Influence of Local Capillary Trapping on Containment System Effectiveness

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Developing the Technologies and Building the
Infrastructure for CO_2 Storage

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Presentation Outline

- Motivation and relevance to Program
- Project goals
- Technical status
- Accomplishments
- Summary
- Future plans

Benefit to the Program

- Program goal being addressed:
  - Develop technologies to demonstrate that 99 percent of injected CO_2 remains in the injection zones
- Project benefits statement:
  - The proposed simulation and experiments will systematically establish proof-of-feasibility of a novel concept, namely the long-term security of CO_2 that fills local (small-scale) capillary traps in heterogeneous storage formations. The outcome will be a geologically grounded method for quantifying the extent of such trapping. The method can be implemented with simulation capabilities already being used to predict storage security. The impact will be a potential reduction in risks associated with long-term storage security, achieved simply by considering the physical implications of geologic heterogeneity.

Project Overview (1): Goals and Objectives

- Overall objective: rigorously assess amount, extent of local capillary trapping possible in storage formations
- Project goals
  - quantify influence of geologic, petrophysical parameters on structure of local capillary barriers in heterogeneous formations, and hence number and volume of local capillary traps
  - determine by simulation and laboratory experiment fraction of traps filled during prototypical CO_2 emplacement operations (injection followed by buoyancy-driven migration)
  - use simulation and experiment to quantify fraction of filled local capillary traps that retains CO_2- if top seal leaks
- Relevance to program goal
  - Accounting for local capillary trapping yields larger probability of 99% containment

Project Overview (2): Goals and Objectives

- Project goals
  - quantify influence of geologic, petrophysical parameters on structure of local capillary barriers in heterogeneous formation, and hence number and volume of local capillary traps.
  - determine by simulation and laboratory experiment fraction of traps filled during prototypical CO_2 emplacement operations (injection followed by buoyancy-driven migration).
  - use simulation and experiment to quantify fraction of filled local capillary traps that retains CO_2- if top seal leaks
- Success criteria
  - assess likely maximum possible amount of local capillary trapping
  - assess likely maximum fraction of local capillary traps expected to be filled during typical CO_2 emplacement scenarios
  - assess likely maximum fraction of filled local capillary traps that retain CO_2 after top seal leaks

Technical status: Motivation

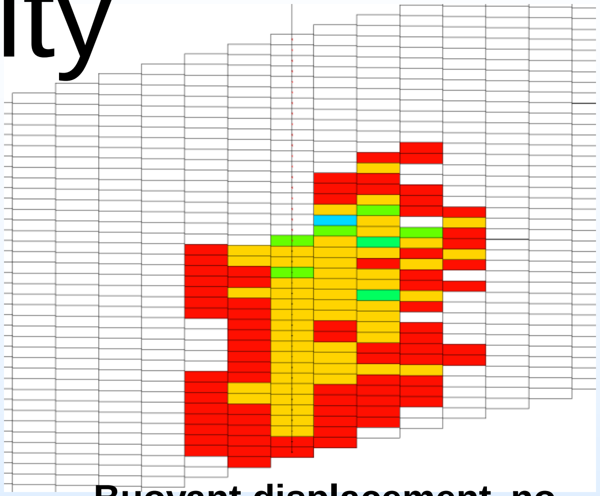
- Buoyancy-driven displacement may dominate many storage projects
- "Inject low and let rise" strategy for maximizing security of storage
  - CO_2 injected at bottom of storage formation
  - CO_2 rises under buoyancy, leaving residual saturation

Saturation Profiles of CO_2-rich Phase
(vertical slice through the injection well in X-Z direction)

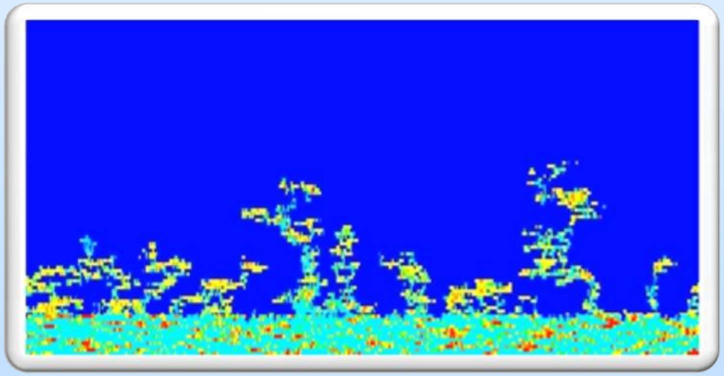
from IPCC Special Report on Carbon Capture and Storage, 2006

Technical Status: Role of Heterogeneity

- Maximum trapping requires maximum contact of rising CO_2 plume with rock – a compact displacement front
- Heterogeneity of capillary entry pressure severely disrupts the displacement front
  - How much reduction in residual phase trapping?
  - Saadatpoor et al 2009 showed that *local capillary trapping* occurs
  - essentially makes up for lack of residual phase trapping



Buoyant displacement, no capillary heterogeneity

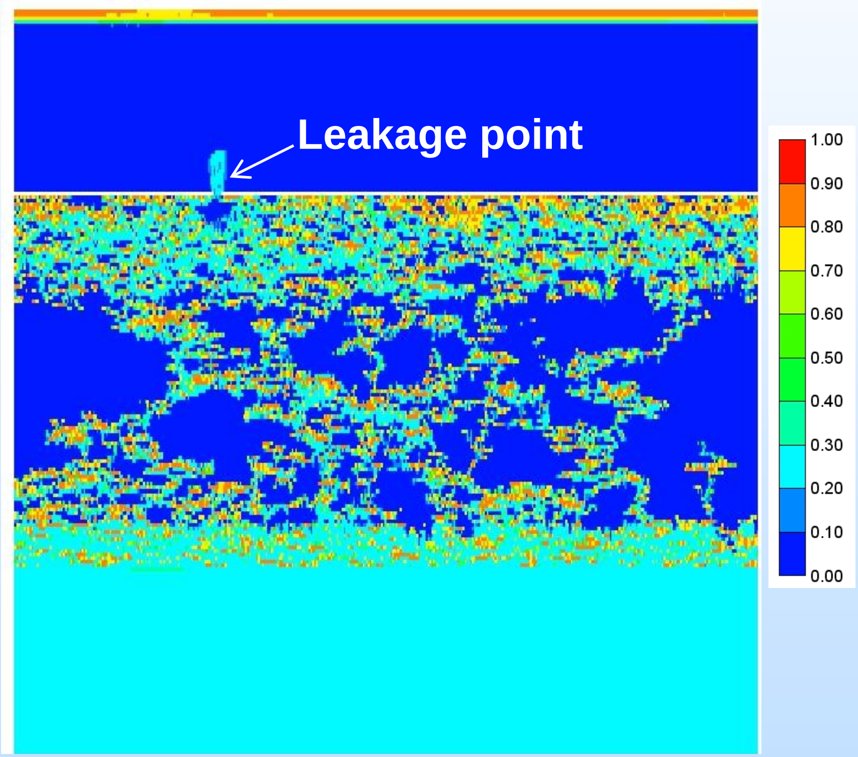


Buoyant displacement, with capillary heterogeneity

Technical Status: implications for storage security in structural traps

- Containment system effectiveness
  - Suppose heterogeneous structure filled via buoyant migration
  - Top seal subsequently compromised
  - What fraction of stored CO_2 leaks out of structure?
- Ignoring heterogeneity gives worst-case estimate of effectiveness

Gas Saturation Profile at 100 years after leak develops



Technical Status: Research Objectives

Overall: determine the extent of local capillary trapping, i.e., CO_2 immobilization beneath small-scale capillary barriers expected in typical heterogeneous storage formations.

