Validation of Models Simulating Capillary and Dissolution Trapping During Injection and Post-Injection of CO_2 in Heterogeneous Geological Formations Using Data from Intermediate Scale Test Systems (FE0004630)

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National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO_2 Storage

August 21-23, 2012

Presentation Outline

- ❑ **Benefit to the Program**
- ❑ **Project Overview**
- ❑ **Technical Status**
  - ➢ **Task 2 – Intermediate-scale laboratory testing of capillary and solubility trapping in homogeneous and heterogeneous systems**
  - ➢ **Task 3 – Evaluation of whether existing modeling codes can capture the processes observed in the laboratory, and developments of the constitutive models based on the findings**
- ❑ **Accomplishments to Date**
- ❑ **Project Summary - Findings and Future Plans**
- ❑ **Appendix**

Benefit to the Program

- **Overall Project Goals**
  - **Improve/develop and validate models by using the data generated in intermediate-scale laboratory test systems simulating capillary and dissolution trapping under various heterogeneous conditions.**
  - **Design injection strategies, predict storage capacities and efficiency for field-scale geological systems by using the improved numerical tools**

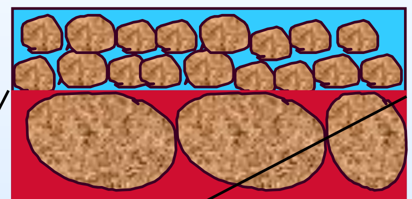
- **The findings will meet objectives of Program research to develop technologies to cost-effectively and safely store and monitor CO_2 in geologic formations and to ensure storage permanence. Developed approach and technologies in this project specifically contribute to the Carbon Storage Program's effort of supporting industries' ability to predict geologic storage capacity to within +/- 30 percent.**

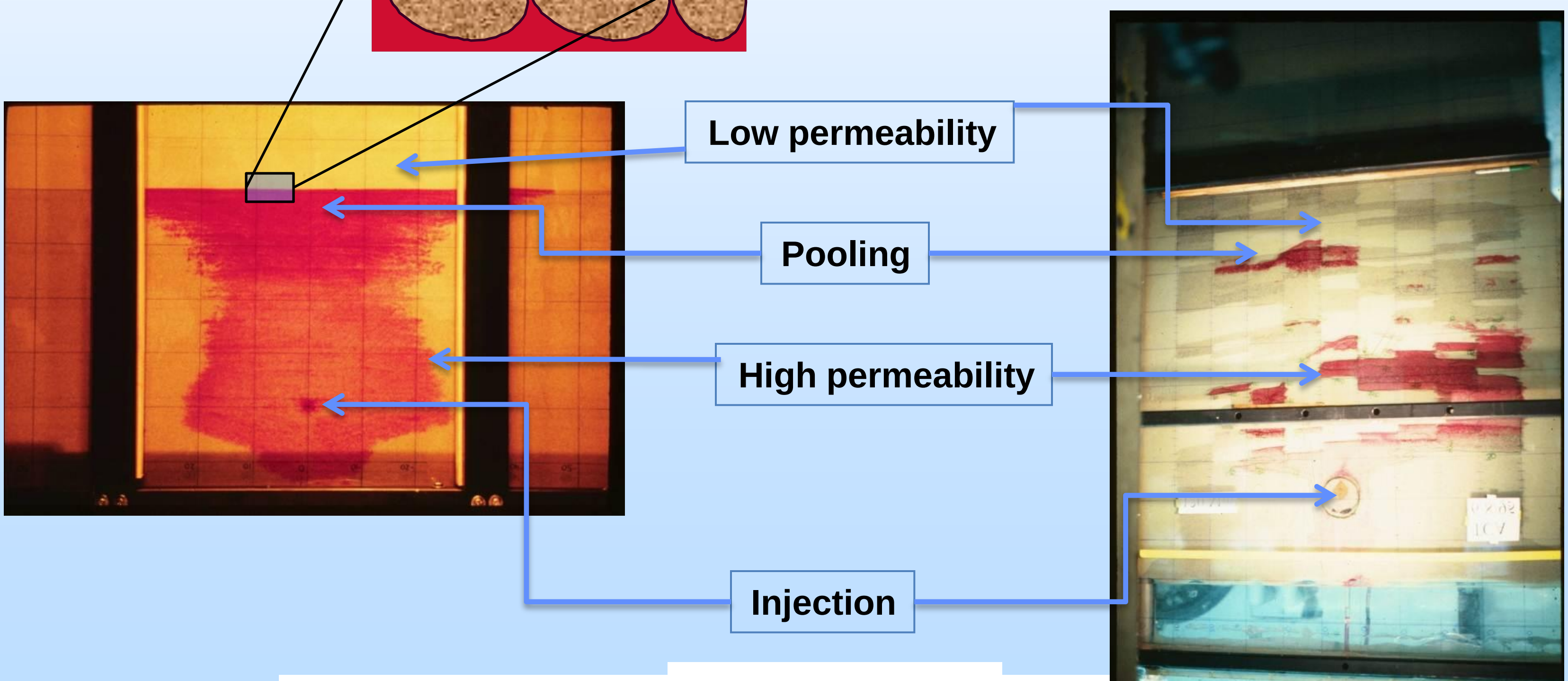
Knowledge gaps and research questions

Heterogeneity and Capillary Trapping

In naturally heterogeneous formations, injected scCO2 will preferentially migrate into higher permeability zones and pool under the interface of the confining low permeability layers due to capillary barrier effects (very high entry pressure).

Knowledge gaps exist on how the heterogeneity influences capillary trapping of CO_2.





Heterogeneity and Dissolution Trapping

Dissolution of CO_2 in heterogeneous systems can be enhanced due to increases in interfacial areas between water and supercritical CO_2.

<u>Knowledge gaps exist on how the heterogeneity influences dissolution trapping of CO_2.</u>

Research Questions

Capillary Trapping

- **How do heterogeneities and connectivity (spatial continuity of different permeability zones) affect entrapment efficiency of $scCO_2$ in deep geological formations?**
- **How well the existing continuum-based models and the constitutive models capture multiphase flow behavior of $scCO_2$ /brine in deep formations?**

Dissolution Trapping

- **What are the effects of heterogeneity on dissolution and density-driven fingers?**
- **Can dissolution of CO_2 in heterogeneous systems be enhanced due to increases in interfacial areas between water and supercritical CO_2?**

Project Objectives and Tasks

- Task 1 – Project Management and Planning
- Task 2 – Generate data in intermediate scale test tanks simulating capillary trapping and dissolution affected by heterogeneity
    - Task 2.1 – Small tank experiments
    - Task 2.2 – Large tank experiments
- Task 3 – Evaluate whether the existing modeling codes can capture processes observed in the test tanks, and improve existing models based on findings

Approach

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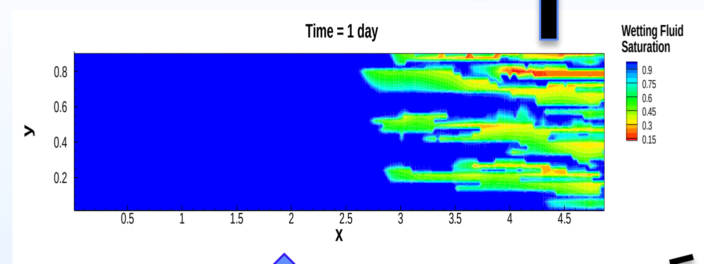
Model Dimension

A multi-scale experimental testing and modeling

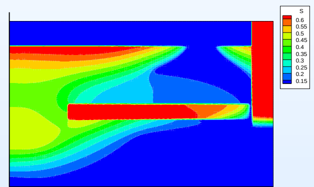
Upscaling

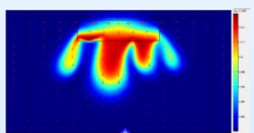
Field Scale

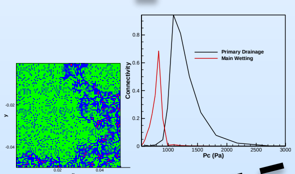
LBNL

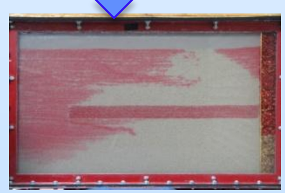


Upscaling









Experiment Dimension

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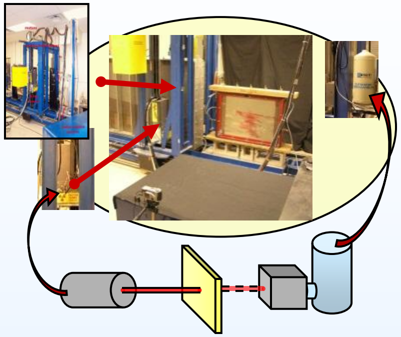
Intermediate-Scale

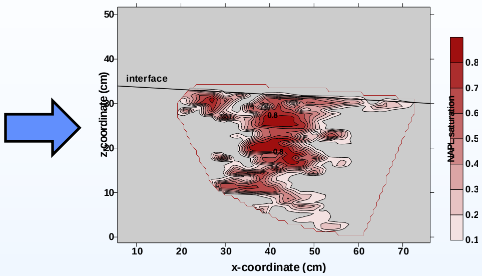
1 to ~ 10 m

Size (cm to basin scale)

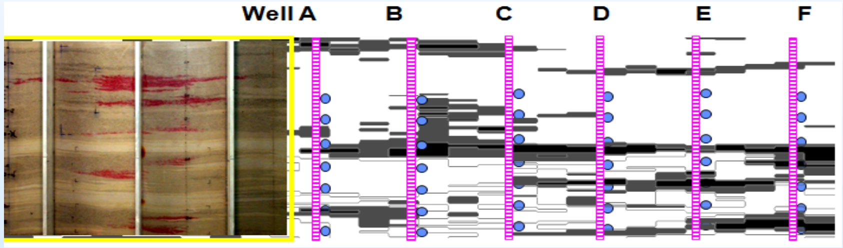
Experimental Methods

- Automated transient and spatially distributed saturations using x-ray attenuation

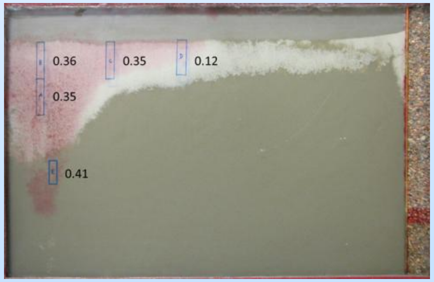




- Aqueous sampling to determine dissolved plume concentrations, and core destructive sampling from low permeability zones



- Core destructive sampling to determine final entrapment saturations.



- Measurement of multiphase model parameters (capillary pressure-saturation-relative permeability relationships)

Task 2 – Experimental Studies

- **Selection of materials and fluids**
  - ✓ Dimensional analysis (*Bo, Ca, density and viscosity ratio*, *Ra number)*
  - ✓ Small test systems in fluid/fluid media and small sand tanks (28cmx15cm)
- **Small tank experiments (28cmx15cm and 92cmx1.2m)**
  - ✓ Capillary trapping in homogeneous and simple heterogeneous packing (8 experiments completed)
  - ✓ Analyses of density-driven finger developments in homogeneous and heterogeneous packing (4 experiments completed)
  - ➢ Capillary trapping in highly heterogeneous systems (in progress)
  - ➢ Capillary and dissolution trapping (homogeneous and heterogeneous packing)
- **Large tank experiments (4.9mx1.2m)**
  - ➢ Capillary trapping (in progress)
  - ➢ Capillary and dissolution trapping

Material and Fluid Selection

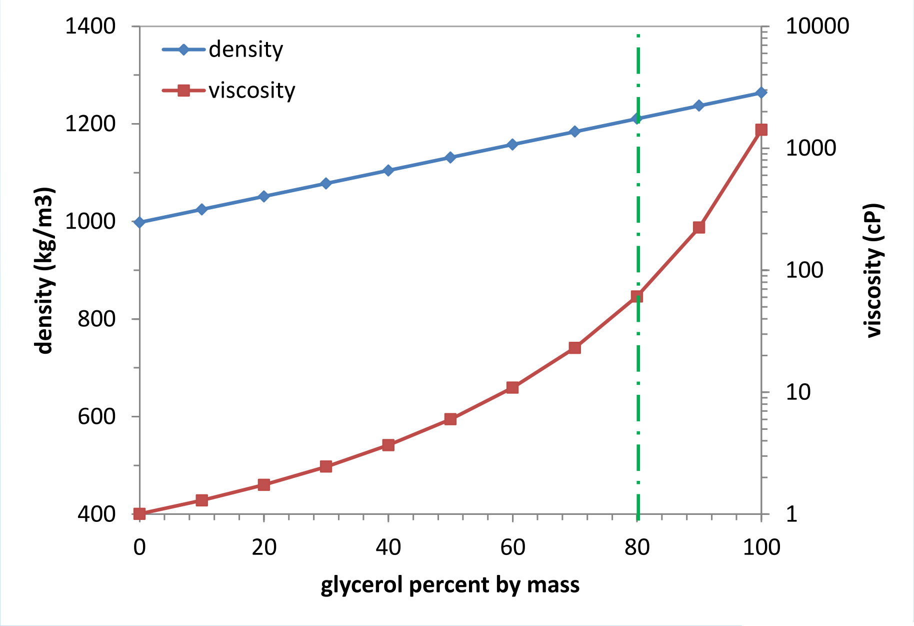
- Laboratory investigation of $scCO_2$ migration without high pressure can be conducted using analogous fluids having similar density and viscosity contrasts as $scCO_2$ – brine phases under sequestration conditions

