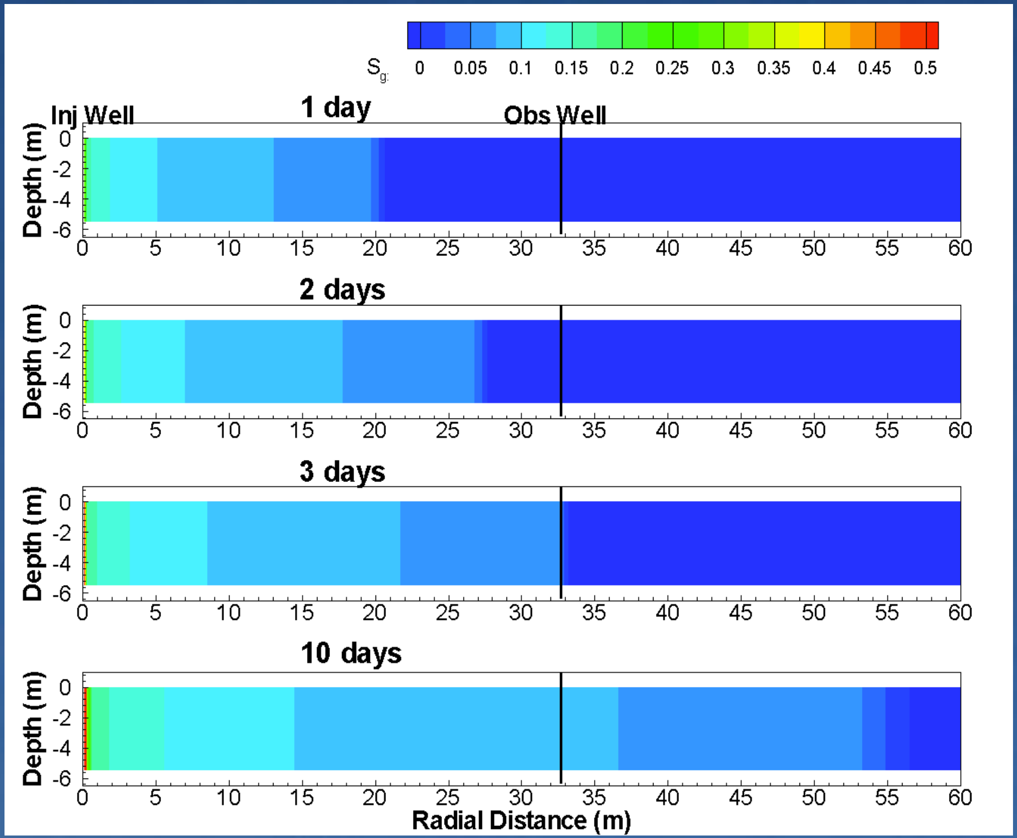




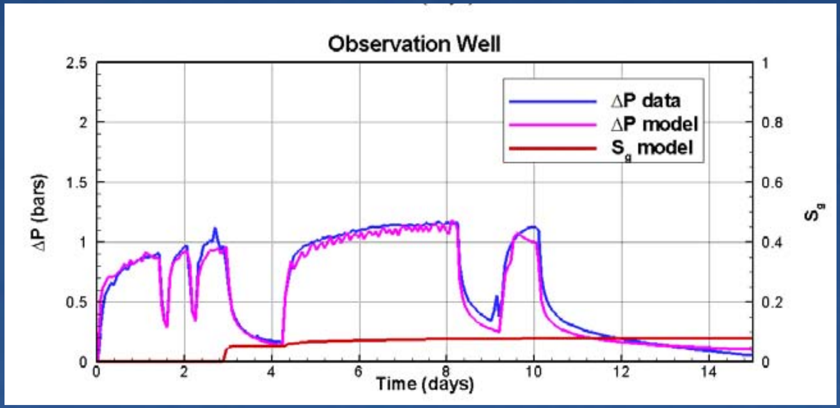


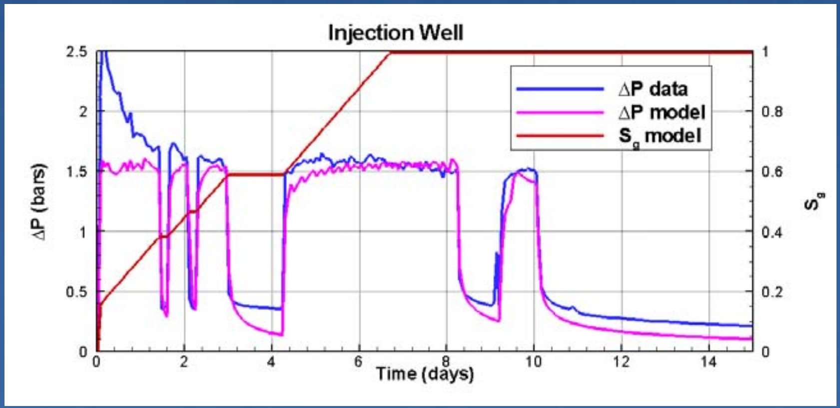
One-D Simulations