1. Characterize petrophysical, geologic controls upon number, volume of potential local capillary traps
2. Determine degree to which potential local capillary traps are filled in anticipated storage schemes
3. Quantify immobilization persisting after loss of integrity of overlying seal
4. Incorporate results into functional form integratable into reservoir simulators
5. Conduct lab experiments to validate simulations

Experimental Design

Experiment Apparatus

- **Polycarbonate lid**
- **Polycarbonate containment box**
- **Pivot steel frame**
- **Fluid flow system**
- **2 ft. by 2 ft. by 0.04 ft. frame mounted on horizontal pivots in a support frame.**
- **Easy flipping of a gravity stable initial condition by 180 deg.**

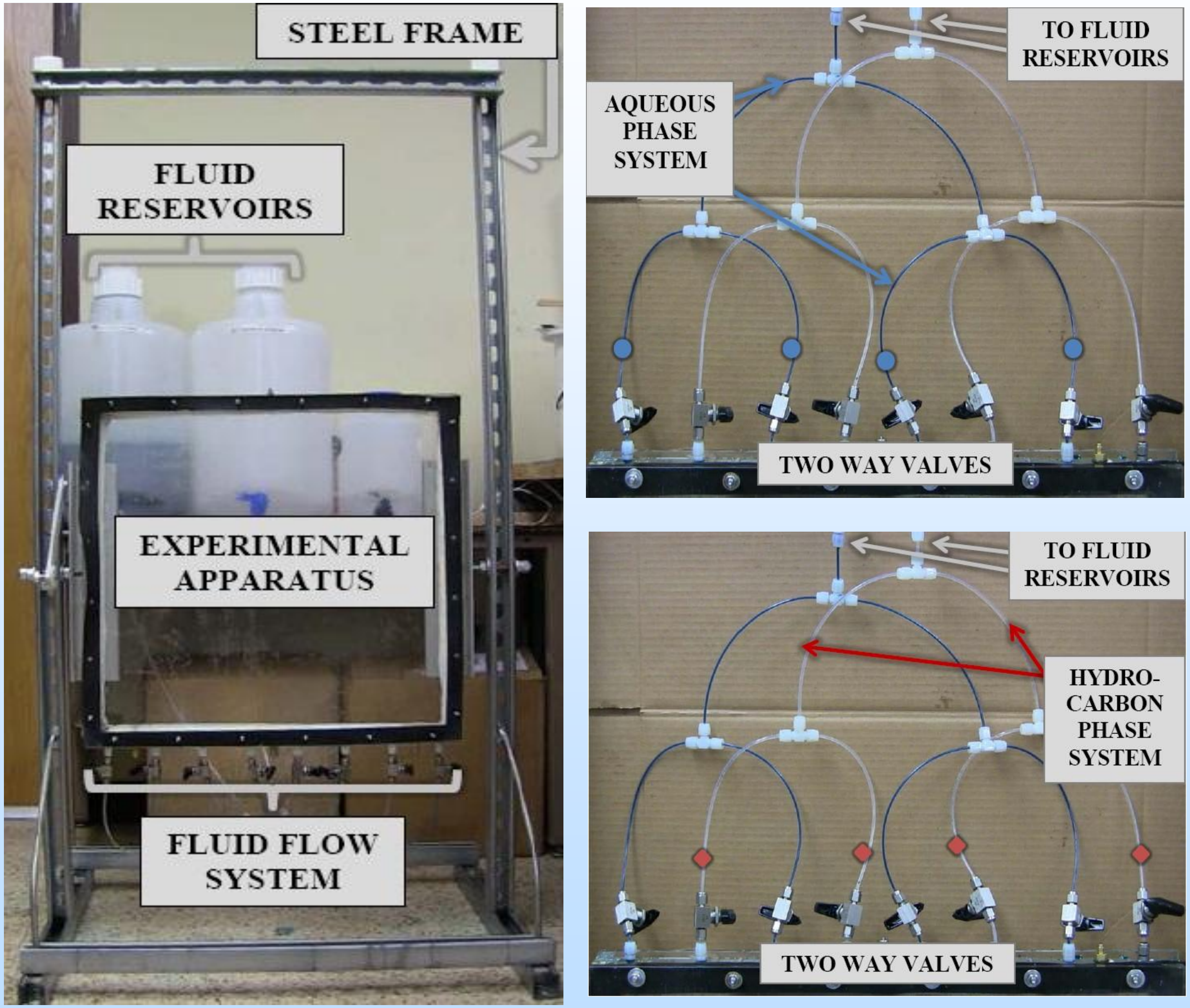
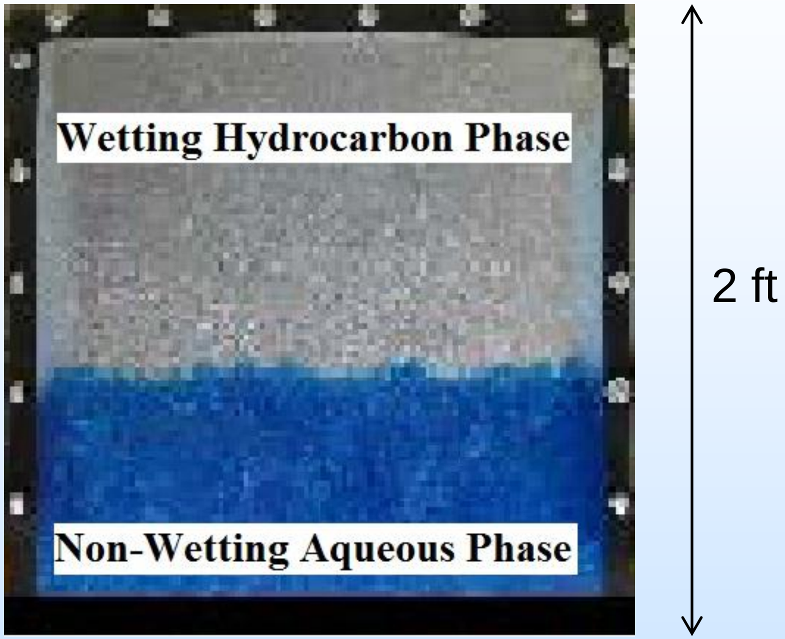


Figure 6. Experiment Apparatus – “Ant-Farm” (left) & Fluid Flow System (right)

Experimental Procedure

The Initial Condition



- Pack granular medium of hydrophobic beads into hydrophobic box
- Inject light mineral oil/decane mixture slowly to fill entire medium
- Slow injection of aqueous phase (blue) to displace prescribed volume of hydrocarbon phase.

Figure 7. Initial Condition: Upper portion of porous medium saturated with hydrocarbon phase, aqueous phase has displaced hydrocarbon from lower third of domain . 5mm silica beads in the picture.

Brine is always blue

Fluid analogues for $scCO_2$/brine

Analogous Fluid Pairs

Fluid	Viscosity (cP)	Density (kg/m^3)
100% Brine	1.0	1000
100% Decane	0.9	720
60% MineralOil 40% Decane	7.0	812
60% Brine 40% Glycerol	7.0	1084

Fluid Pairs		Approx. μ Ratio	Δρ kg/m^3
Nonwetting Phase	Wetting Phase		
Brine	60% MineralOil 40% Decane	1:7	188
Brine	Decane	1:1	280
60% Brine 40% Glycerol	Decane	7:1	354

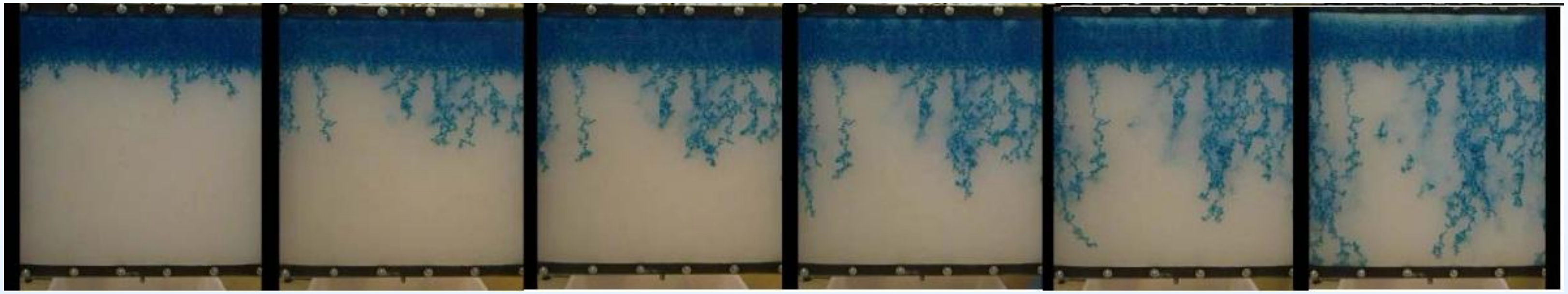
Table 1. Analogous Fluid Pairings / Properties