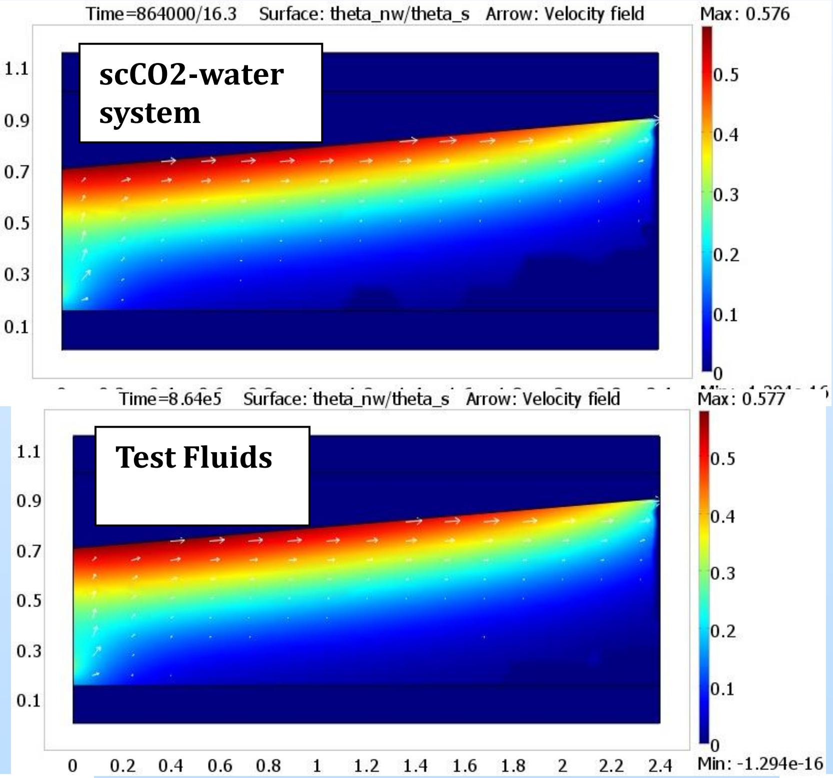
Dimensionless Numbers	scCO2-brine @ Typical Reservoir Conditions	Soltrol220-glycerol/water @ 20C, 1 atm	Water in Propylene Glycol @ 20C, 1 atm	Methanol in glycerol/water @ 20C, 1 atm
Bond # $Bo = \frac{\Delta\rho g k}{\sigma}$	~ 10^{-7} - 10^{-8}	~10^{-6}- 10^{-7}	~10^{-6}- 10^{-7}	~10^{-6}- 10^{-7}
Capillary # $Ca = \frac{\mu_{nw} u_T}{\sigma}$	~ 10^{-5} - 10^{-8}	~10^{-6}- 10^{-7}	~10^{-7}- 10^{-8}	~10^{-7}- 10^{-8}
Viscosity Ratio $\frac{\mu_{nw}}{\mu_w}$	~ 0.05 - 0.2	~0.074	~0.017	~0.07
Density Ratio $\frac{\rho_{nw}}{\rho_w}$	~ 0.2 – 0.8	~0.66	~0.9	~0.6

Testing of the Scaling Approach

- Identical results can be obtained if the same dimensionless numbers are chosen for the geometrically similar two systems (Shook et al., 1992; Gharbi et al.,1998).

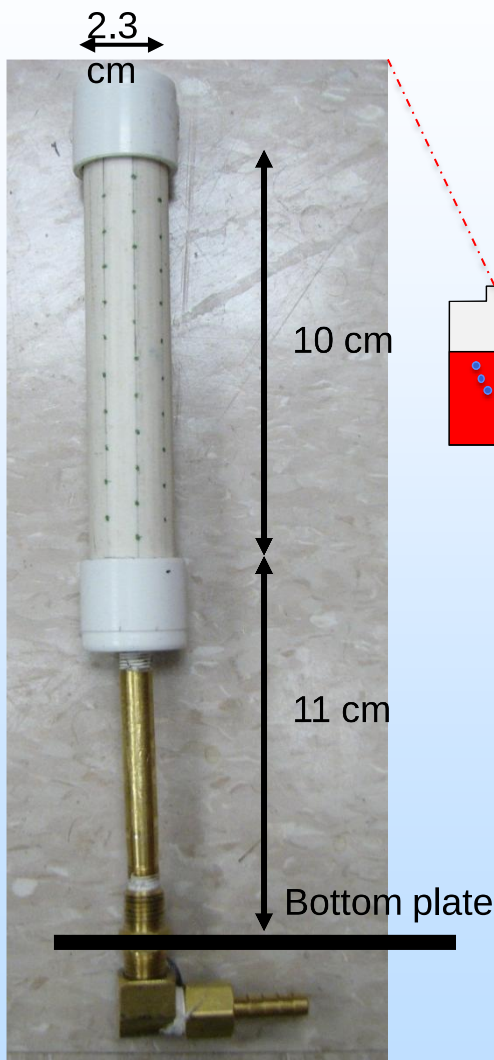
Glycerol/water mixture at ambient conditions

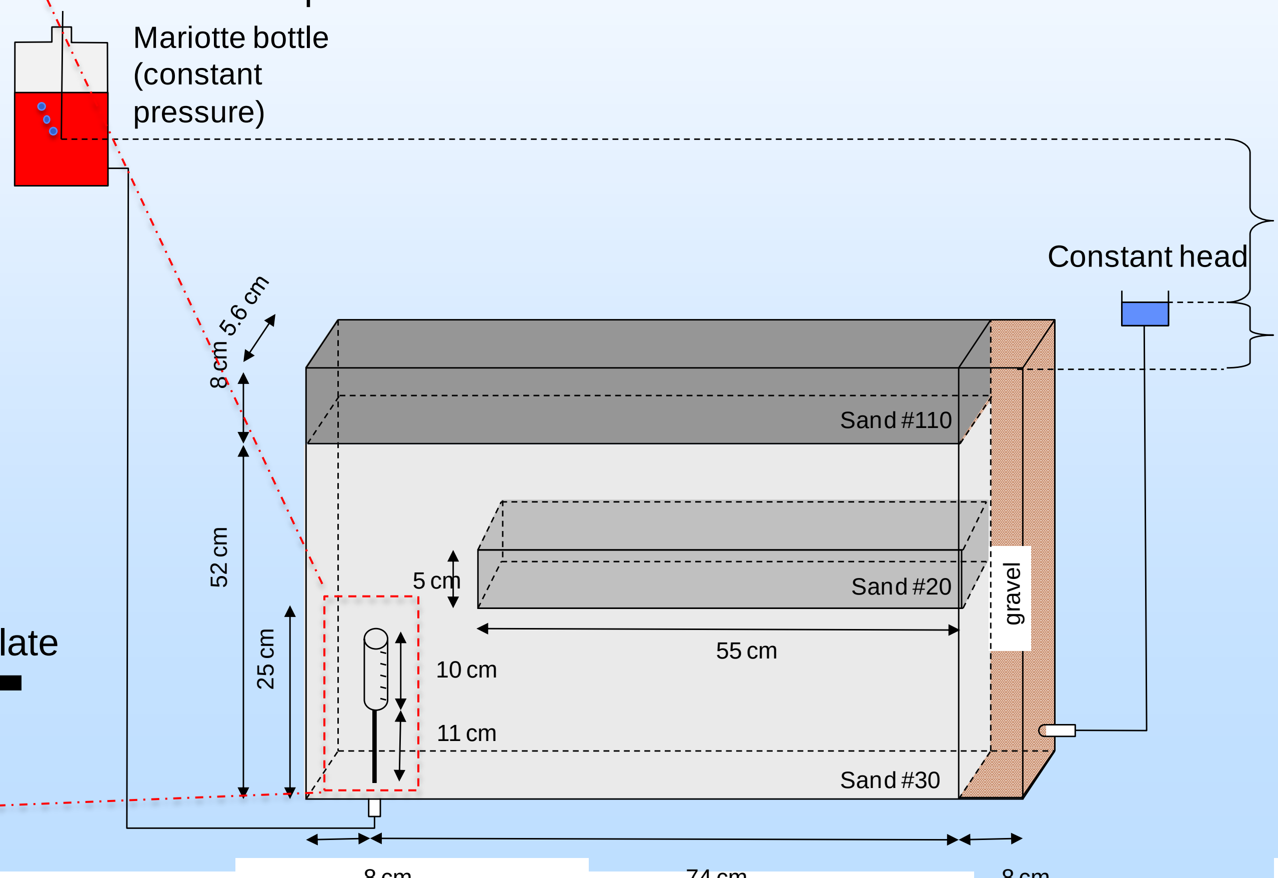




Small Tank Experiments For Capillary Trapping in Homogeneous and Heterogeneous Systems

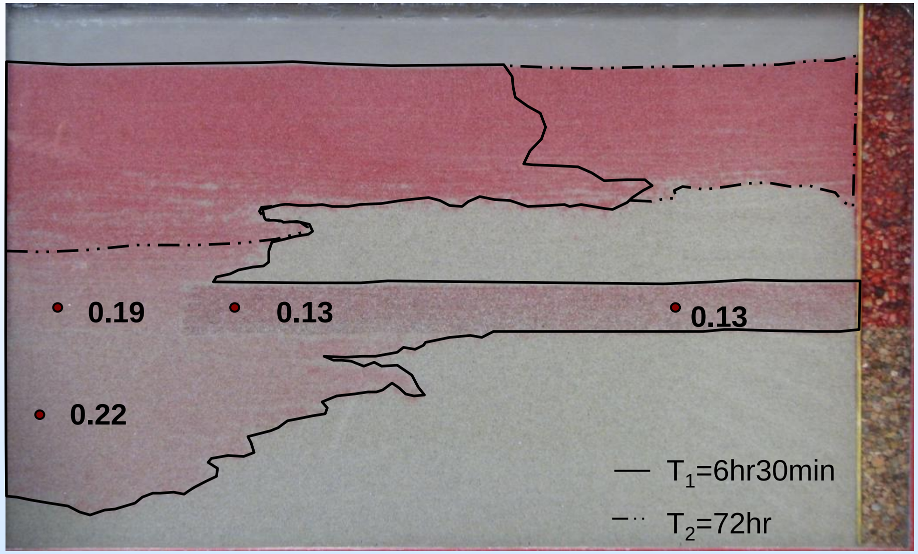
- **Injected fluid: Soltrol 220**
- **Displaced fluid: Glycerol-Water mixture (80%-20% w/w)**
- A total of 8 small tanks experiments with both homogeneous and heterogeneous packing completed.
- Plume injection and plume configuration recorded.
- Soil samples removed and the fluids extracted to determine final entrapment saturations.



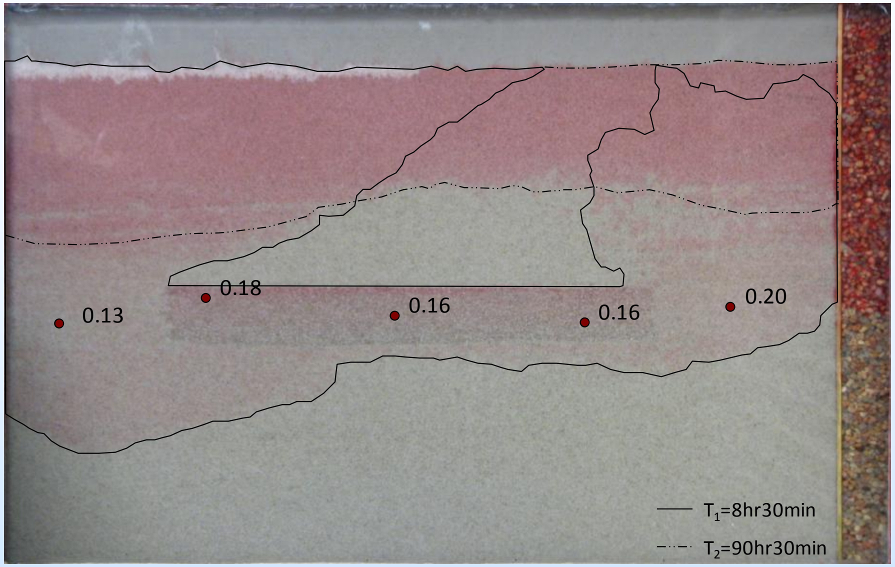


Small Tank Experiments for Capillary Trapping in Mildly Heterogeneous Systems

Heterogeneous with a continuous high-permeability layer



Heterogeneous with a discontinuous high-permeability layer



- ❑ Can models that use macroscopic multiphase parameters capture the flow and entrapment behavior ?
- ❑ Are the relative permeability models generated from retention functions adequate?
- ❑ What are the effects of injection rates (entrapment zone development and final entrapment saturations) ?
- ❑ Does the final entrapment depend on rate of injection?

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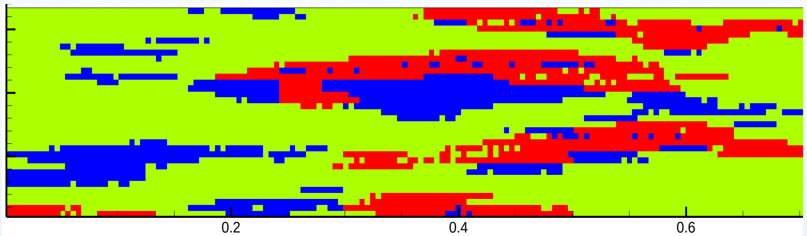
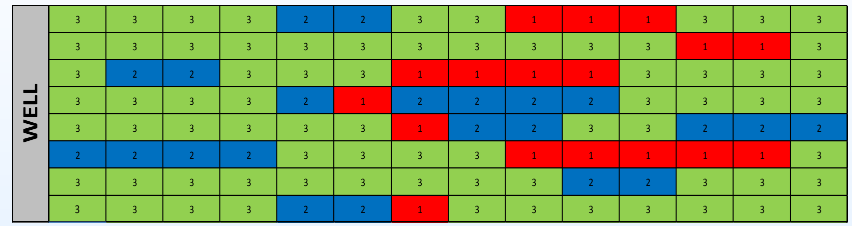
Small Tank Experiments in Highly Heterogeneous Systems (in progress)