CO_2 Migration



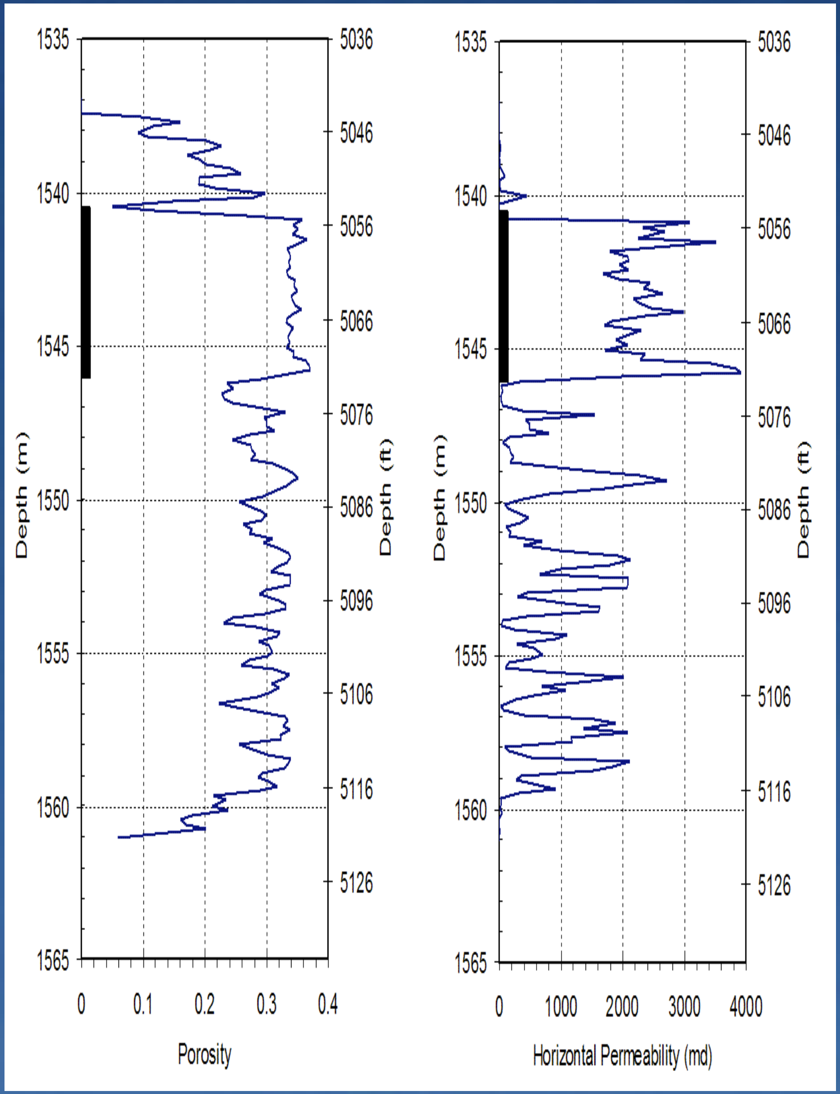
Match of Pressure Transient Data





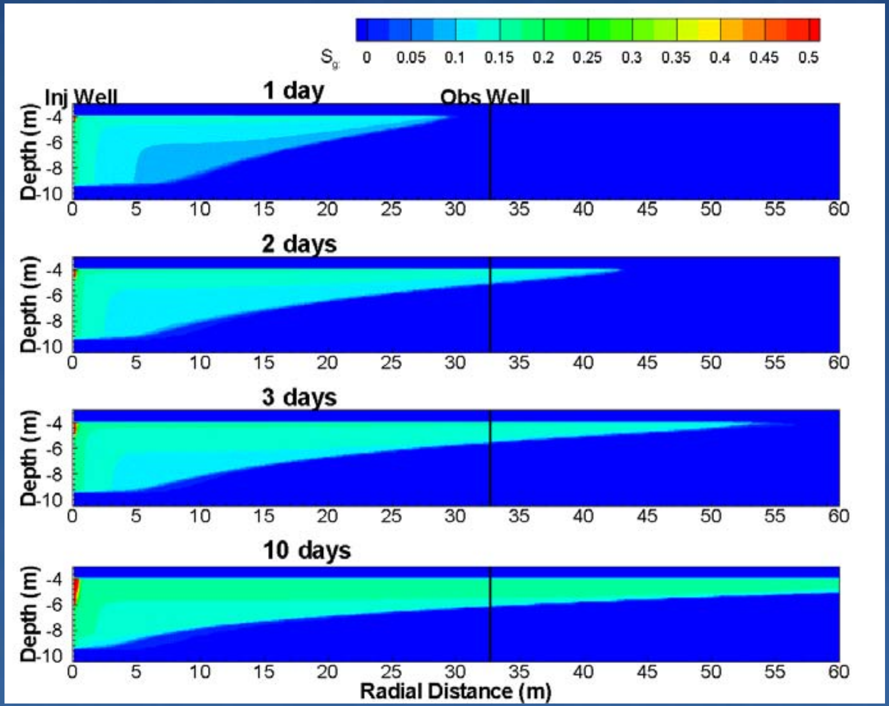
But, s_{lr}=0.8!