Requires porous media treated to be hydrophobic

Buoyancy driven displacement

Viscosity Effect– homogeneous domain

3mm treated HDPE*, Brine vs. 60%MinOil-40%Decane (1:7)** ,(150sec/300sec)***

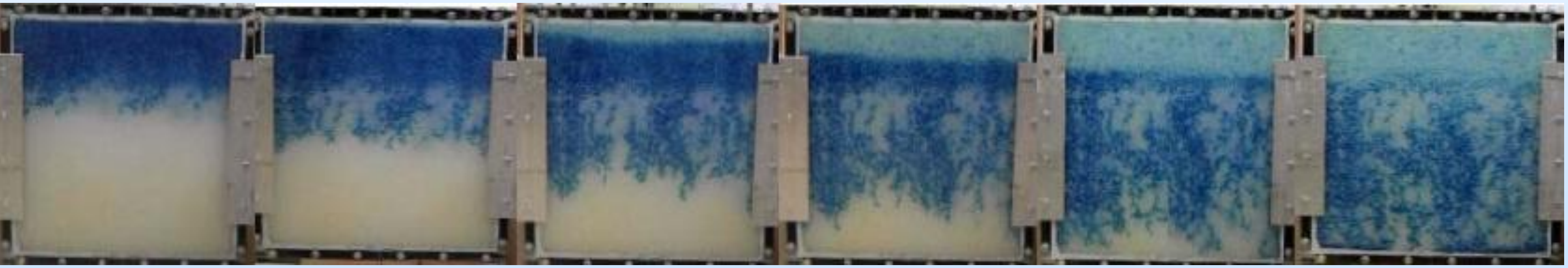


***High Density Polyethylene Beads**

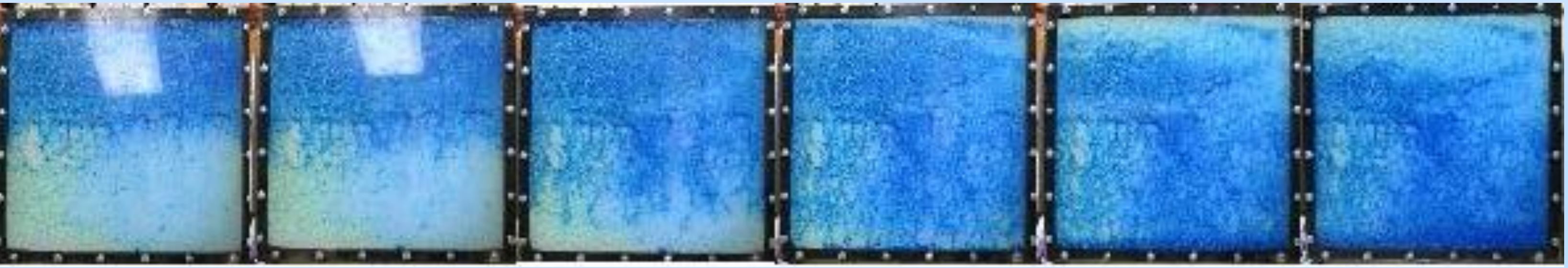
****viscosity ratio**

*****time for front reaches the bottom / time for completion**

3mm treated HDPE, Brine vs. 100%Decane (1:1), (40sec/60sec)

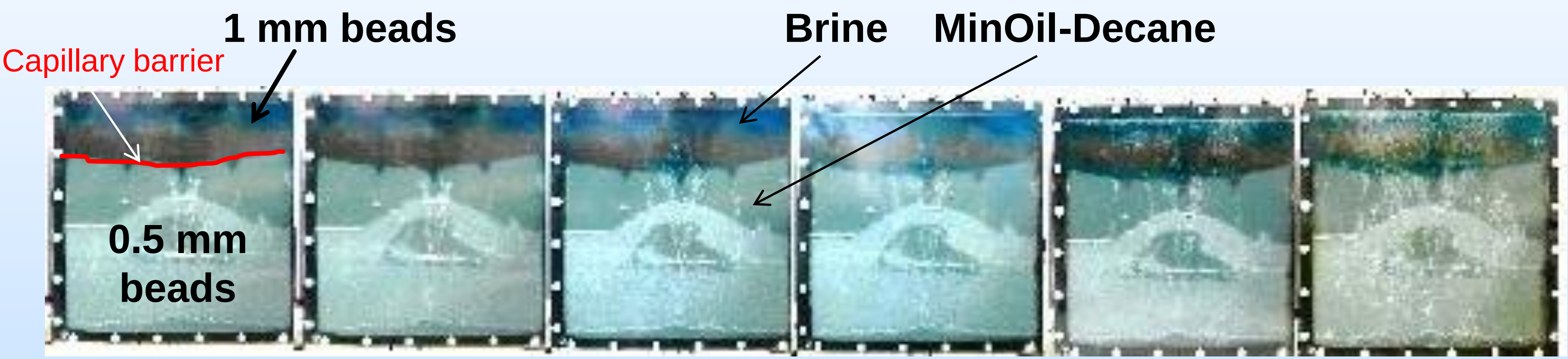


3mm treated HDPE, 60%Brine-40%Glycerol vs. 100%Decane (7:1), (20sec/40sec)



Heterogeneity as capillary barrier

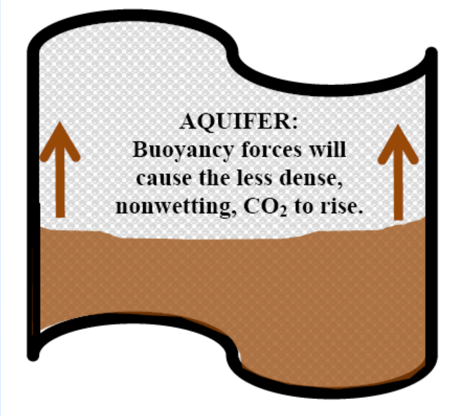
Heterogeneity Effect Experiment



- **Grain size change, from coarser to finer grain (factor of two in size), sufficient to stop migration (consistent with prediction).**

Laboratory Future Work

- New apparatus of hydrophilic material (such as Pyrex Glass) currently under construction
  - Making silica beads or sand grains hydrophobic is time consuming, labor intensive.
  - Fluid pairs must be reversed.
    - Now (hydrophobic Apparatus): brine (non-wetting, mimic CO_2) falling, oil (wetting, mimic brine) rising.
      Future (hydrophilic Apparatus): brine (wetting, mimic brine) falling, oil (non-wetting, mimic CO_2) rising up.



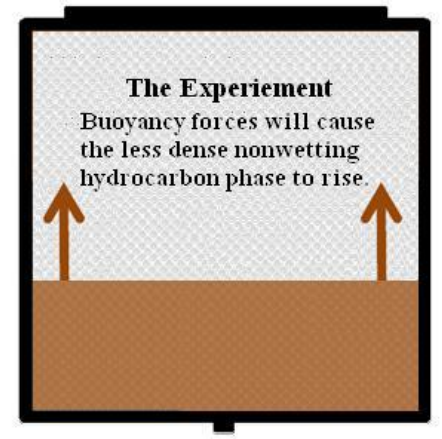


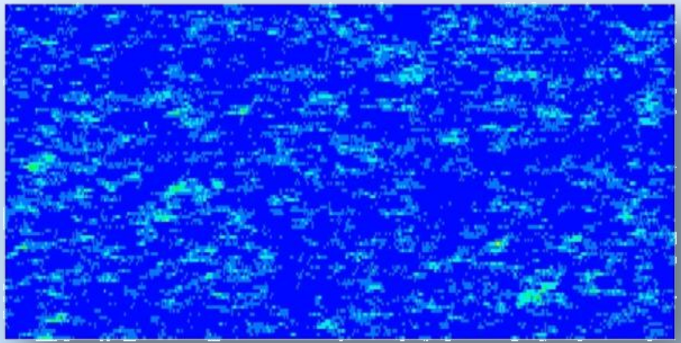
Figure 12. Experiment Concept after changing the apparatus to hydrophilic.

Such that the experiment concept matches exactly the actual aquifer condition.

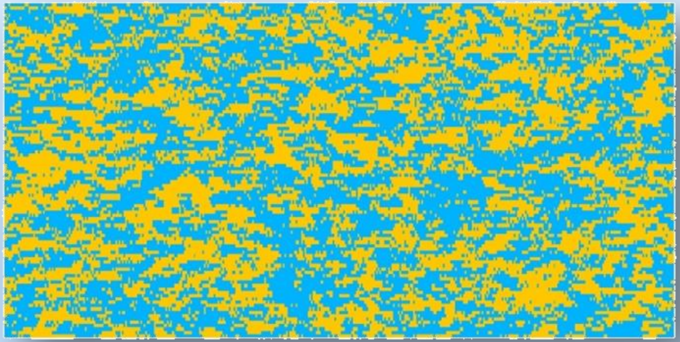
Finding Local Capillary Traps in Geologic Models

- A set of subroutines that carry out the following steps on a 3D domain of capillary entry pressure:

1. Given a value of critical capillary entry pressure, find all cells in domain that have entry pressures exceeding the critical value



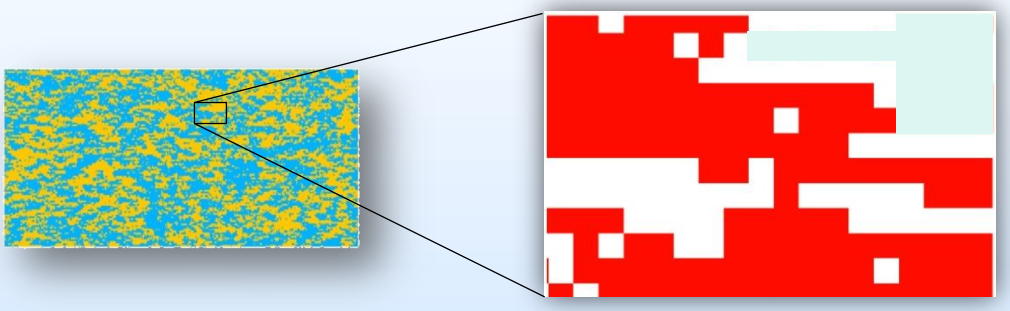
Domain with heterogeneous capillary entry pressure