A computer-generated realistic heterogeneous aquifer

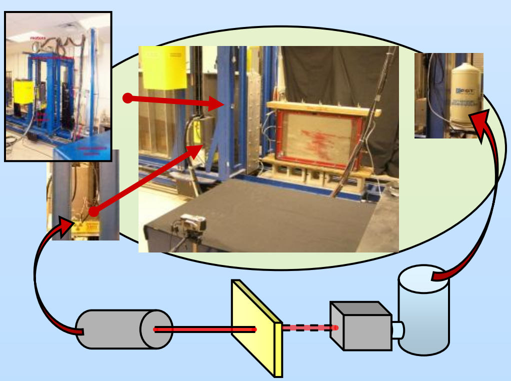


red (#30) Coarse | green (#50) Medium | blue (#70) Fine

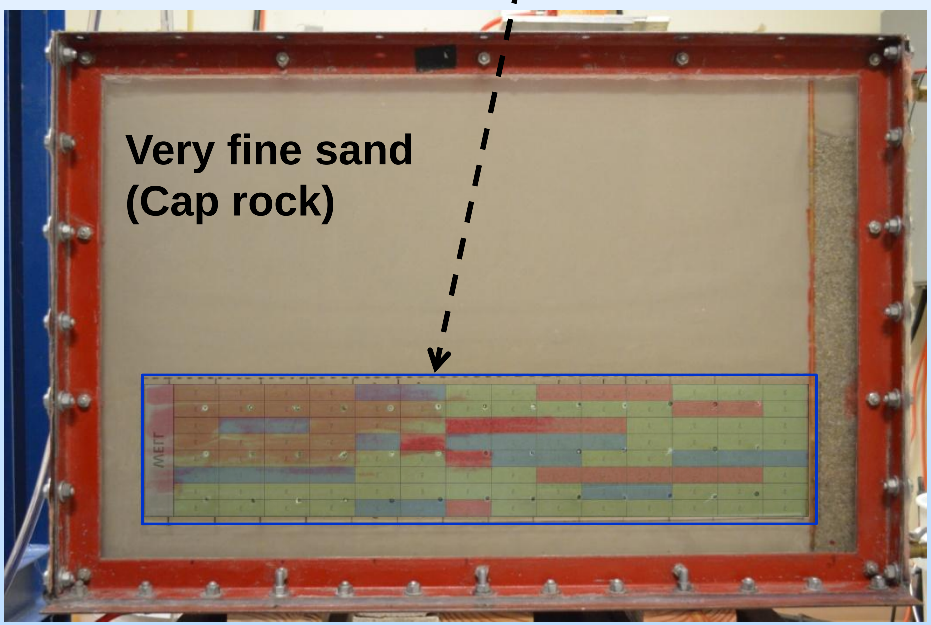
Simplified for packing



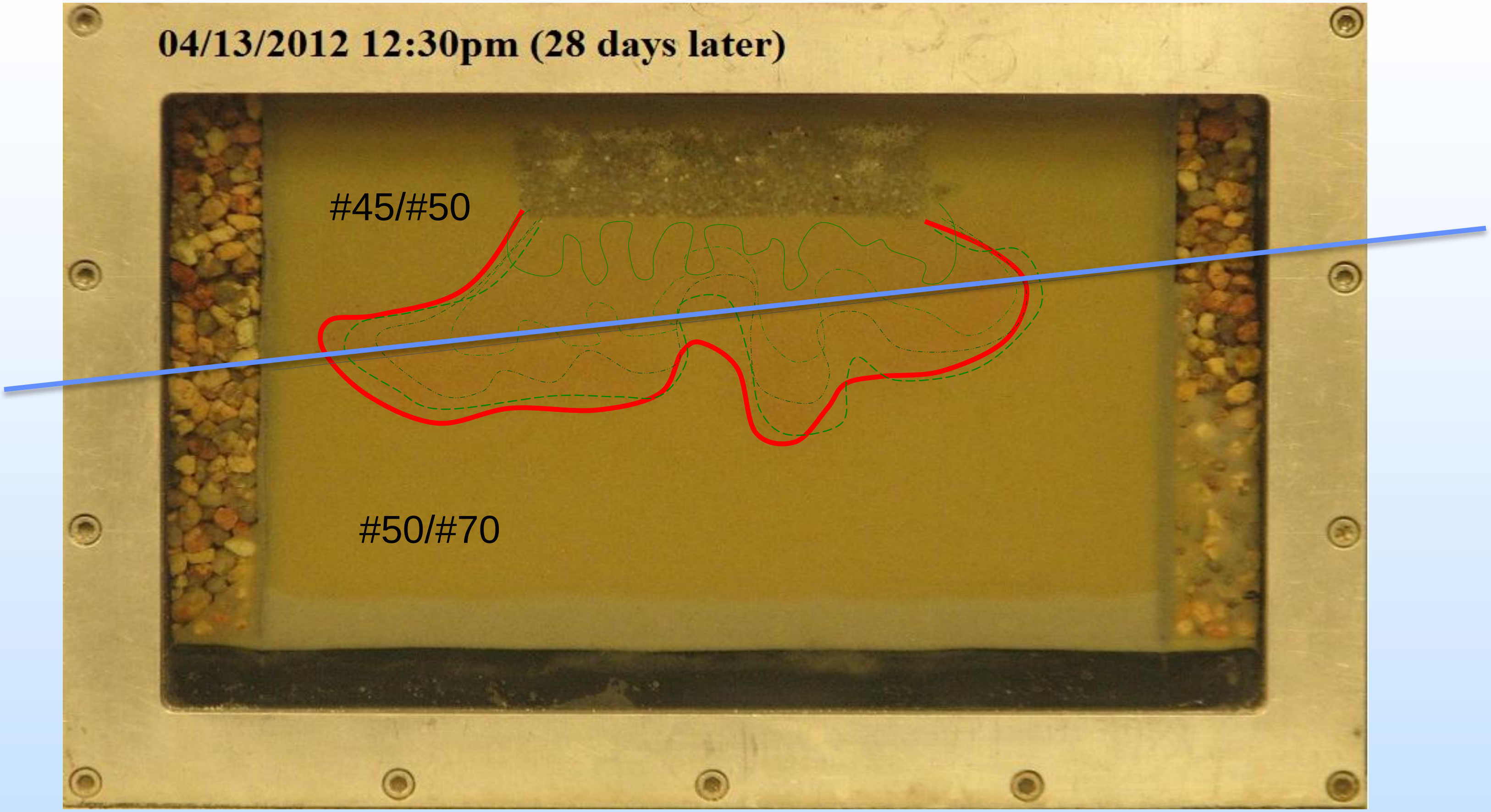
Repair of X-ray systems will be completed at the end of August



For phase saturation measurement



Small-Tank Experiments: Heterogeneity effect on density-driven fingering (water/propylene glycol)



- ✓ Fingering is dampened out by heterogeneity
- ✓ From high permeability medium to low permeability medium, finger flow is replaced by bulk flow

Large Tank Experiments (in progress)

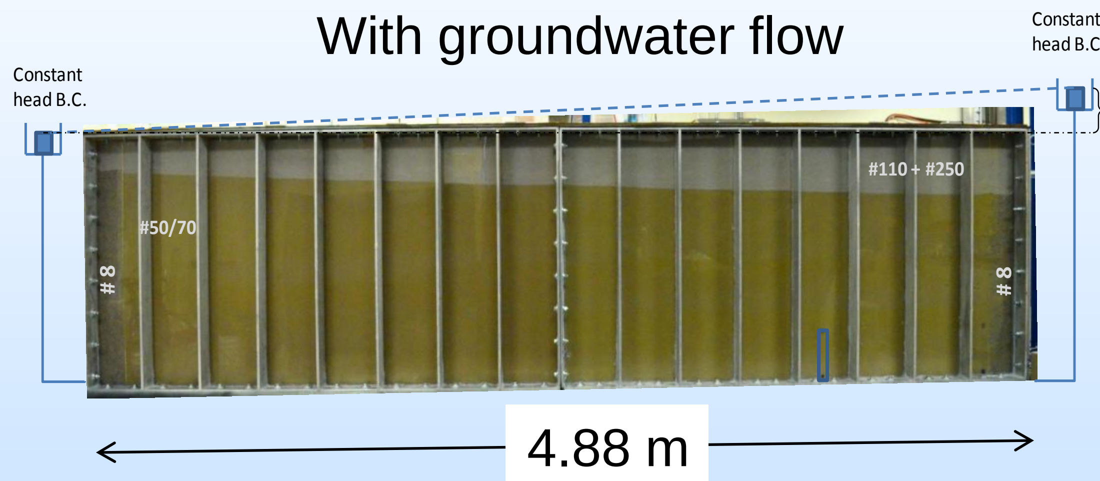
✓ Problems encountered in early design of the 16ft large tank experiment were mostly resolved

Previous

- Well configuration => non-wetting phase moves upward inside the well; only top portion of the screen injects Soltrol into the aquifer (reduced vertical sweep)
- Difficulties to avoid preferential pathway between confining layer and gasket

Current Setup for the Large Tank Experiments

With groundwater flow



Task 3 – Modeling

- **Guiding the laboratory experiments**
  - ✓ Injection rate and period, sampling frequency, different packing configurations, and effect of different boundary conditions; *i.e.*, constant head versus no flow.

- **Testing continuum models and upscaling methodologies**
  - ✓ Verify models (numerical codes solving classical two-phase flow equations) based on experimental measurements in homogeneous and heterogeneous experiments
  - ➢ Test/develop constitutive models for accurate prediction of the CO_2 entrapment
  - ➢ Utilize improved modeling and up-scaling tools to predict the effective capillary and dissolution trapping at actual reservoir conditions and large scale CO_2 storage scenarios
  - ➢ Design injection strategies to optimize CO_2 trapping.

Model Testing

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- ❑ **Small tank experiment in a mildly heterogeneous domain with a continuous high-permeability zone – During Injection**

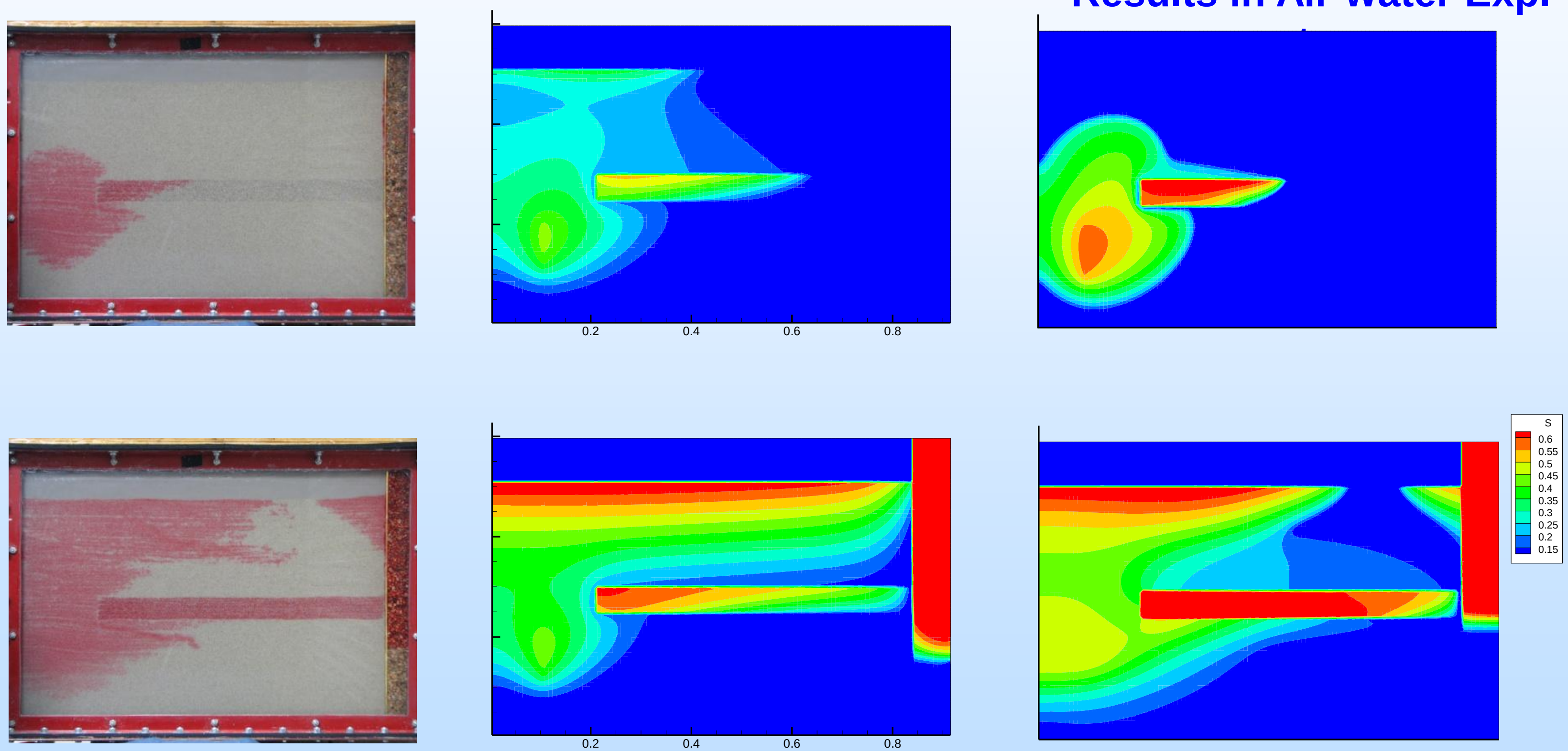
Time

VG-Mualem & Corey

Relative perm. from Previous Results in Air-water Exp.