Hydrologic Properties

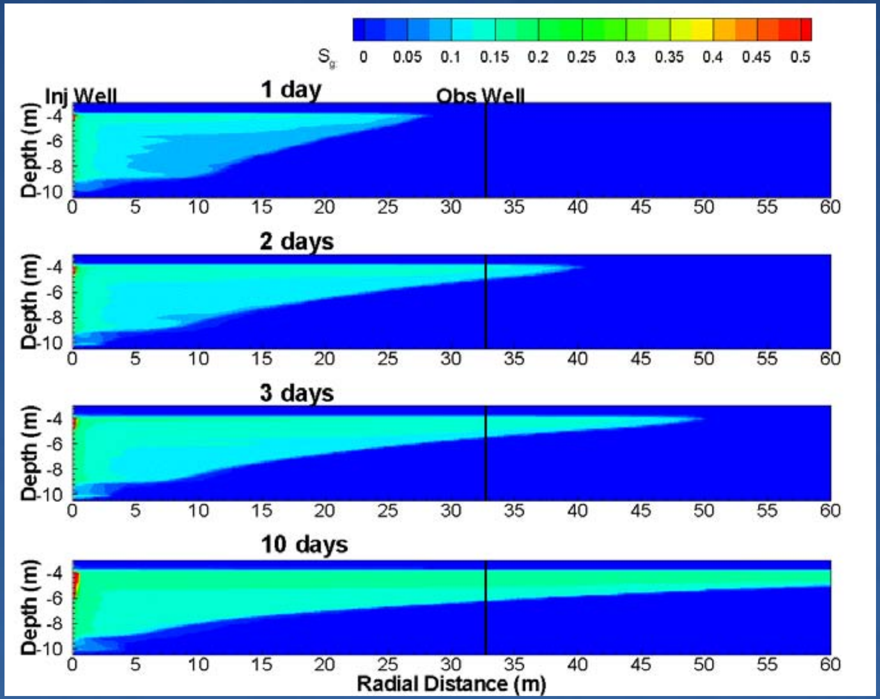


Data provided by Shinichi Sakurai, TBEG

2-D Simulations



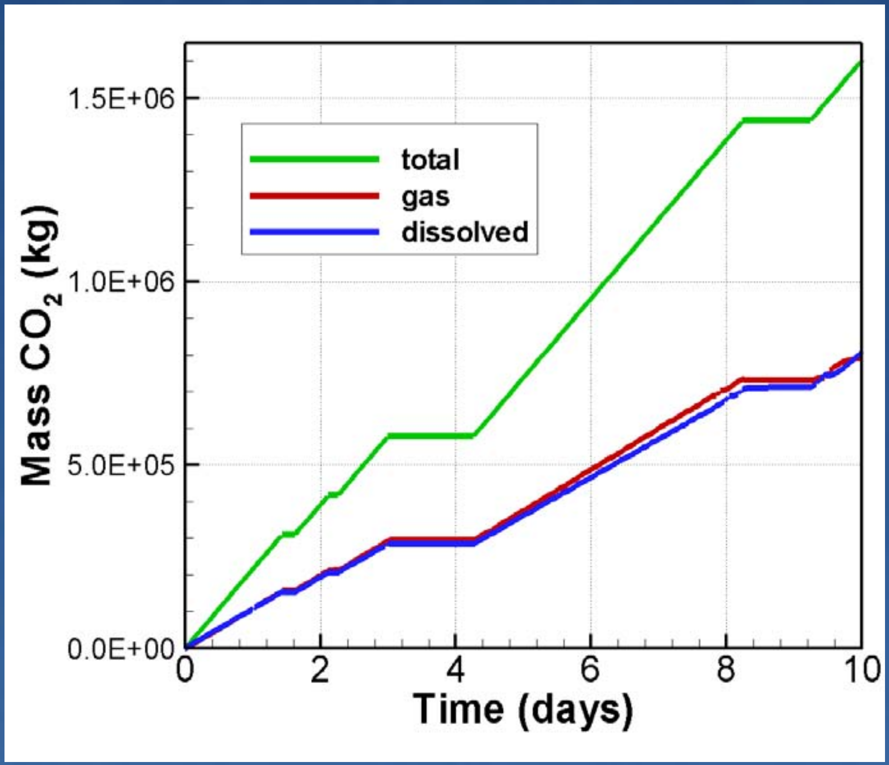