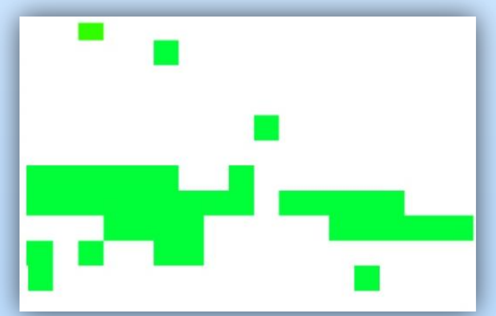
Orange cells have $P_{c,entry} > P_c^{crit}$

Algorithm

2. Find all connected clusters in the set of cells from step 1 (Barriers)

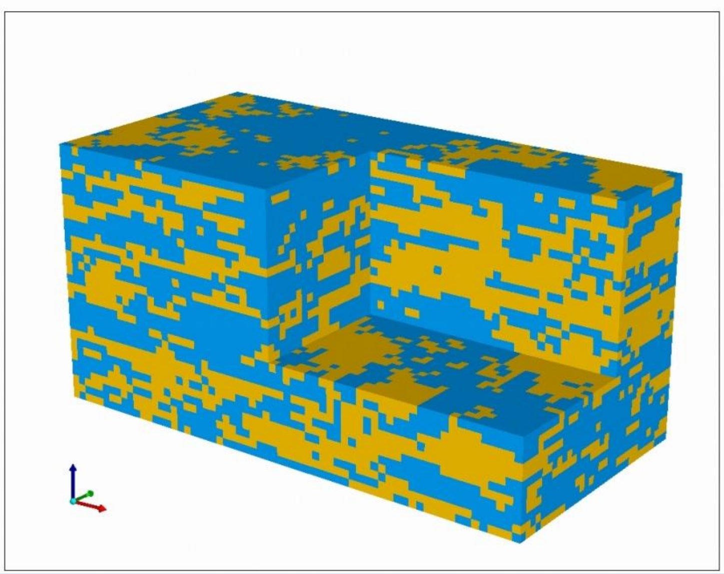


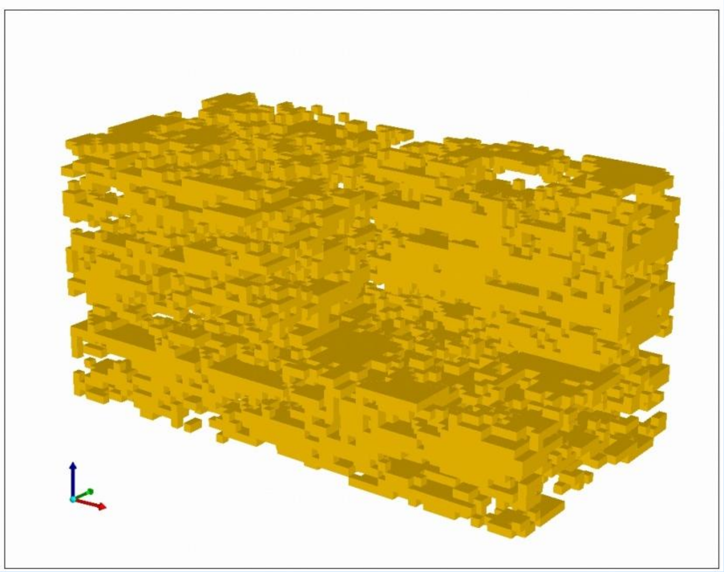
3. Find non-barrier clusters that are surrounded by set of clusters from step 2 (Traps)



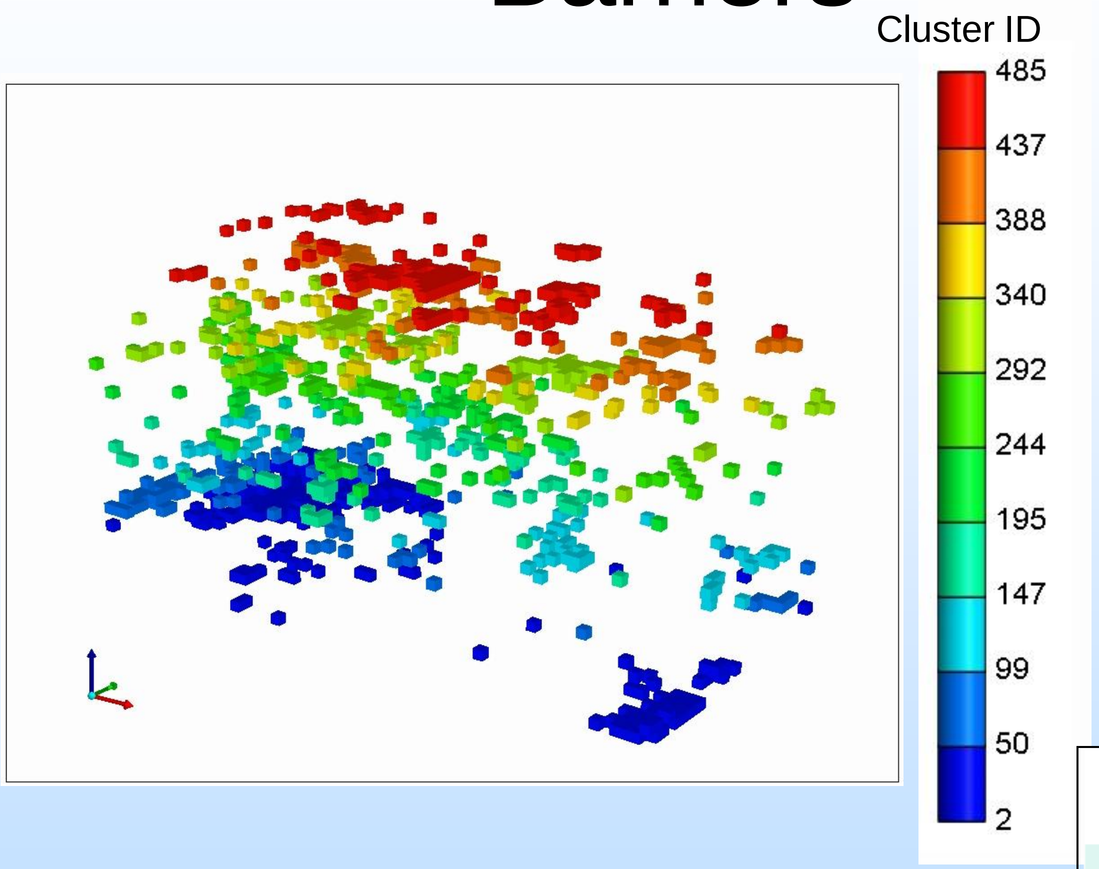
Example Application to 3D Model
Step 1: Barriers

- **Orange blocks represent barriers**

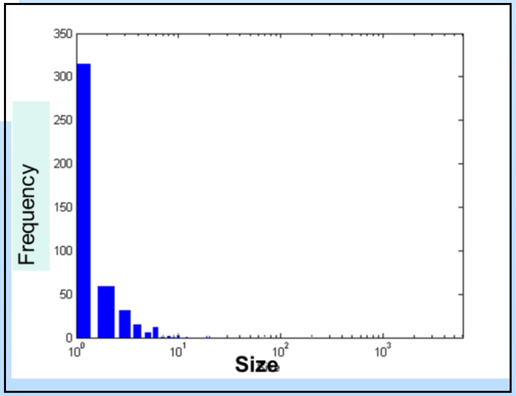




Step 2: Connected Clusters of Barriers



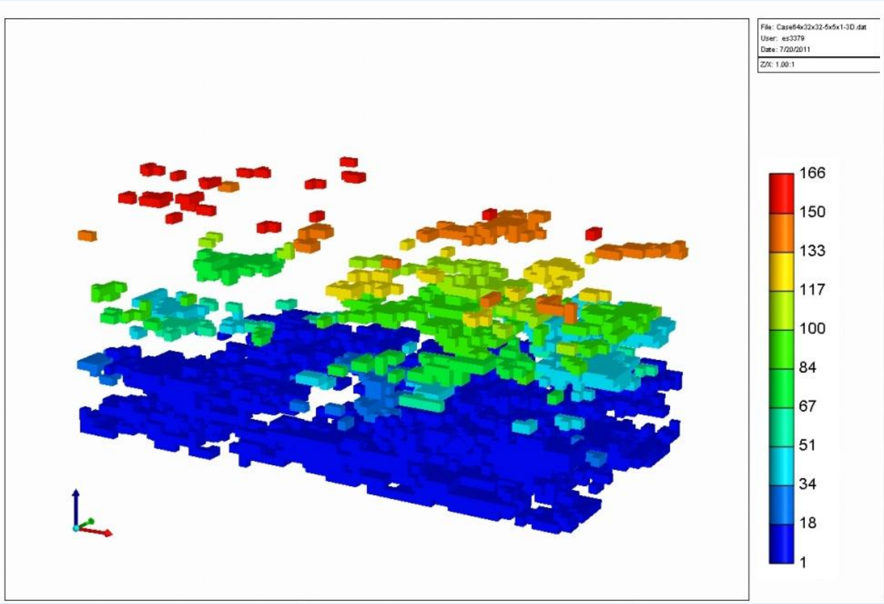
- 485 different connected clusters exist, most of them with size 1