2 hr

7.5 hr



Model Testing

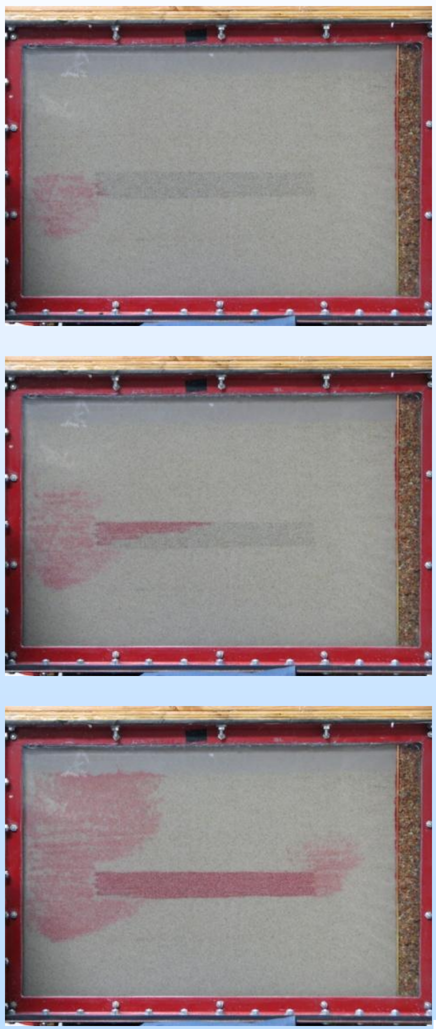
- Small tank experiment in a **mildly heterogeneous domain** with a **discontinuous high-permeability zone** – During Injection

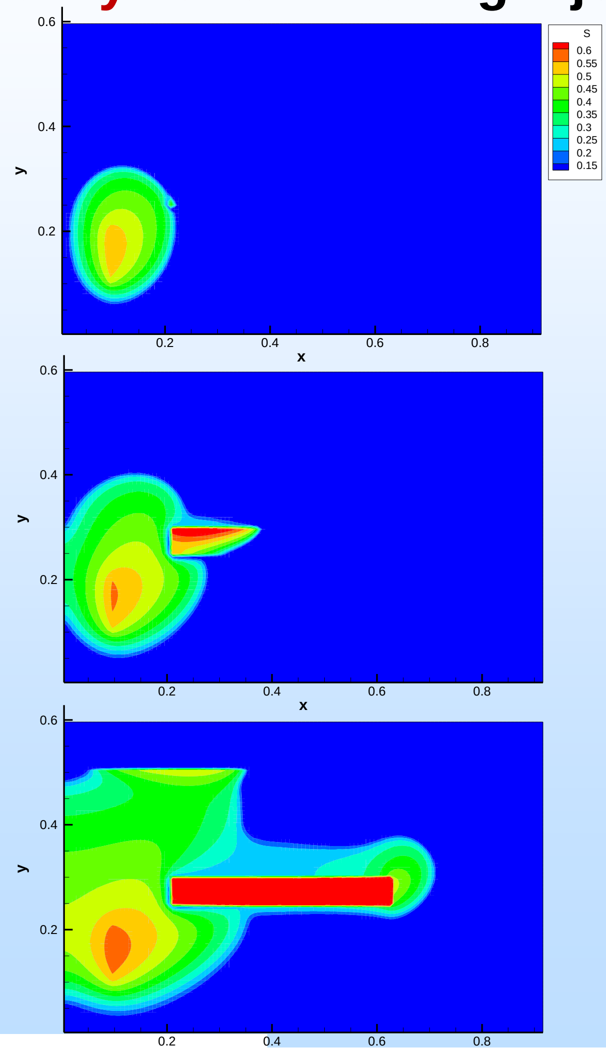
Time

1 hr

2 hr

6 hr





Model Testing

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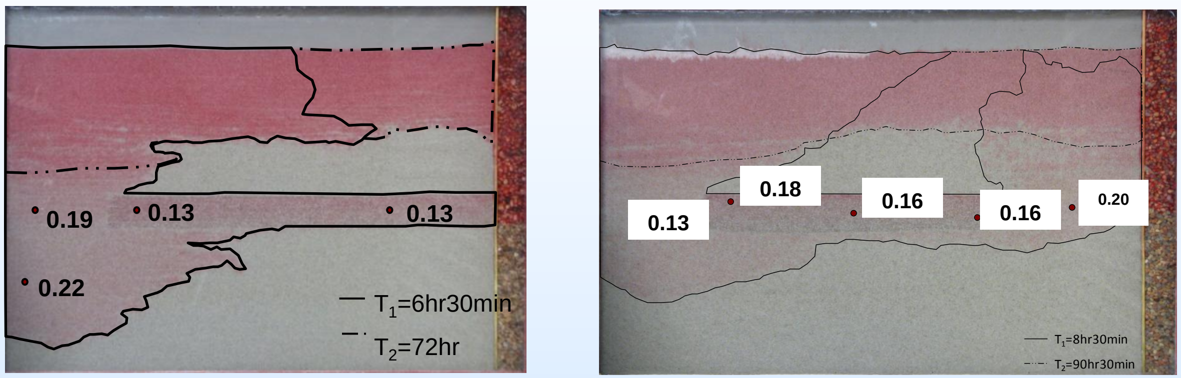
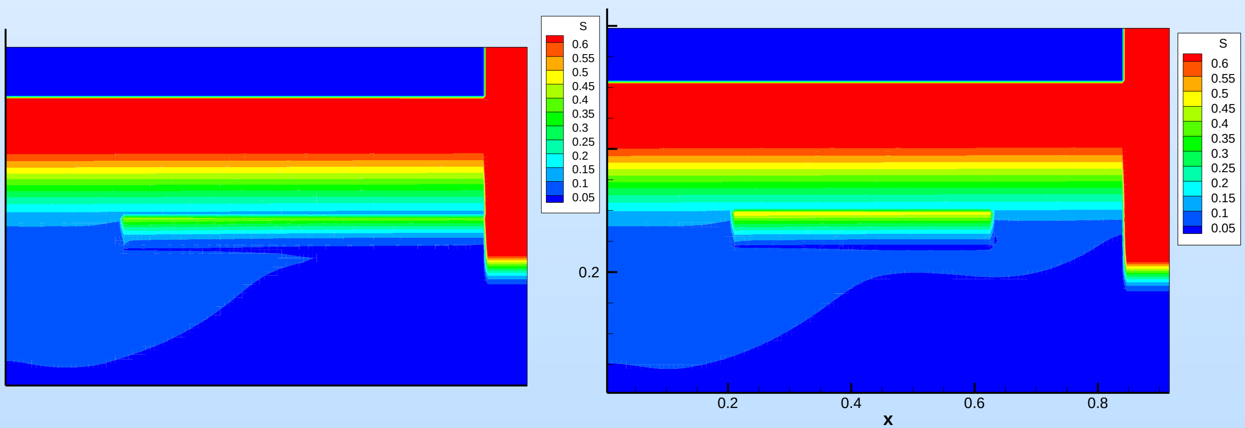
Saturation distributions at the end of the experiments

Simple Heterogeneous Packing





Two-phase model results with hysteresis effects

Development of a Theoretical Hysteresis Model

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Void Sizes $r_1 > r_2 > \cdots > r_n$

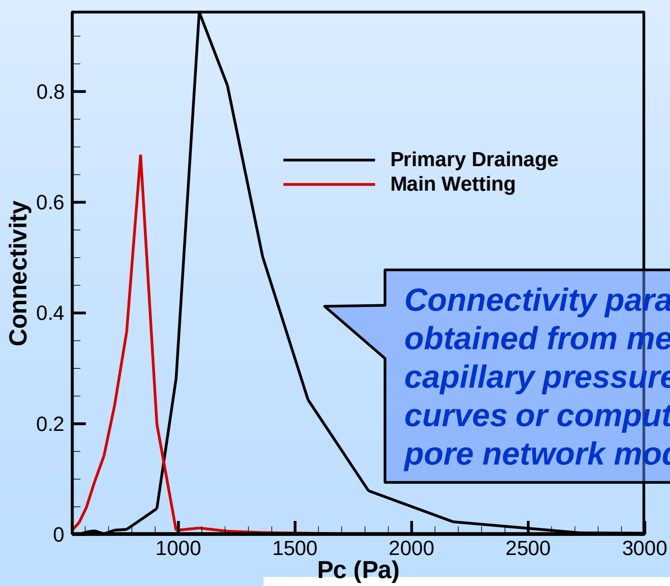
Volume Fractions $f_1, f_2, \ldots, f_n$

Drainage $$S_{nw}(P_{c,m}) = \sum_{i=1}^{m}\sum_{j=i}^{m} f_i p_{ij}^{d} \prod_{k=i}^{j-1}\left(1-p_{ik}^{d}\right); \qquad P_{d,m} \le P_c,\ m=1,2,\ldots,n$$

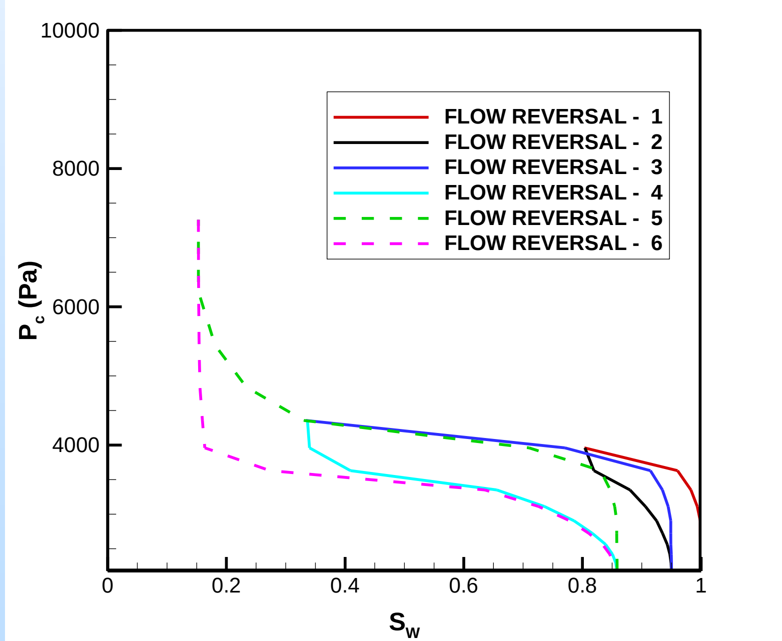
Imbibitions $$S_{nw}\left(P_{c,m}\right) = S_{nw}\left(P_{c,n}\right) - \sum_{i=m}^{n} f_i'\left[\sum_{j=m}^{i} p^{w}_{ij} \prod_{k=j+1}^{i}\left(1-p^{w}_{ik}\right)\right]; \qquad P_{d,m} > P_{c,m}, m=n,n-1,\cdots,1$$

$$f_i' = f_i \underbrace{\left[\sum_{l=i}^{n} p^{d}_{il} \prod_{k=i}^{l-1}\left(1-p^{d}_{ik}\right)\right]}_{\text{Represents the fraction of pores filled with non-wetting phase at the end of drainage}}$$

Represents the fraction of pores filled with non-wetting phase at the end of drainage

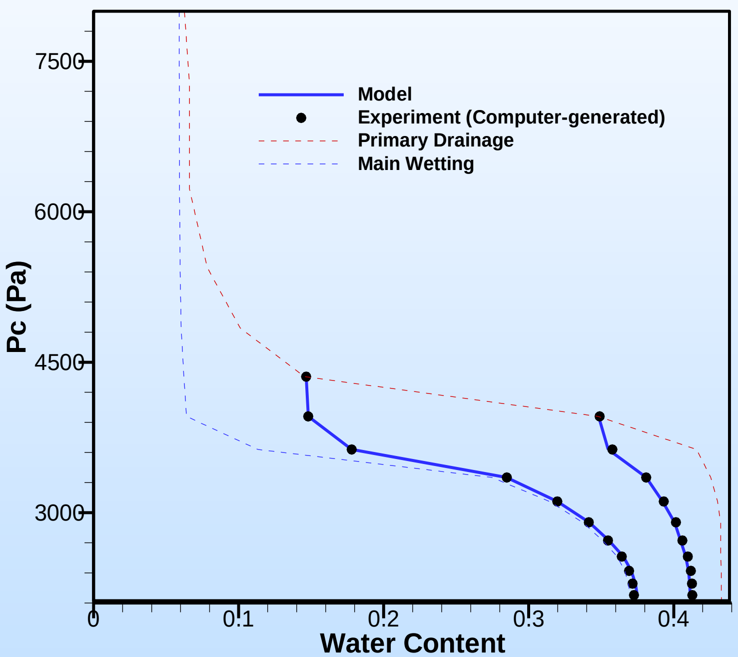


Connectivity parameters are obtained from measured capillary pressure-saturation curves or computer-generated pore network models

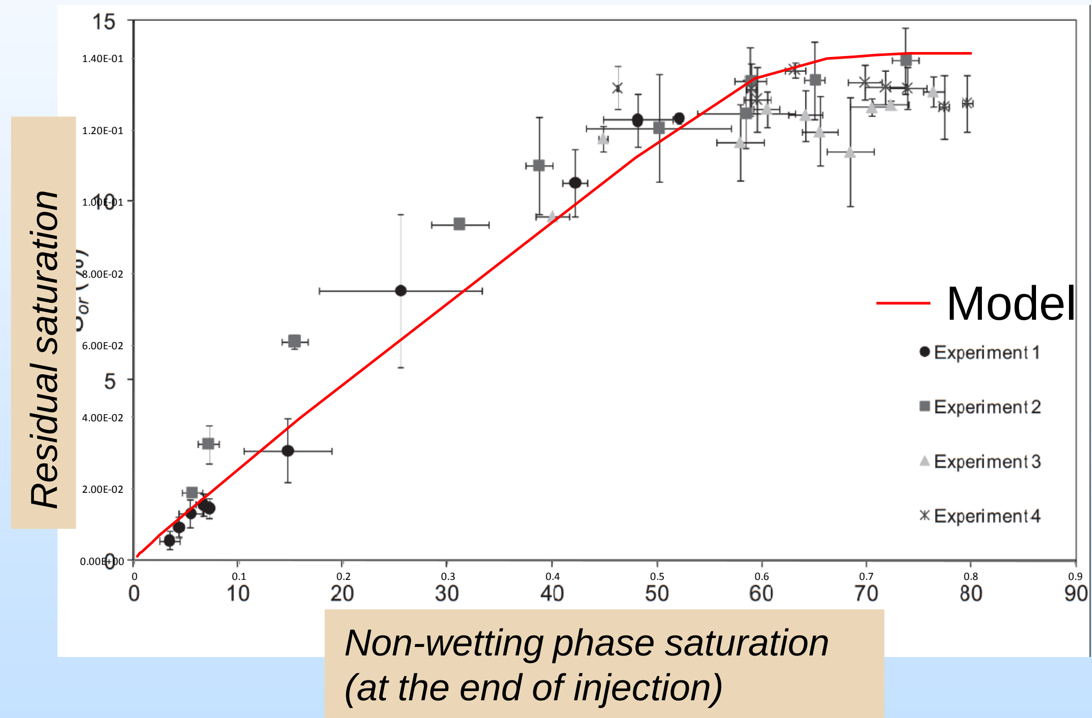


Preliminary Results
Verification of the Hysteresis Model

With computer-generated data

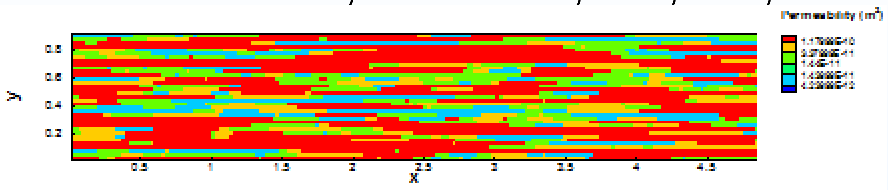


With laboratory experiments in LV60 sand with Octane/brine (*Pentland et al. 2010)*