Gravity Only



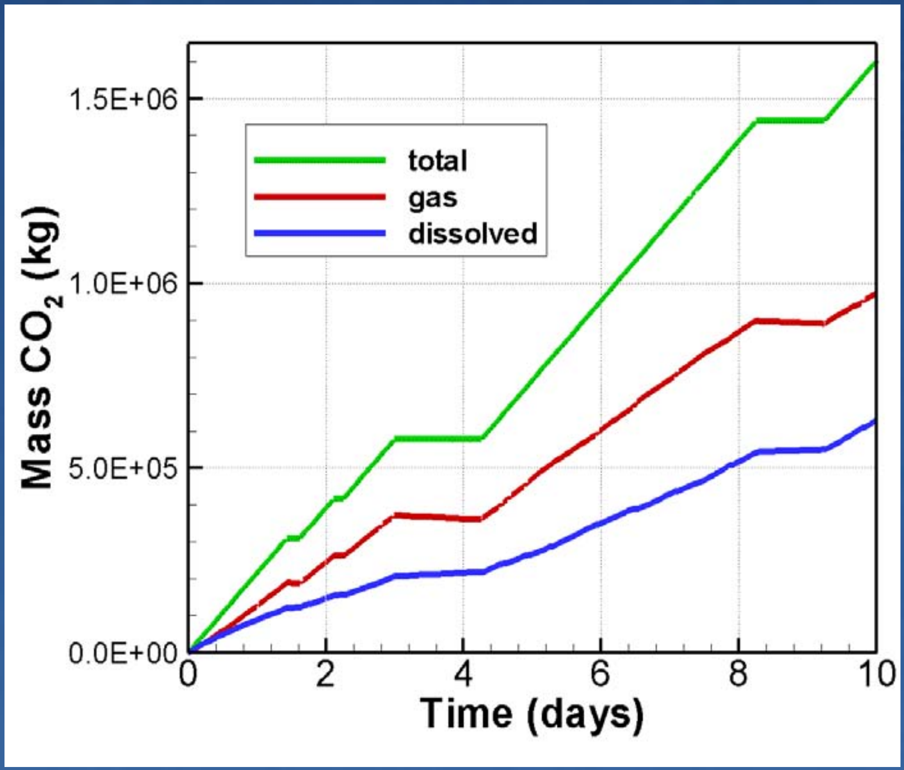
Gravity Plus Heterogeneity

Best match of breakthrough with $s_{lr} = 0.4$

Dissolution of CO_2