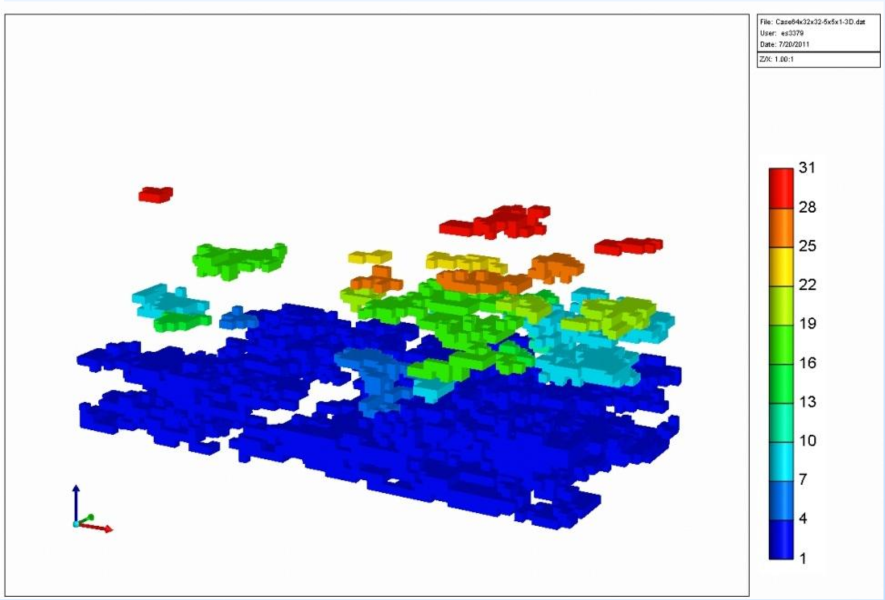


Step 3: Discard Small Clusters

Cluster size > 2
166 different connected clusters

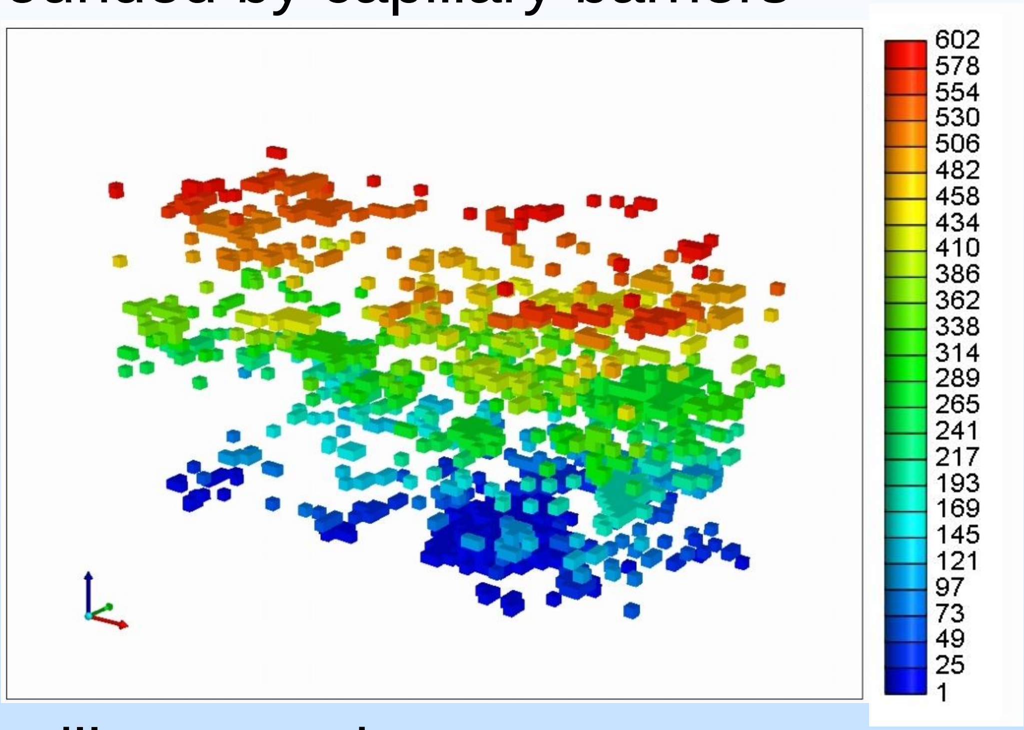
Cluster size > 10
31 different connected clusters





Step 4: Trapped Volumes

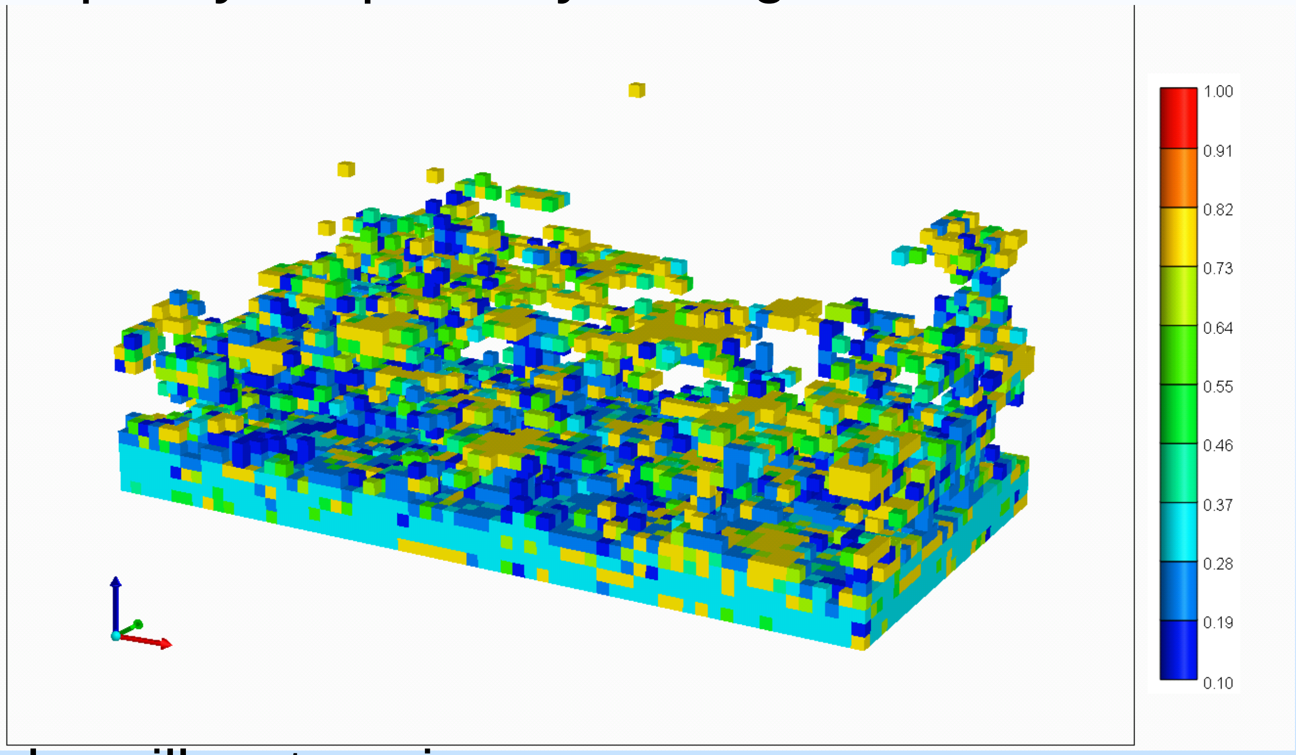
Holes surrounded by capillary barriers



- Local capillary trapping:
  - 1791 grid blocks
  - 2.8% of total grid blocks

Comparison with Full-physics Simulation

Local Capillary Traps are yellow grid blocks



- Local capillary trapping:
  - 2054 grid blocks
  - 3.2% of total grid blocks
    (Note that CO_2 has not reached the top)