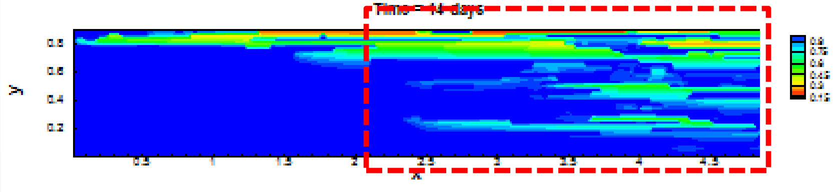


Modeling in the Large Tank and Effect of Heterogeneity

Four-Facies Case, Sands #30, #50, #70, #110

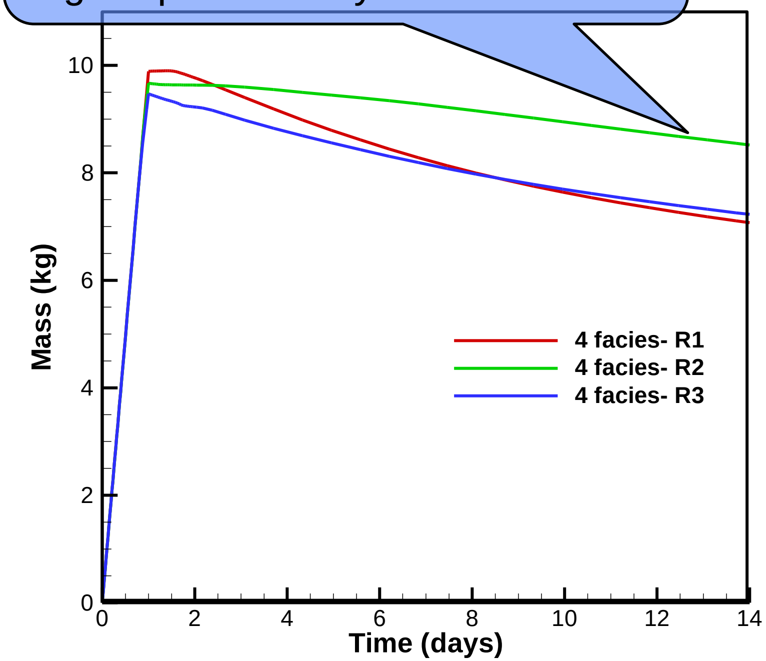


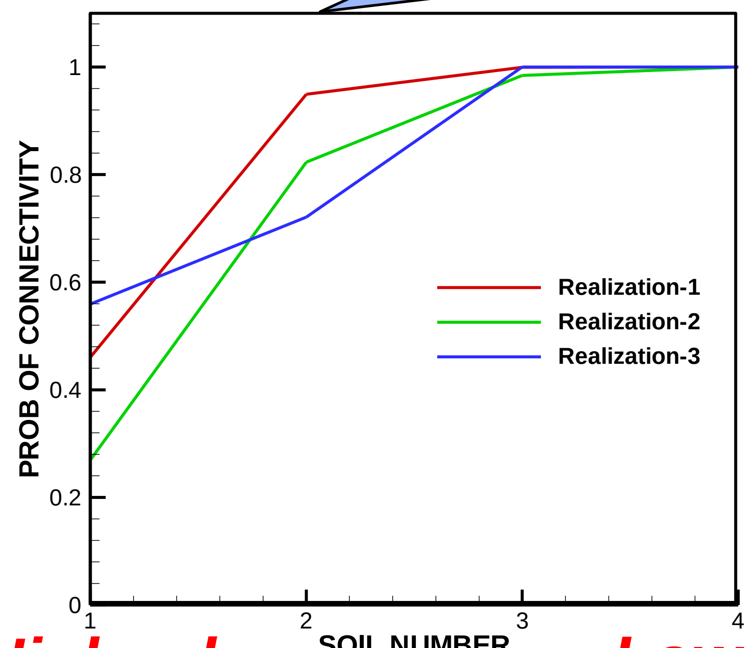
Control Volume



More mass retained in Realization-2 as a result of less connectivity of higher-permeability zones

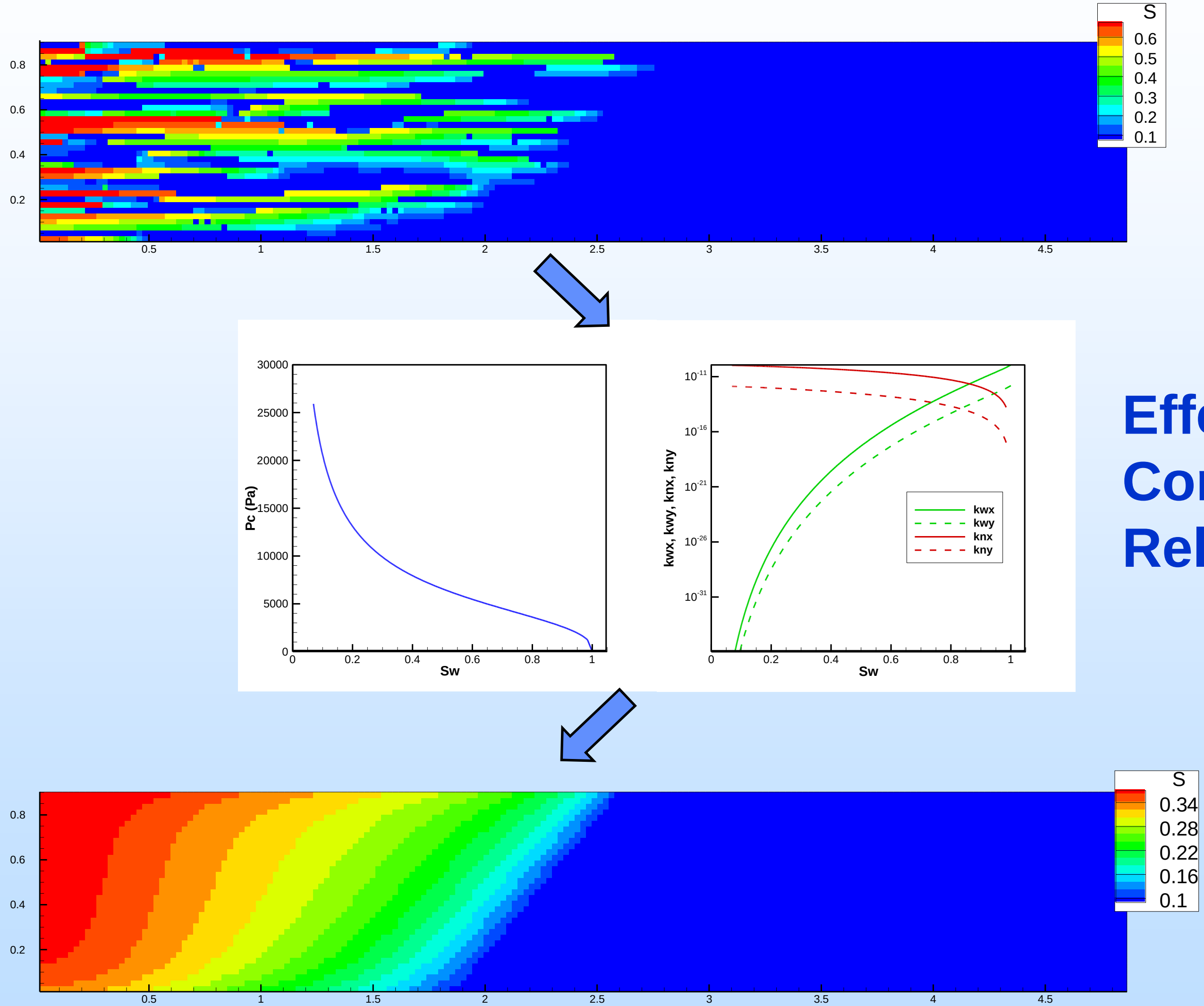
Large-scale capillary entrapment affected by connectivity!





Higher k → **Lower k**

Model Simplification Through Upscaling



Effective Constitutive Relationships

Accomplishments to date

- **Task 2 – Experiments in intermediate-scale**
  - ✓ Selected and tested surrogate fluids
  - ✓ Small tank experiments completed for testing capillary trapping and density-dependent fingers in homogeneous and simple heterogeneous systems
  - ✓ Initiated large tank experiments for capillary trapping
- **Task 3 – Modeling**
  - ✓ Developed a multiphase flow solver (based on the Finite Volume method) for analysis of the experimental data and new constitutive models and non-equilibrium mass transfer
  - ✓ Simulated the two-phase flow in small tank experiments and compared the model results with experimental data
  - ✓ Developed a new code for analyzing heterogeneity: Computes connectivity based on invasion percolation algorithm. This code also involves algorithms to upscale two-phase flow parameters.
  - ✓ Developed a new hysteresis model and tested against few data sets

Project Summary

Findings

- The numerical model based on the classical two-phase flow theory was able to capture the main features observed during the migration of the CO_2 surrogate fluid in the small tanks
- Incorporating hysteresis effects into the numerical models required for accurate prediction of post-injection capillary entrapment.
- Intermediate-scale heterogeneity (existence of lower and higher permeability zones) enhances the capillary entrapment.
- Density-driven convective mixing in highly heterogeneous formations may not be important.

Project Summary

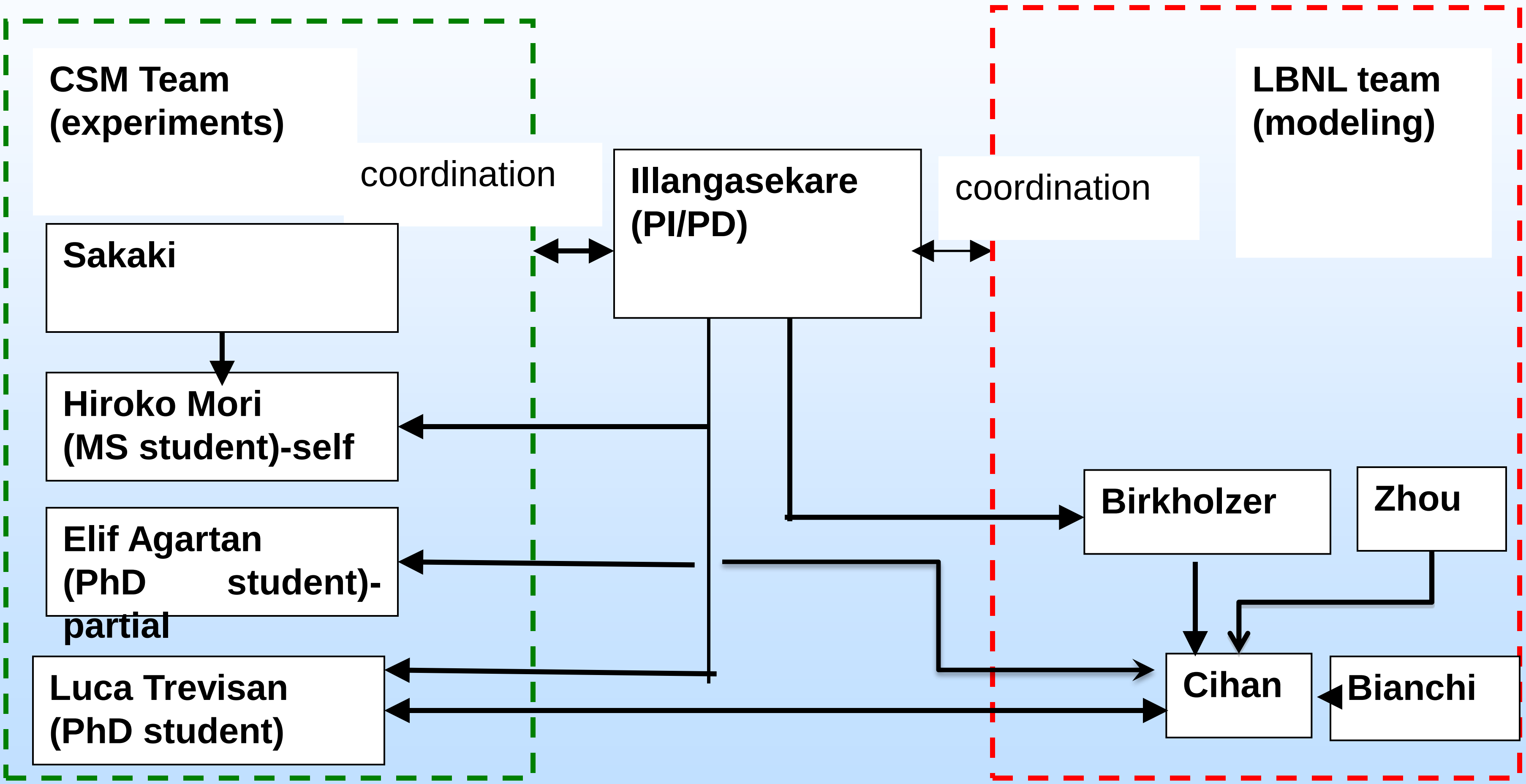
Future Efforts

- Obtain quantitative data on temporal and spatial saturation changes using the X-ray system
- Complete measurements of relative permeability of the sands in separate homogeneous column tests
- Update the model results in the small tank with measured relative permeability curves in separate homogeneous column tests
- Intermediate-scale heterogeneous experiments and models involving both capillary and dissolution trapping.
- Improve the numerical models by incorporating the validated constitutive models