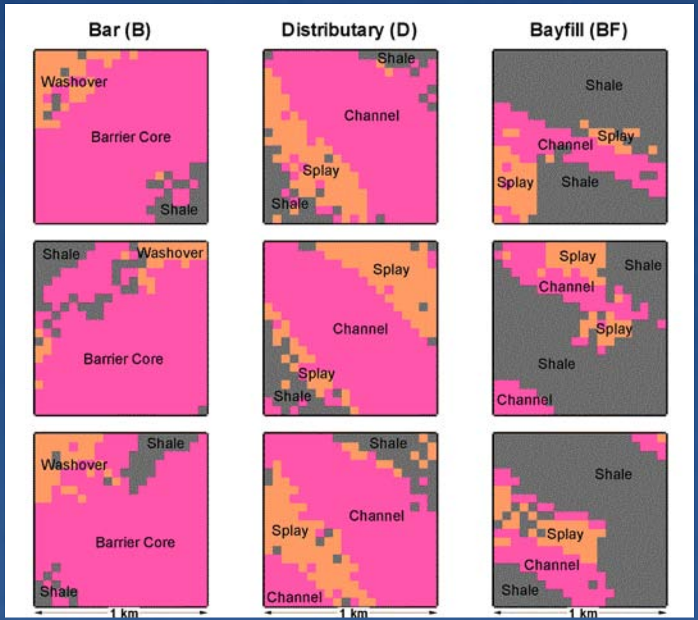
1-D Simulation

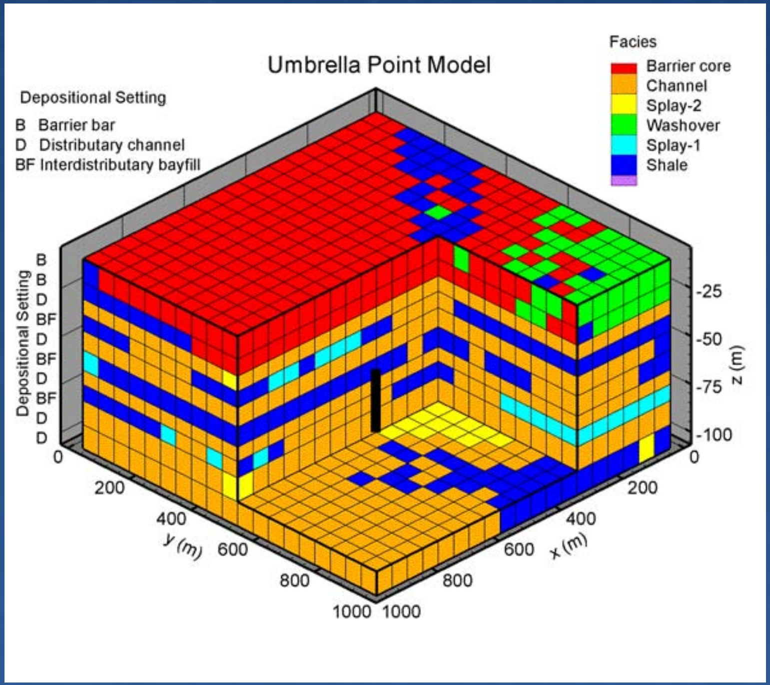


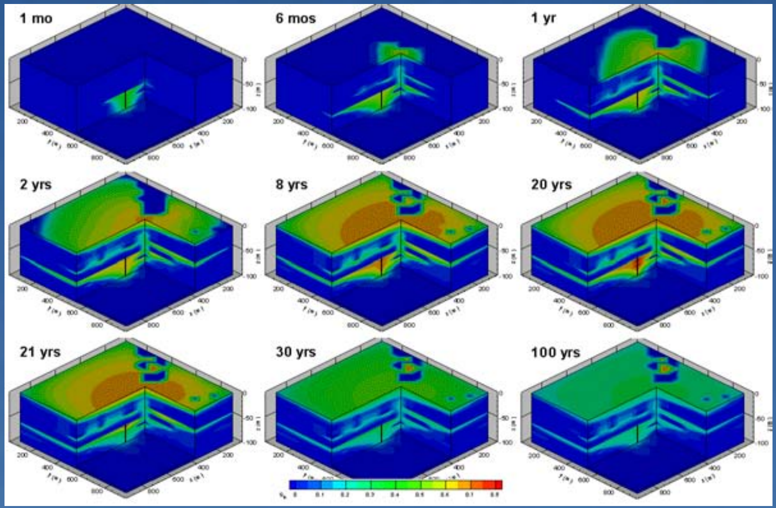
2-D Simulation with Gravity