3D Results

excellent match in part of the domain

Flow Simulation

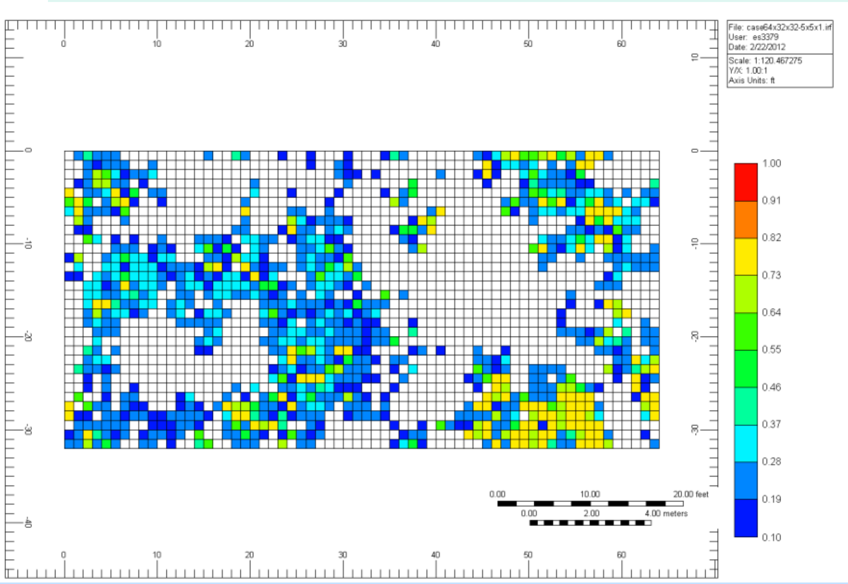
86,382 sec run time

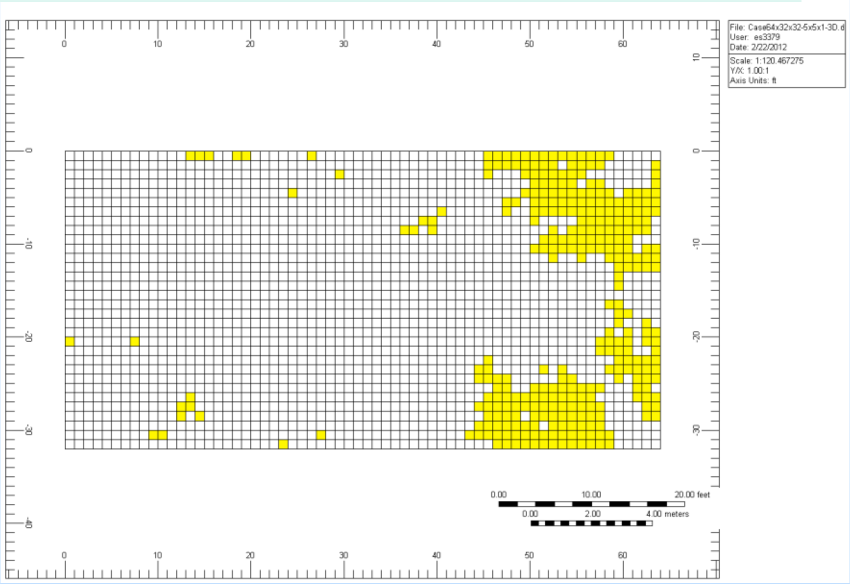
Algorithm

< 60 sec run time

Top View (IJ)

Layer 28 of 32 (right above the initial emplacement)