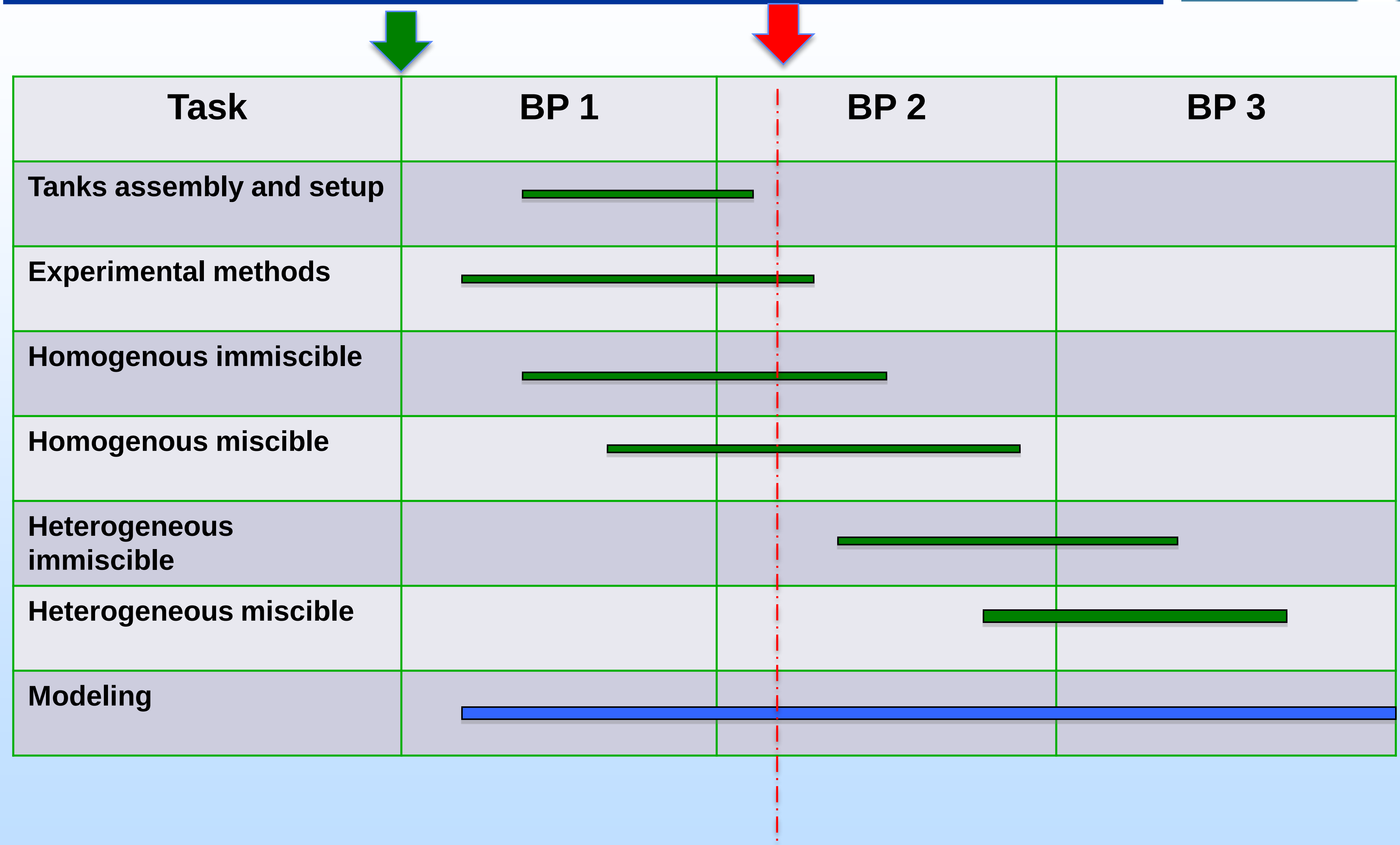
Questions?

Appendix: Organization and Gantt Charts

Task 1.0 – Project Management and Planning



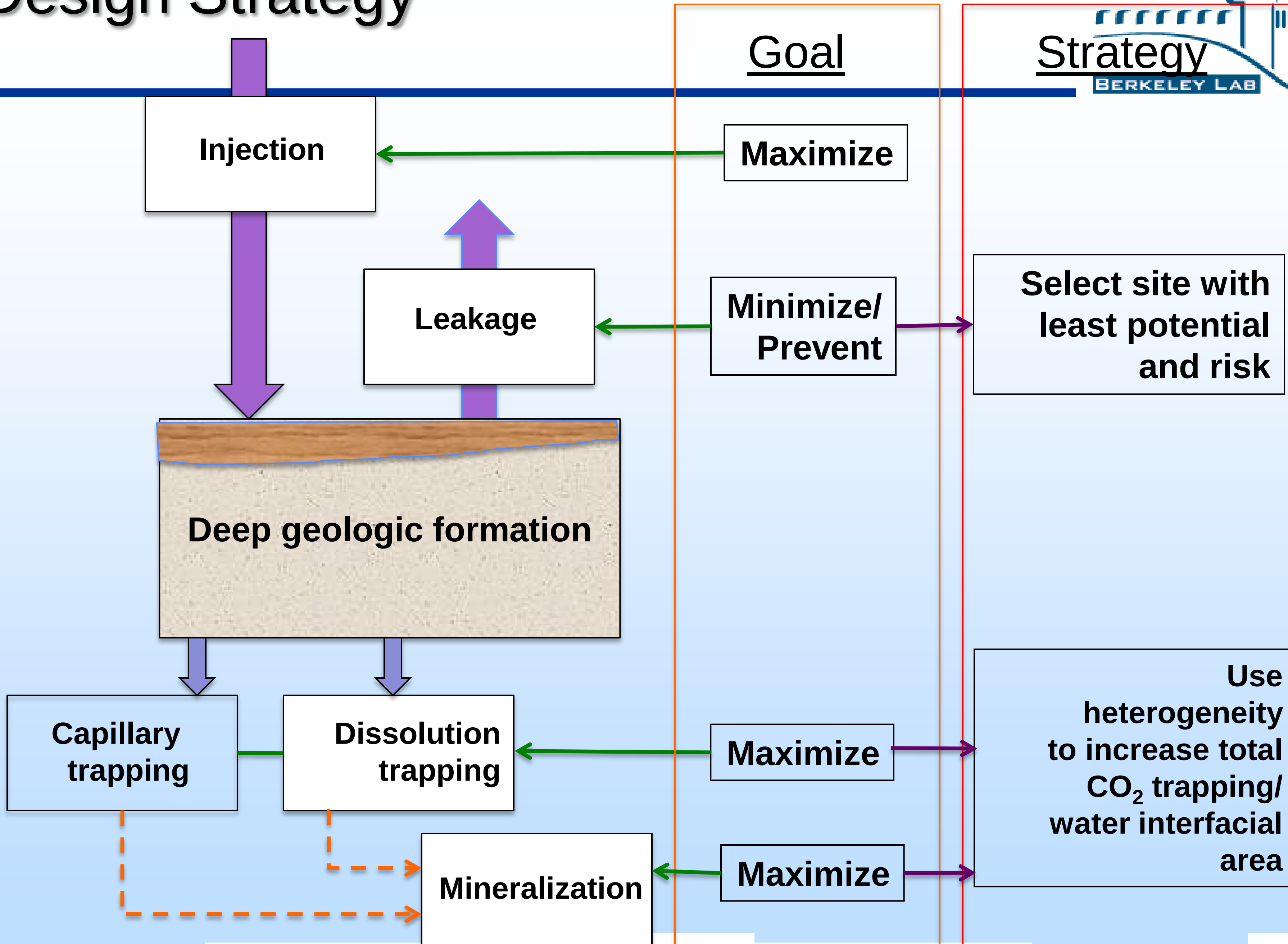
Updated Time Line



Appendix: Bibliography

Backup Slides

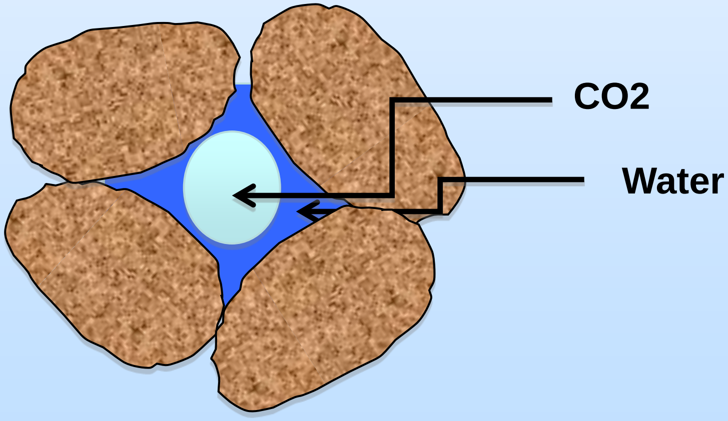
Design Strategy



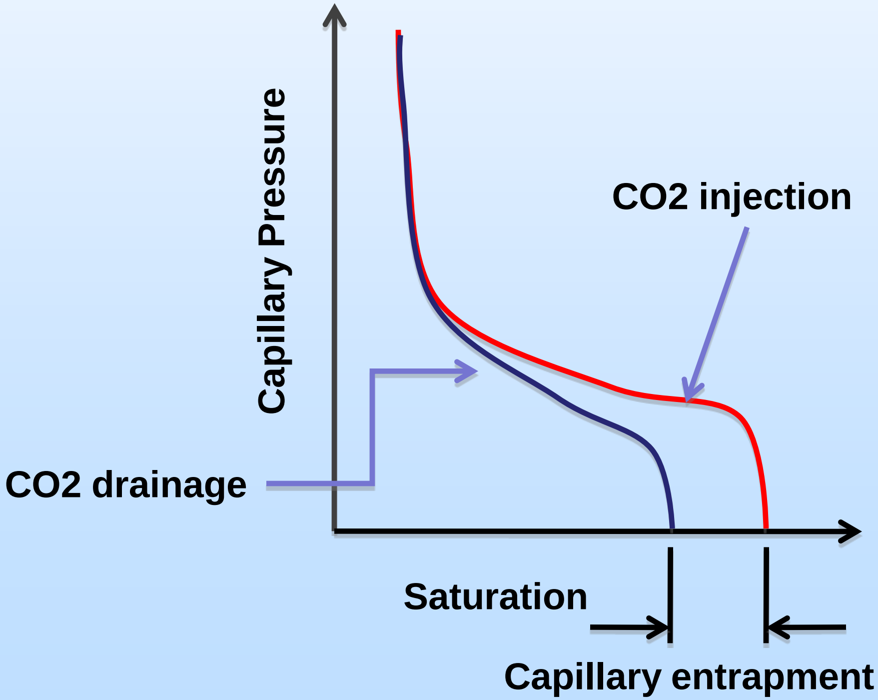
Physically based theory for predicting entrapment

In conventional multiphase flow modeling approaches, residual non-wetting phase content are either calculated based on empirical relationships or fitted from experimental data.

There is no physically based theory predicting entrapment of CO_2 in homogeneous and heterogeneous systems.

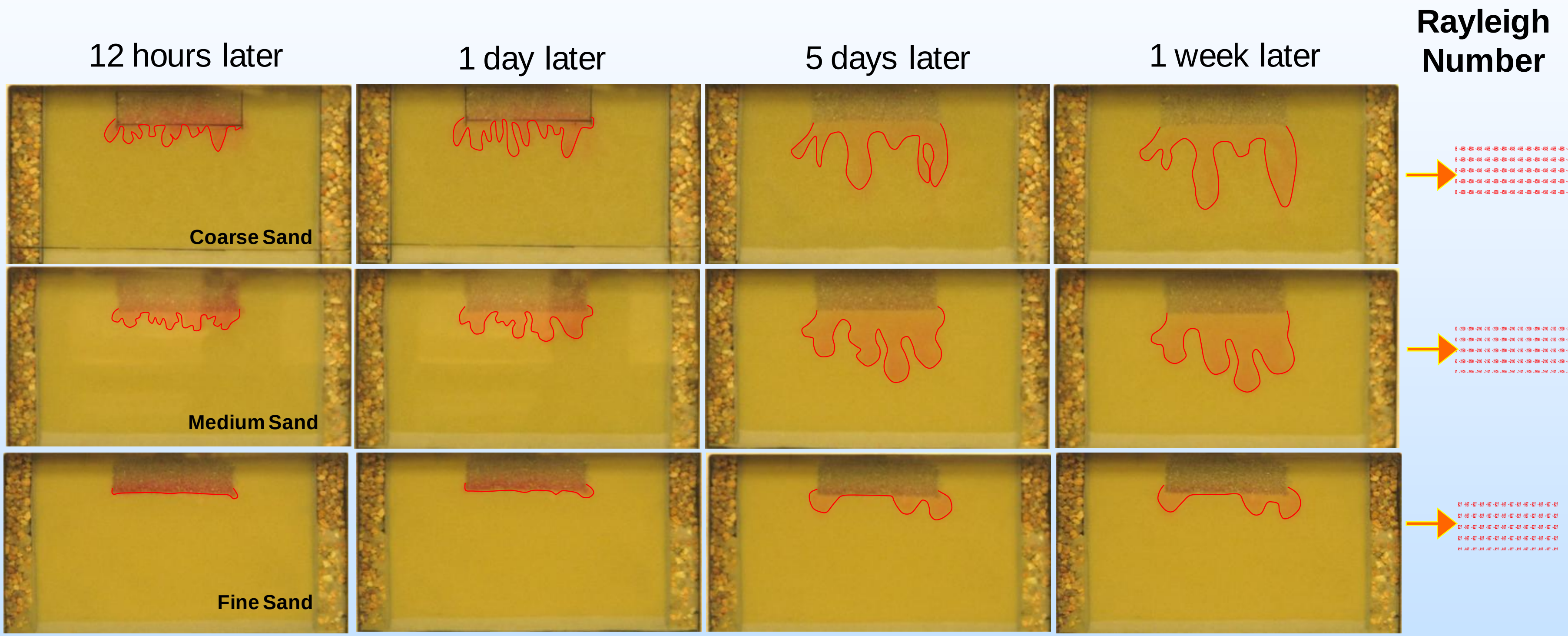


Pore scale



Small Tank Experiments: Density-driven fingering and (water/propylene glycol) in homogeneous domains