Simulated Dissolution Rates Depend Strongly on Flow Geometry

Reservoir Scale Phenomena



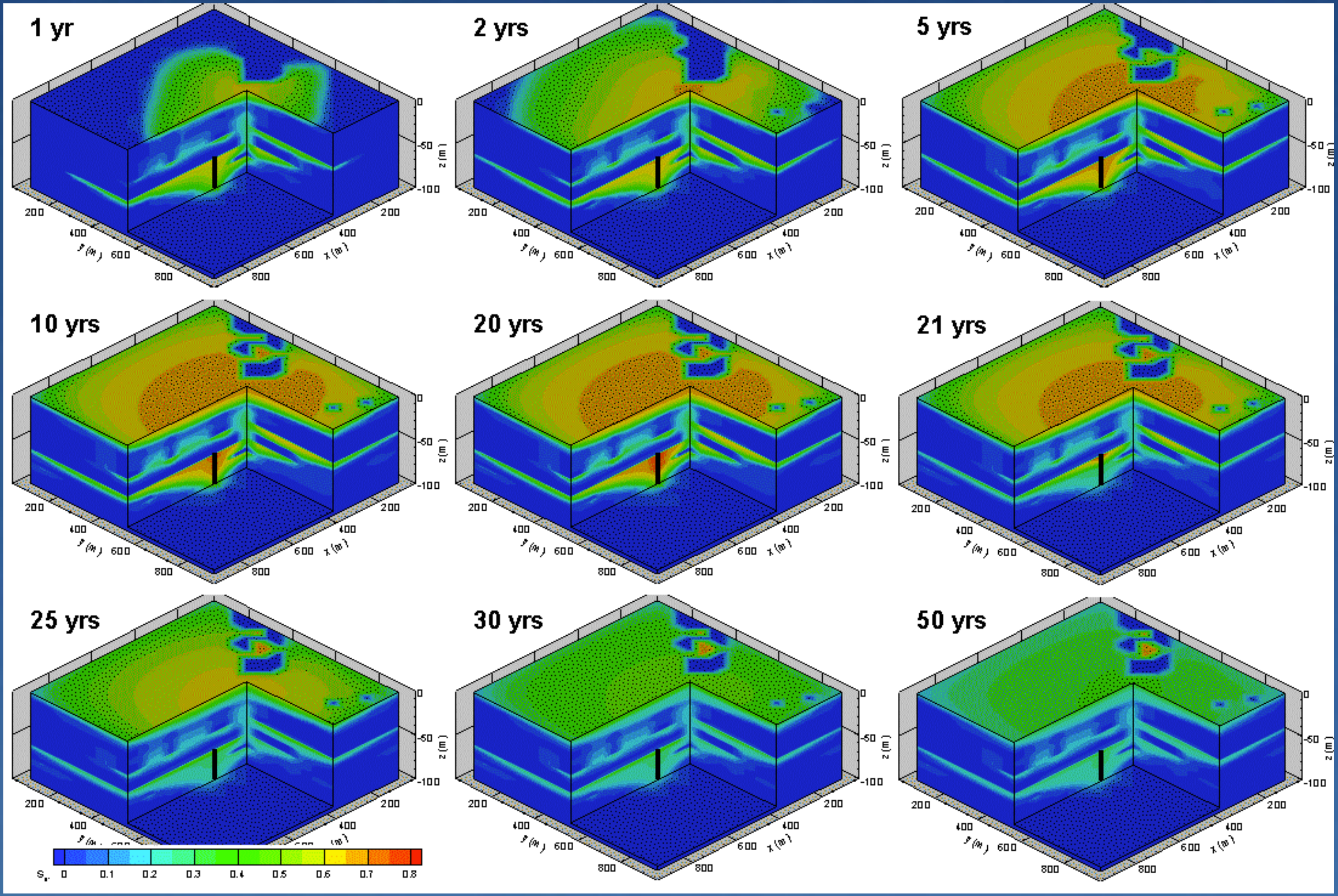




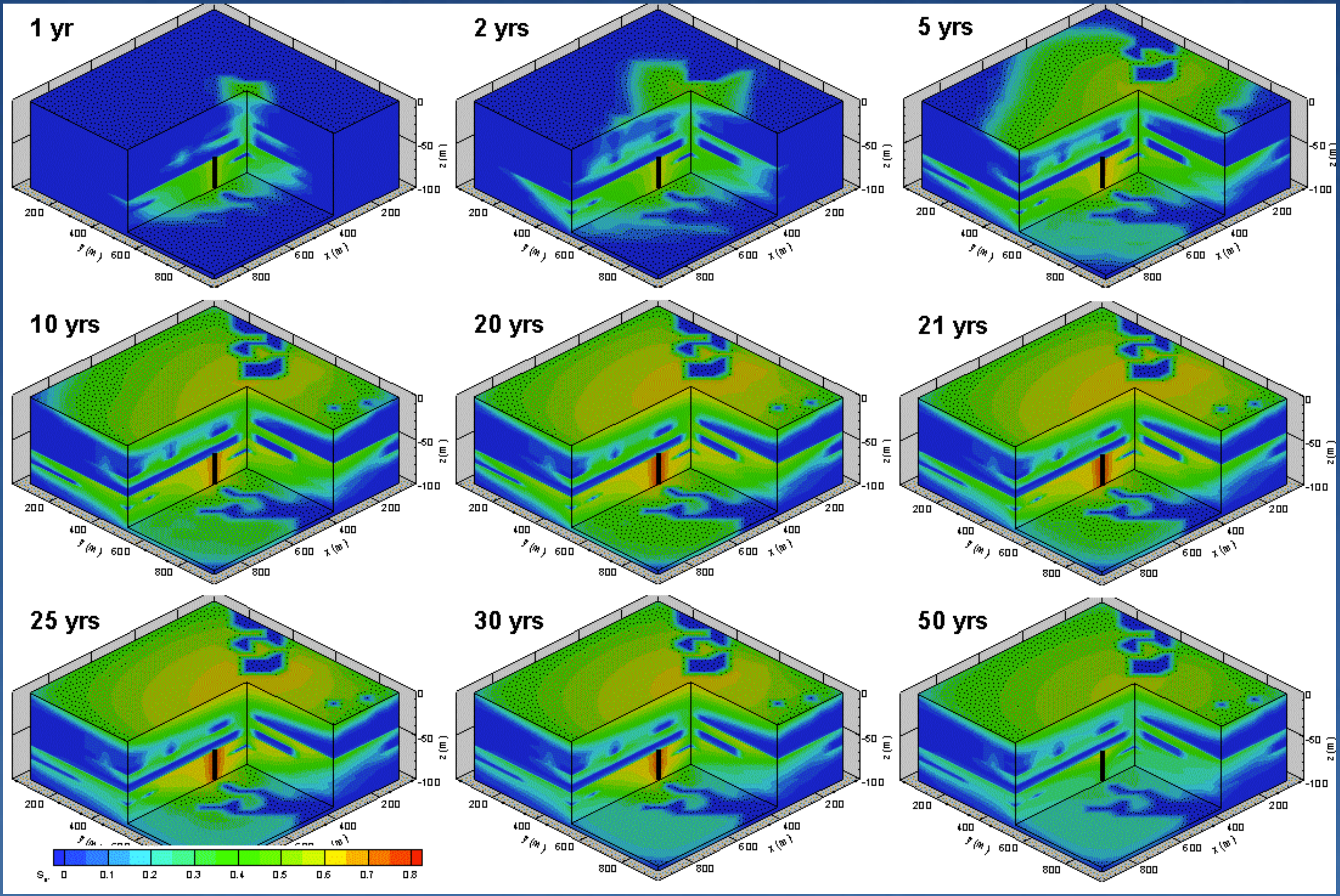