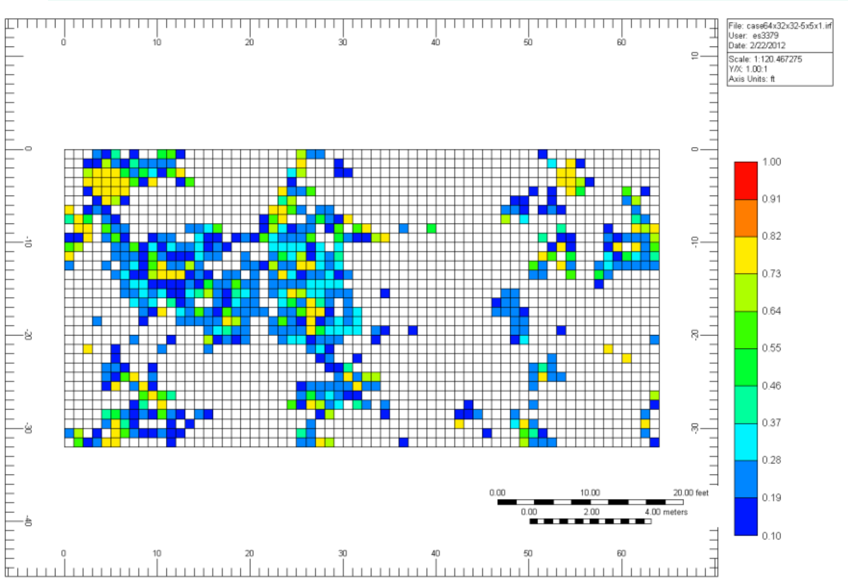


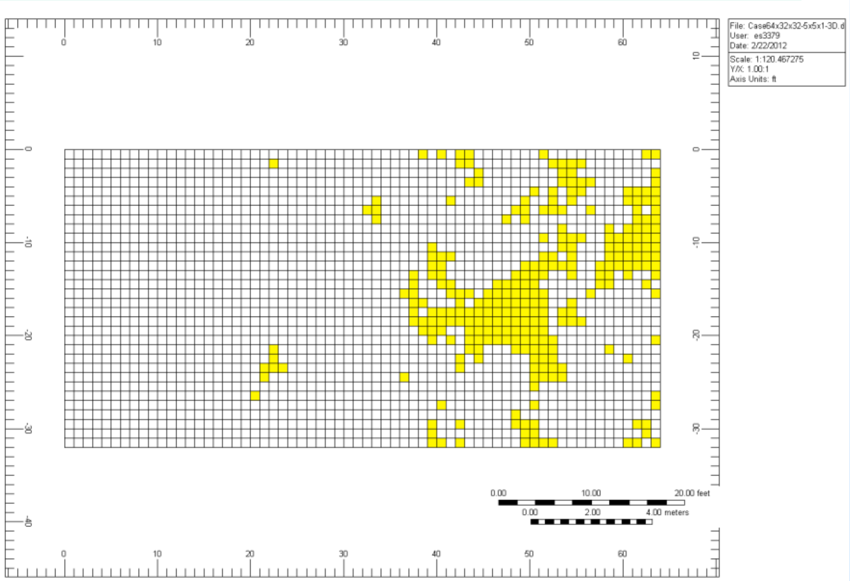
Yellow cells are local capillary traps

3D Results
good match in part of the domain

Flow Simulation **Algorithm**

Top View (IJ)
Layer 27 of 32





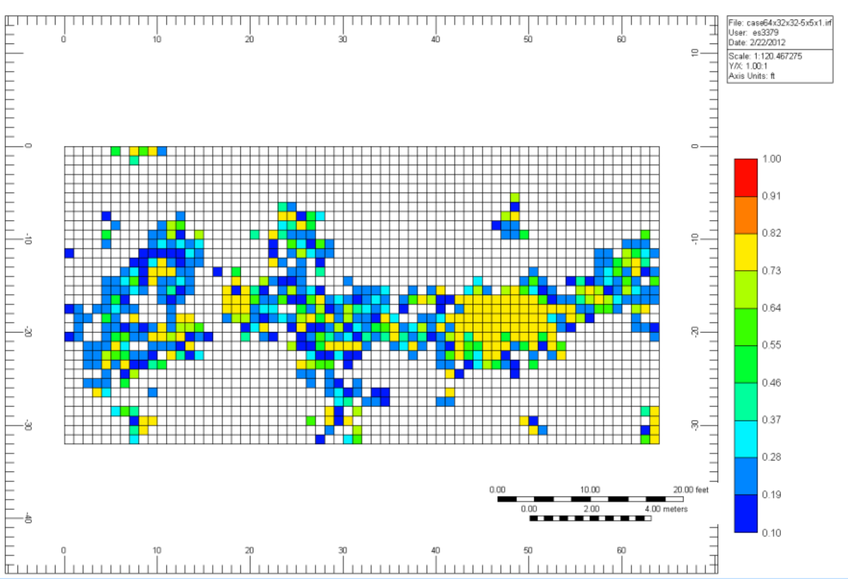
Yellow cells are local capillary traps

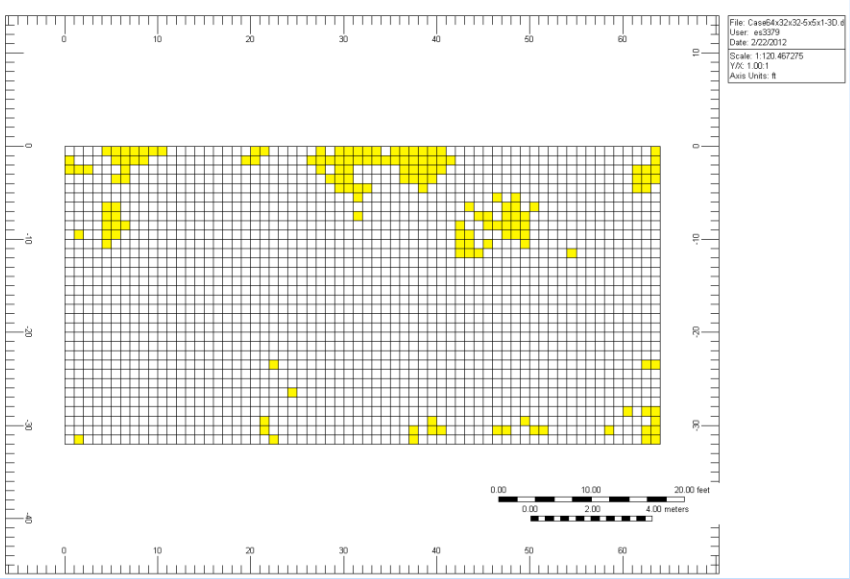
3D Results

poor match in part of the domain

Flow Simulation | **Algorithm**

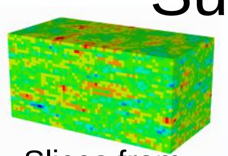
Top View (IJ)
Layer 26 of 32





Yellow cells are local capillary traps

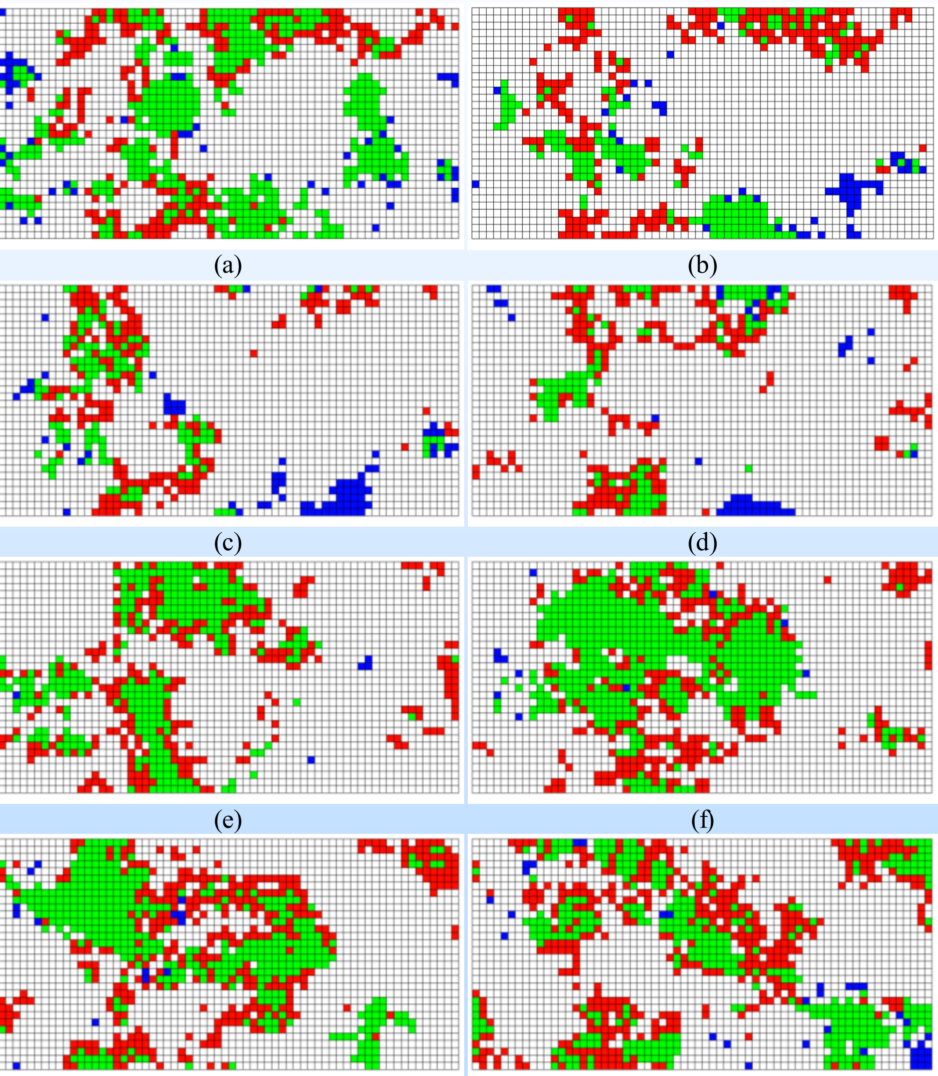
Success of Algorithm at Identifying Barriers Depends on Choice of Critical Capillary Entry Pressure