Rayleigh Number for scCO2-brine @ Typical Reservoir Conditions ~ 6 - 10^3



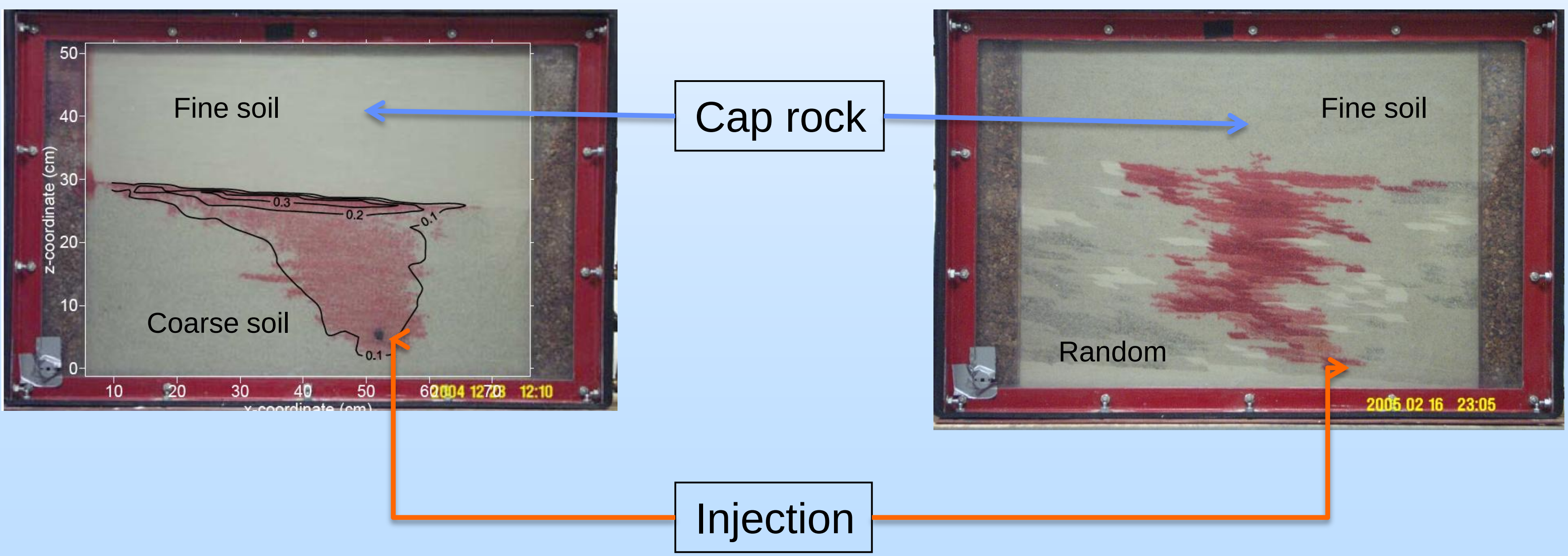
$$Ra = \frac{k \Delta \rho g H}{D \mu \emptyset}$$

$$Ra_c > 4\pi^2 (\sim 40)$$

Heterogeneity and Capillary Trapping

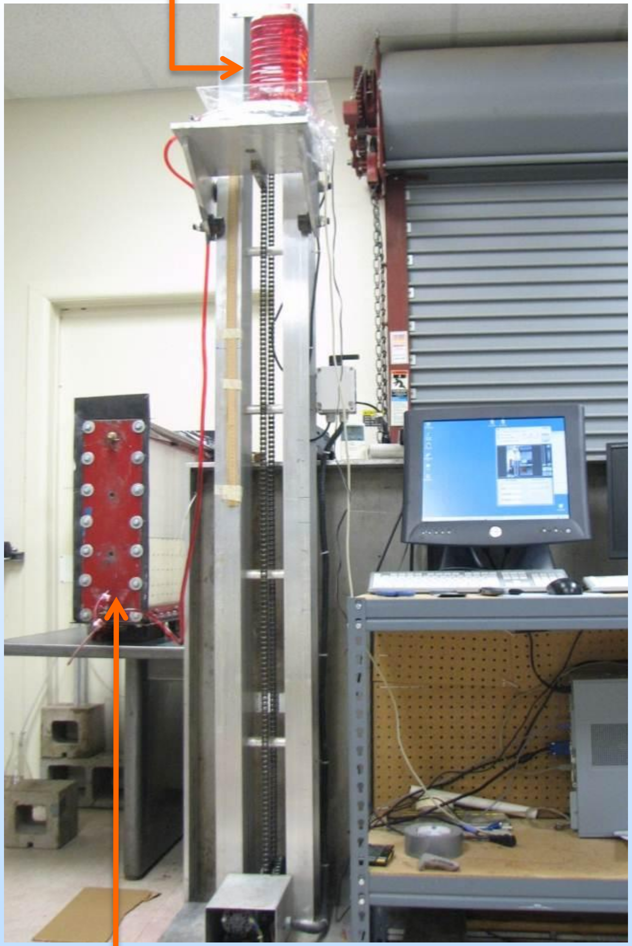
Entrapment efficiencies of CO_2 (*defined as the total mass trapping per unit volume of the formation*) in relatively homogeneous and highly heterogeneous systems can be quite different. *Knowledge gaps exist on how the heterogeneity influences capillary entrapment of CO_2.*

Homogeneous *Heterogeneous*



Small Tank Experiments for Capillary Trapping

Mariotte bottle with Soltrol 220 on an automated balance



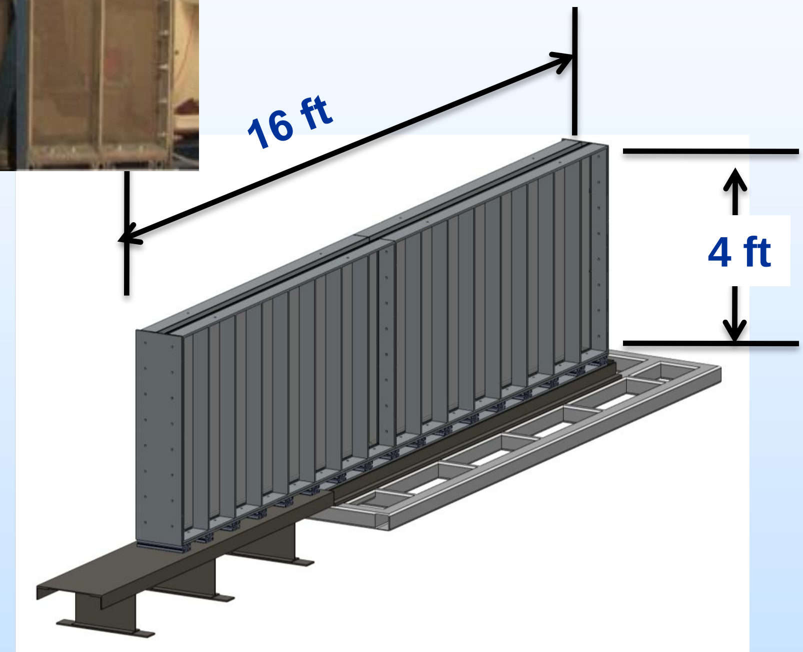
Small tank (90 cm x 60 cm x 5.6 cm)

Goal is to generate a data set for validation of models to simulate macro-scale processes of capillary entrapment

- A total of 8 small tanks experiments with both homogeneous and heterogeneous packing completed.
- Plume injection and plume configuration recorded.
- Soil samples removed and the fluids extracted to determine final entrapment saturations.

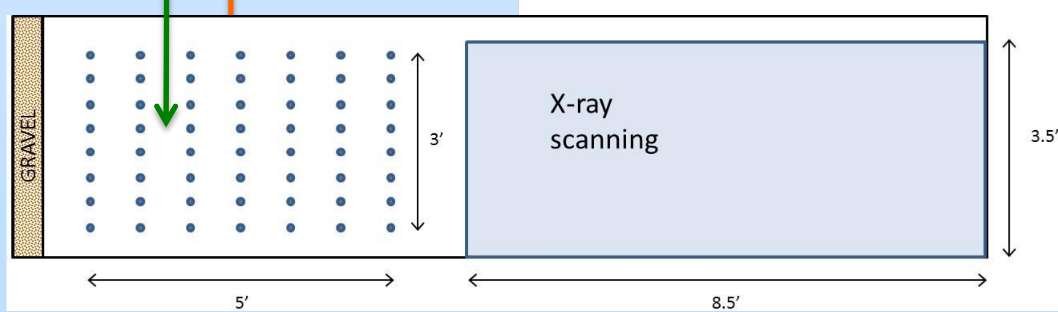
Large Tank Experiments: Design and assembly of large tanks for confined conditions

Sloping capping layer



X-ray attenuation
For phase saturation measurement

Ports for aqueous sampling

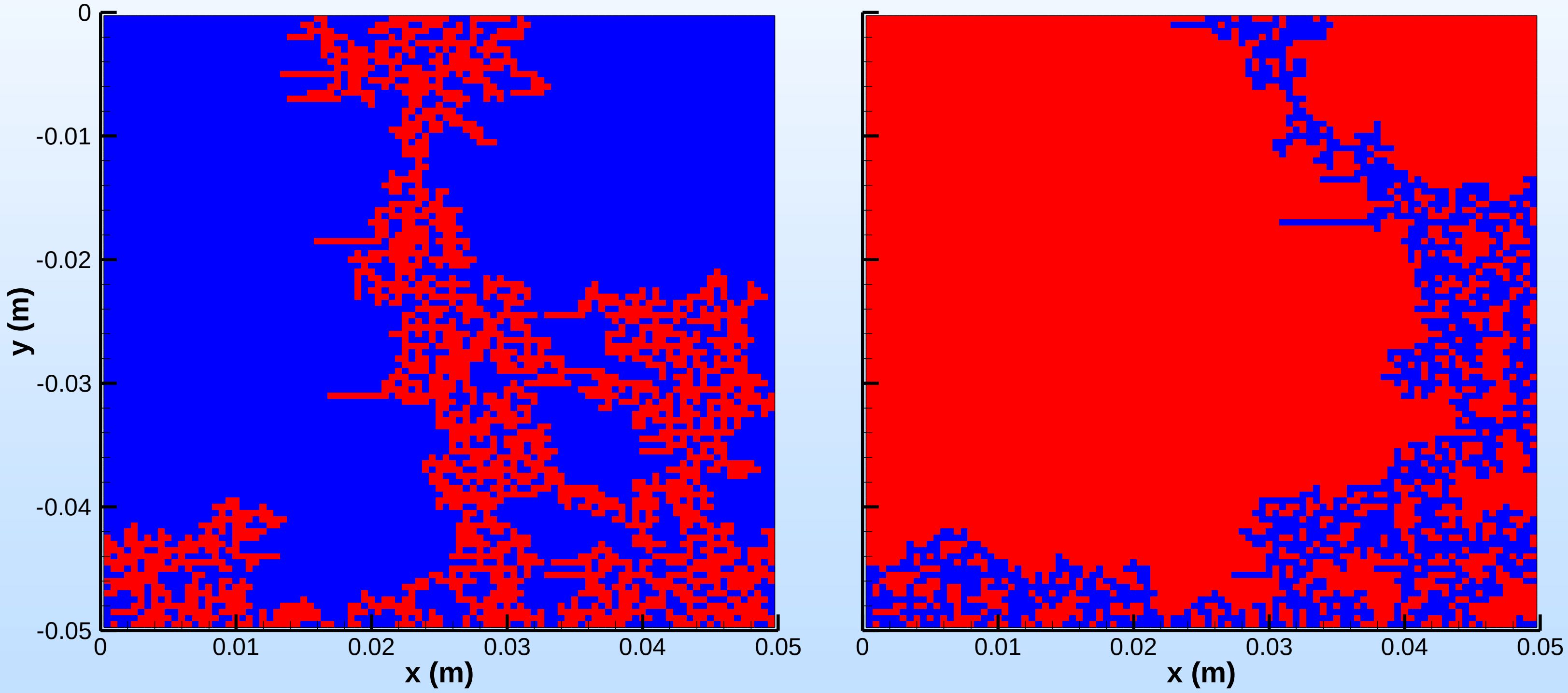


Conceptual Model :
Near-Pore-Scale Macroscopic Invasion Percolation

- Problem domain discretized into a grid (two- or three-dimensional) with a chosen critical "throat" or critical "pore", r_m, values assigned to each grid block for nonwetting or wetting fluid invasion (Glass et al., 2001, WRR)
- A grid block contains a small void space characterized with a r_m value.

$$Young - Laplace\ Equation,\ P_c = P_a - P_w = \frac{2\sigma}{r_m}$$

No Trapping



Drainage path

Imbibitions path

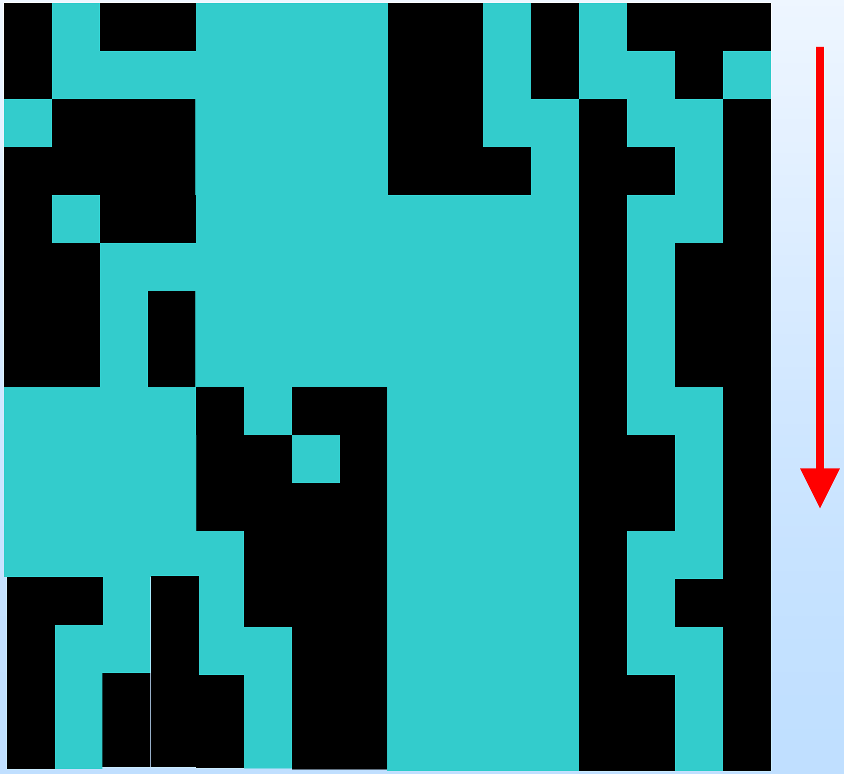
Development of Constitutive Models Using Pore Connectivity

$$Young-Laplace\ Equation,\ P_c = P_a - P_w = \frac{2\sigma}{r_m}$$

Assumptions:

- During drainage, the largest pores drain first
- During wetting, the smallest pores fill up first

Drainage



$$i=1 \qquad \phi - \theta_1 = p_{11} f_1$$

$$i=2 \qquad \theta_1 - \theta_2 = p_{12}(1 - p_{11}) f_1 + p_{22} f_2$$

$$p_{11} = 5/6$$

$$p_{12} = 1,\ p_{22} = 54/60$$

Development of A Theoretical Hysteresis Model

Pore Sizes $r_1 > r_2 > \cdots > r_n$

Volume Fractions $f_1, f_2, \ldots, f_n$

Connectivity for the Drainage Paths

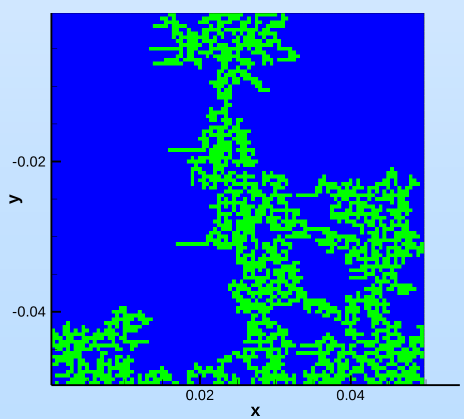
Large Pores ↓ Small Pores

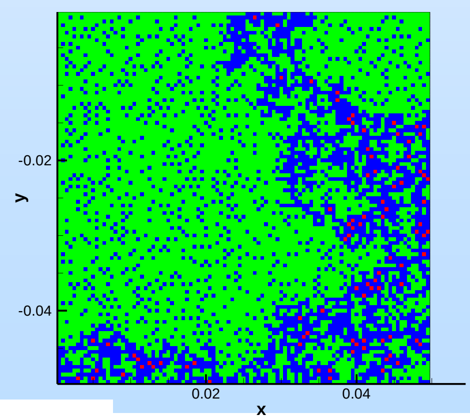
$$\begin{array}{cccc} p^d_{11} & & & \\ p^d_{12} & p^d_{22} & & \\ p^d_{13} & p^d_{23} & p^d_{33} & \\ \vdots & \vdots & \vdots & \ddots \\ p^d_{1n} & p^d_{2n} & p^d_{3n} & \cdots \end{array}$$

Connectivity for the Imbibitions Paths

Small Pores ↓ Large Pores

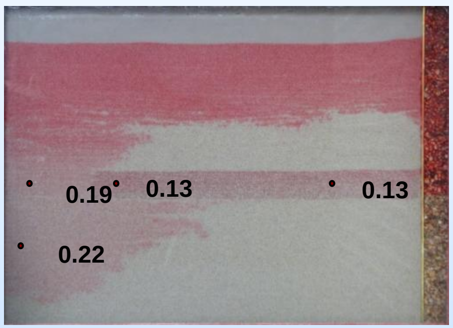
$$\begin{array}{cccc} p^w_{n,n} & & & \\ p^w_{n,n-1} & p^w_{n-1,n-1} & & \\ p^w_{n,n-2} & p^w_{n-1,n-2} & p^w_{n-2,n-2} & \\ \vdots & \vdots & \vdots & \ddots \\ p^w_{n,1} & p^w_{n-1,1} & p^w_{n-2,1} & \cdots \end{array}$$



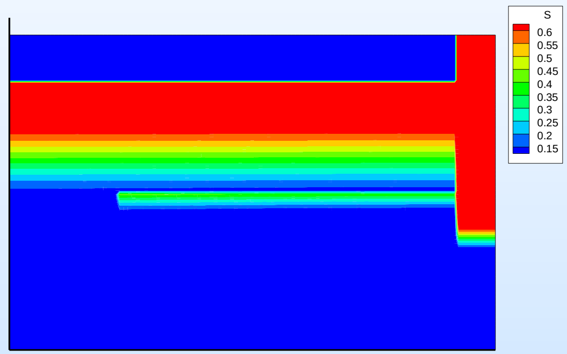


Model Testing

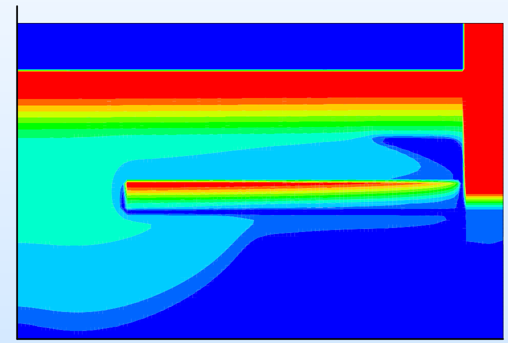
A Small Tank Experiment – Post-Injection



No hysteresis effects



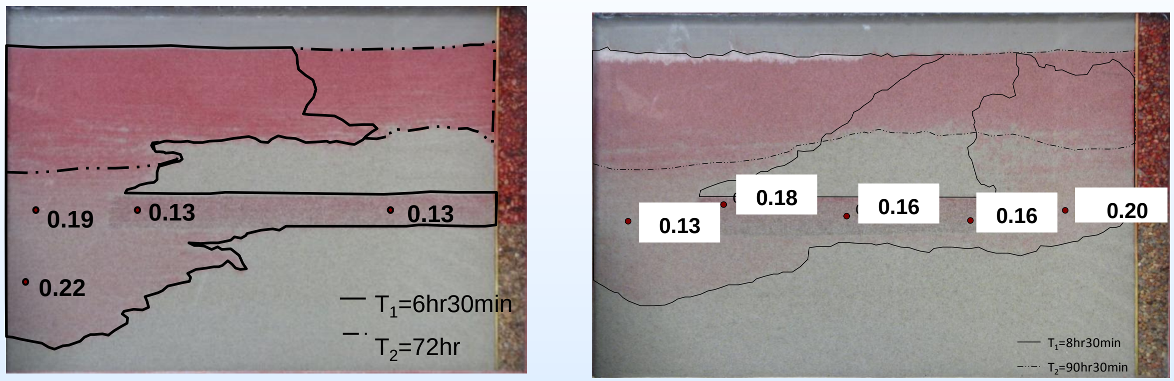
With hysteresis

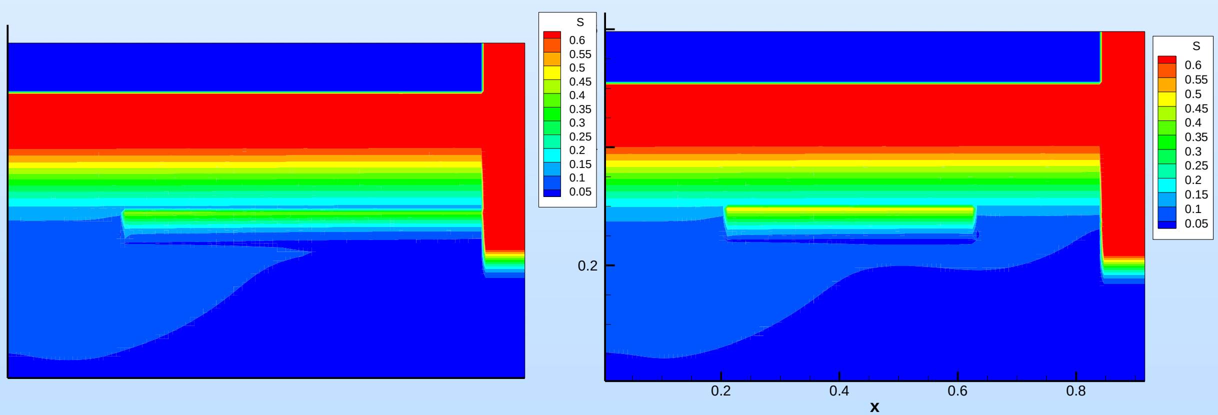


Model Testing

Saturation distributions at the end of the experiments

Heterogeneous Packings



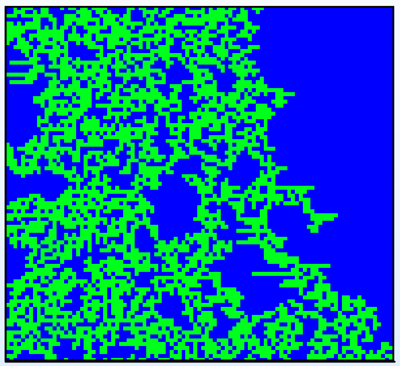


Two-phase model results with hysteresis effects

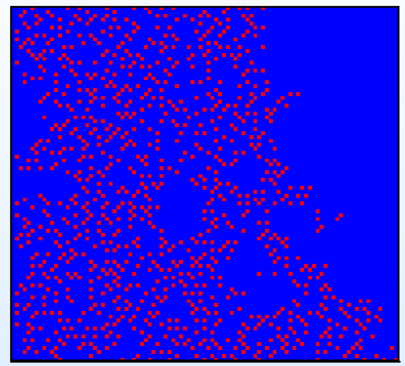
Dependence of Residual Saturation on Maximum Saturation

Near-Pore Scale Invasion Percolation (sand#30)

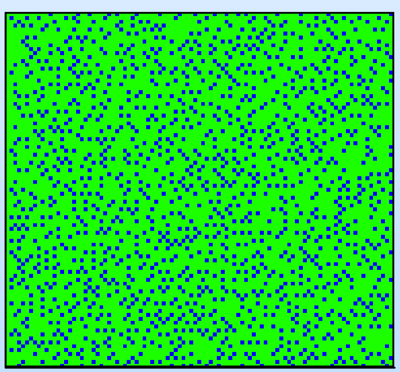
End of Drainage | *End of Imbibitions*



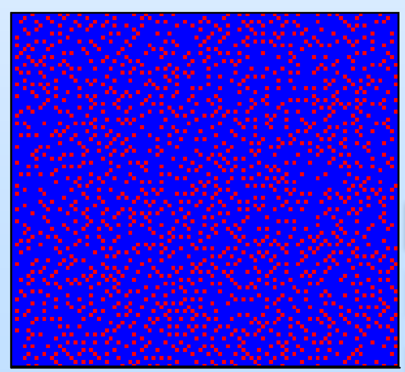
S_{max}=0.40



S_r=0.11



S_{max}=0.84



S_r=0.17

Wetting Phase

Non-wetting Phase

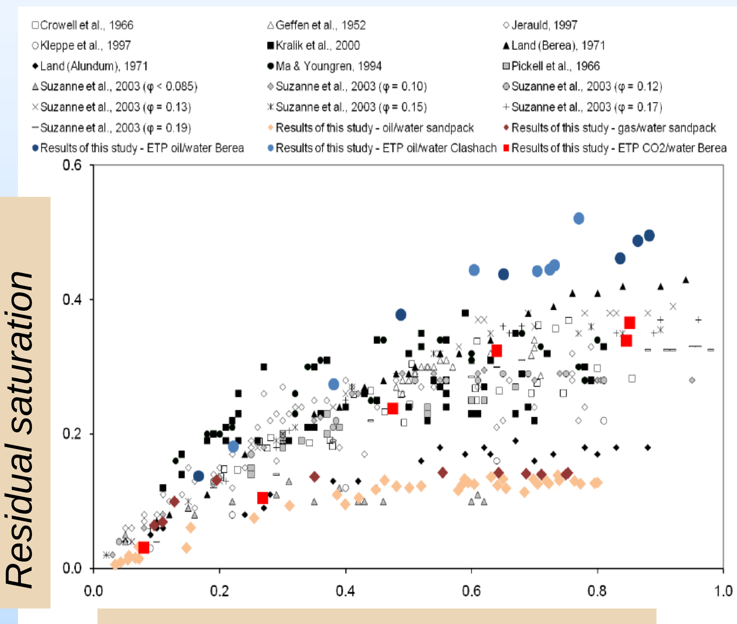
Trapped Non-wetting Phase

Dependence of Residual Saturation on Maximum Saturation

- ❑ **Results show that the residual non-wetting phase saturation is strongly function of the saturation at the end of injection**

Pentland et al. 2010, SPE

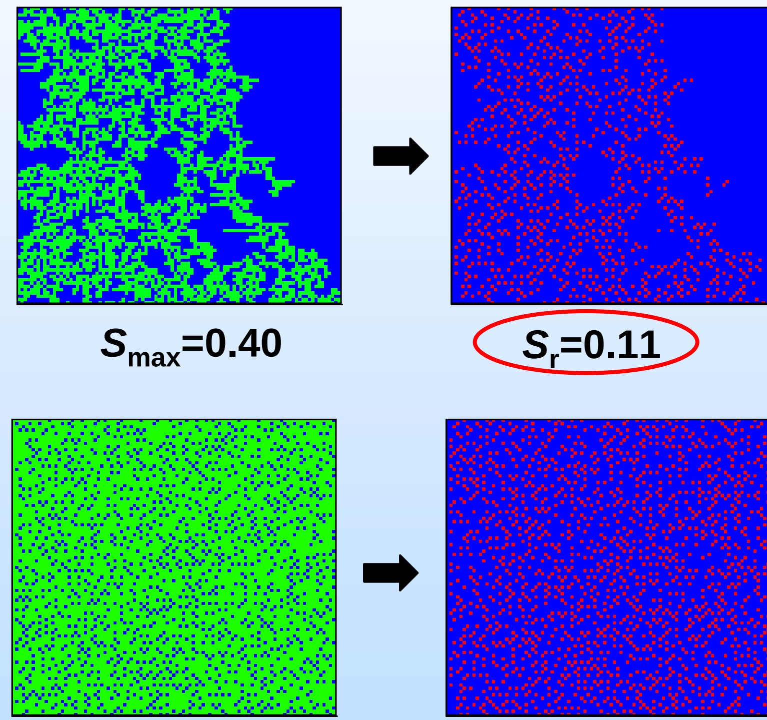
Residual saturation



Non-wetting phase saturation (at the end of injection)

Near-Pore Scale Invasion Percolation (sand#30)

End of Drainage ***End of Imbibitions***



S_{max}=0.40 **S_r=0.11**

S_{max}=0.84 **S_r=0.17**

Wetting Phase

Non-wetting Phase

Trapped Non-wetting Phase