Injection Scenario

20 years Injection @ 0.66 Mt/year	30 year rest and observation period

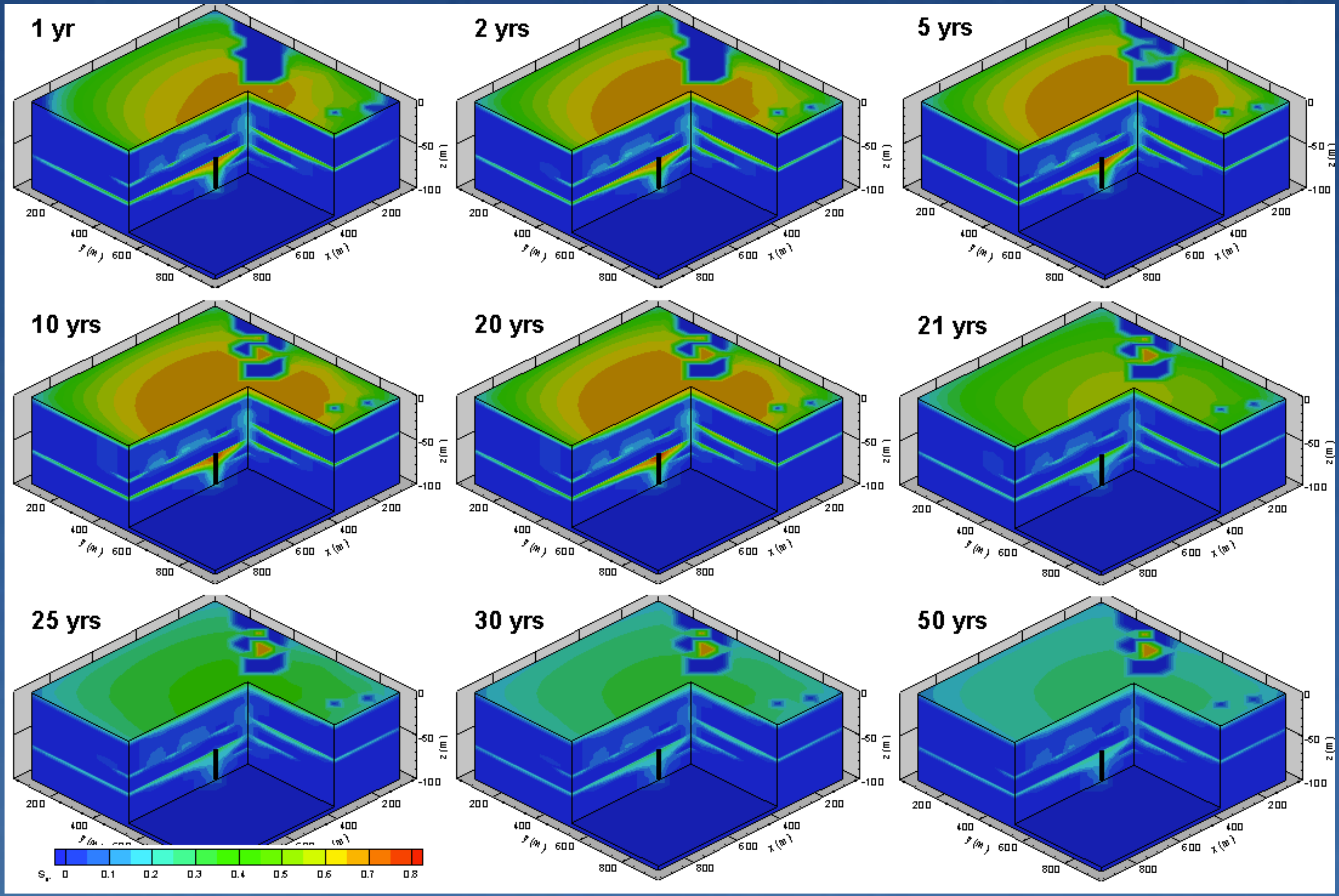
Base Case (Moderate Permeabilty)



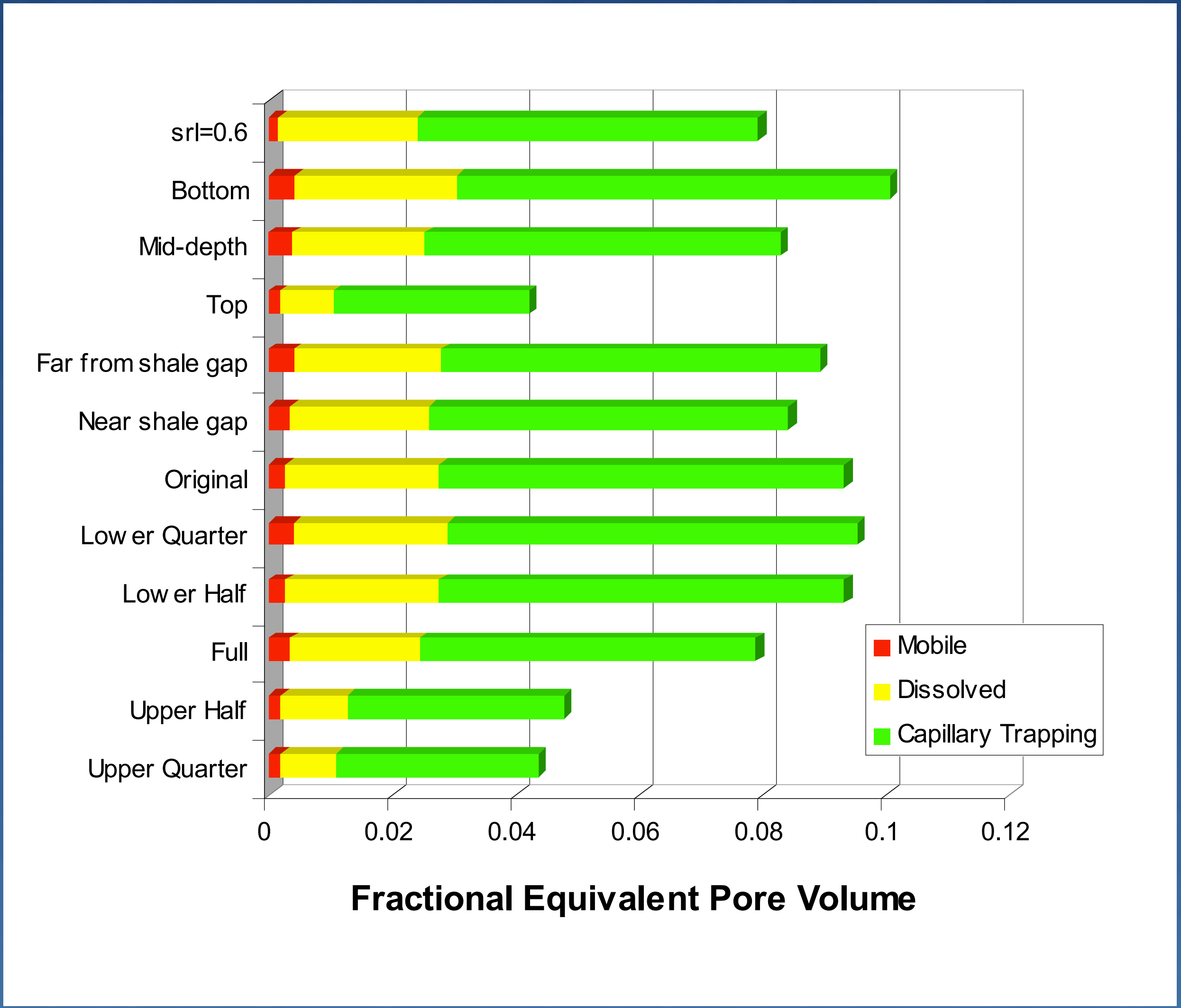
Low Permeability Reservoir



High Permeability Reservoir



Storage Capacity and Trapping at the End of the 30-year Rest Period



Conclusions

- Heterogeneity at every scale results in complex behavior which influences
  - CO_2 migration rates
  - Pressure buildup
  - Capacity
  - Dissolution
  - Capillary trapping
- Dominant processes depend on scale; for the examples presented here
  - Core scale variability controlled by capillary effects
  - Intra-reservoir scale processes dominated by gravity
  - Reservoir scale controlled by complex interplay of all of the above
- Up-scaling schemes that simultaneously predict all of the key properties need to be developed
- High resolution experimental observations are needed to gain insight and guide theory and modeling