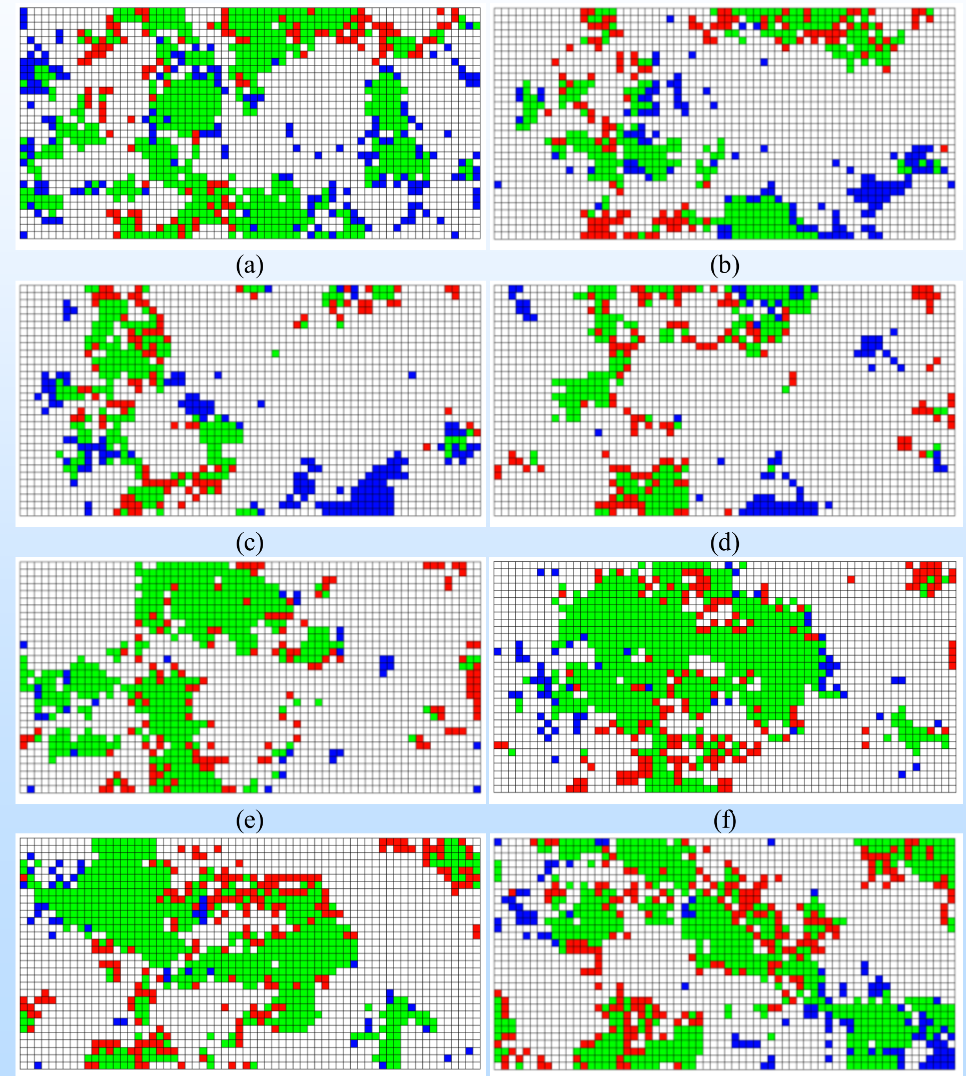
Slices from 3D domain

Predicted by algorithm AND simulation

P_c^{crit} = 1.0 psi



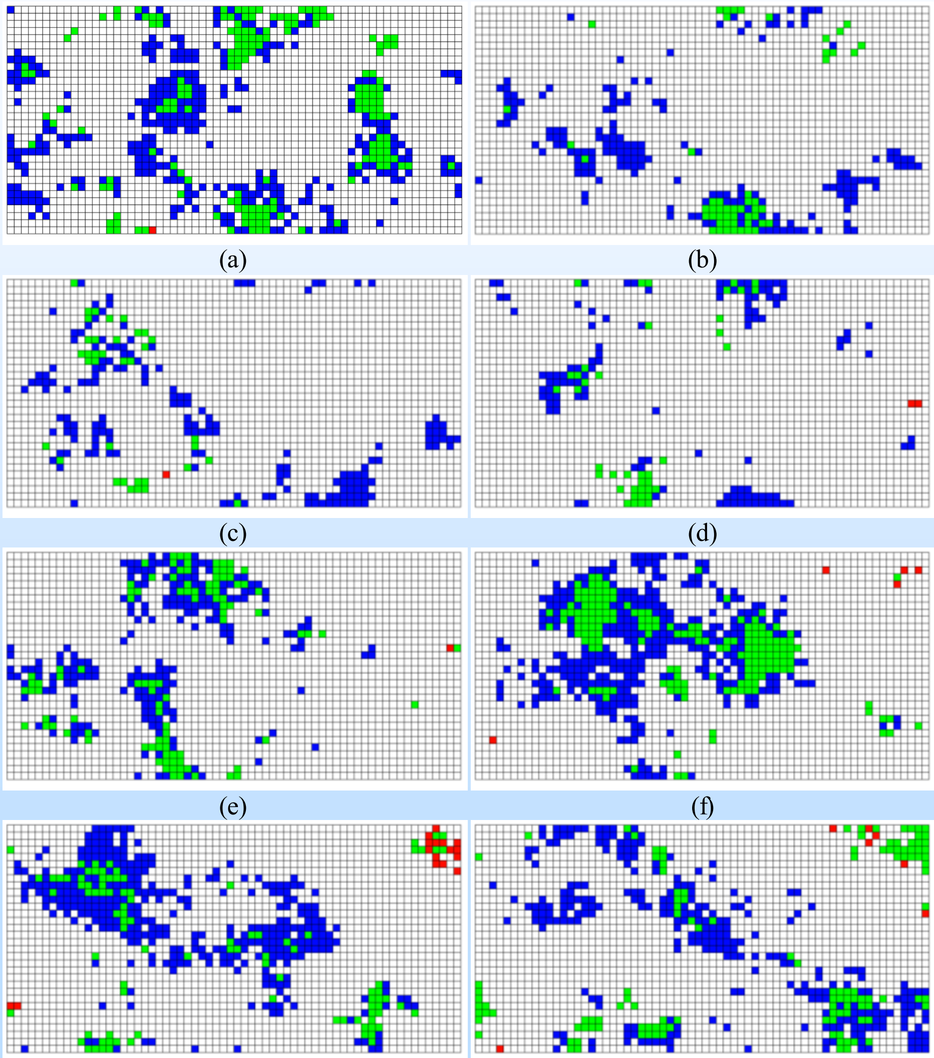
P_c^{crit} = 1.2 psi



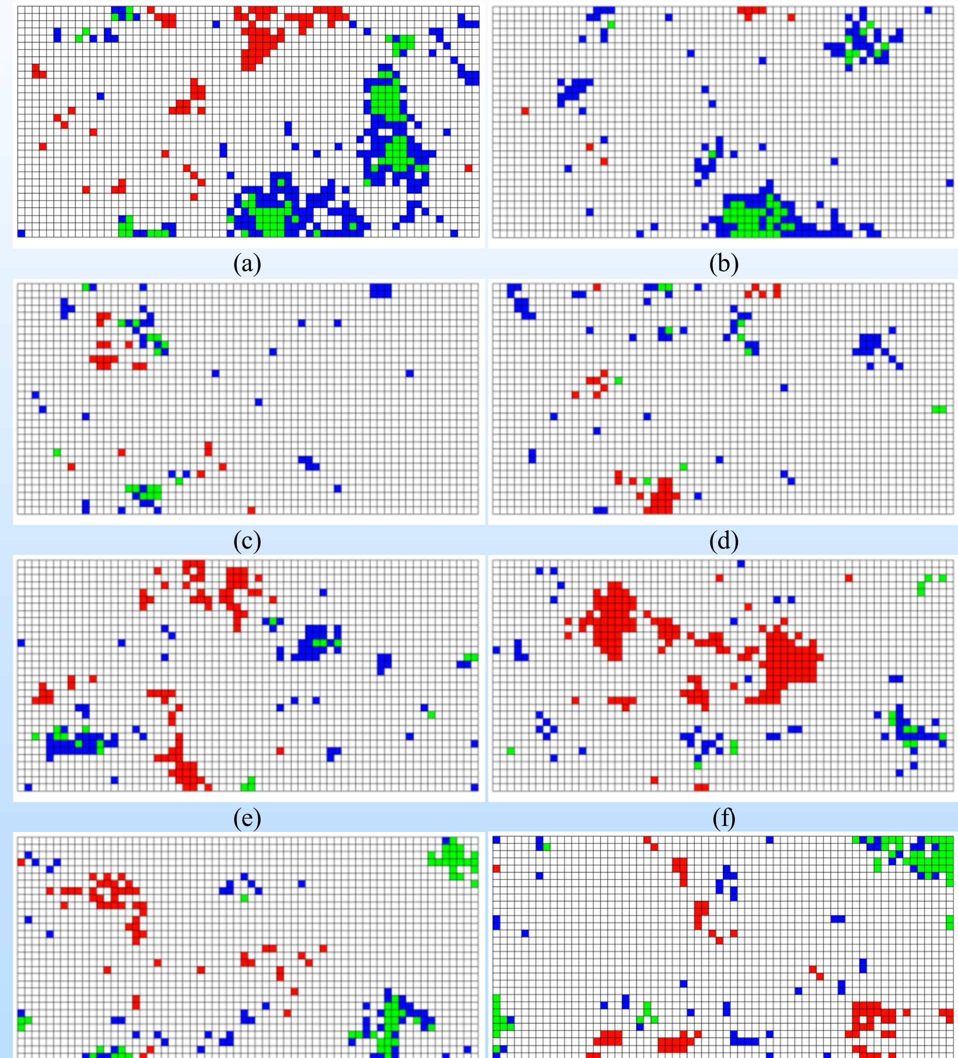
Success of Algorithm at Identifying Traps Depends on Critical Capillary Entry Pressure, Displacement Dynamics

Predicted by algorithm AND simulation

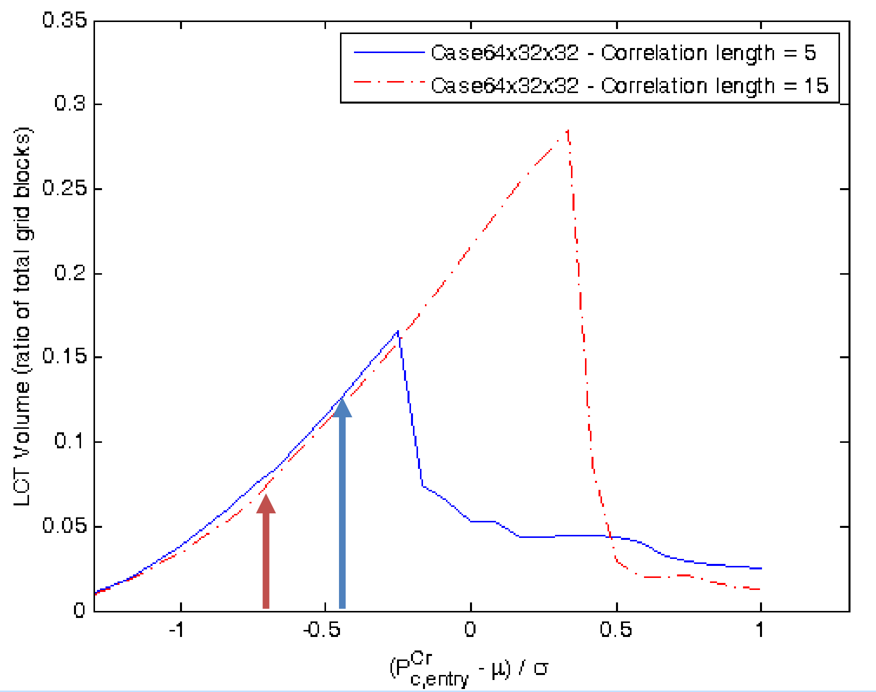
P_c^{crit} = 1.0 psi



P_c^{crit} = 1.2 psi



Algorithm Finds Barriers and Potential Traps Fast



Critical capillary entry pressure and correlation length affect maximum volume of local capillary traps

CPU seconds used for finding local capillary trapping capacity for different cases studied in this work using simulation method and geological method.

	2D		3D	
	5 ft	**50 ft**	**5 ft**	**15 ft**
Simulation Method	95,000	87,000	456,000	401,000
Geological Method	97	3	2	1

Accomplishments to Date

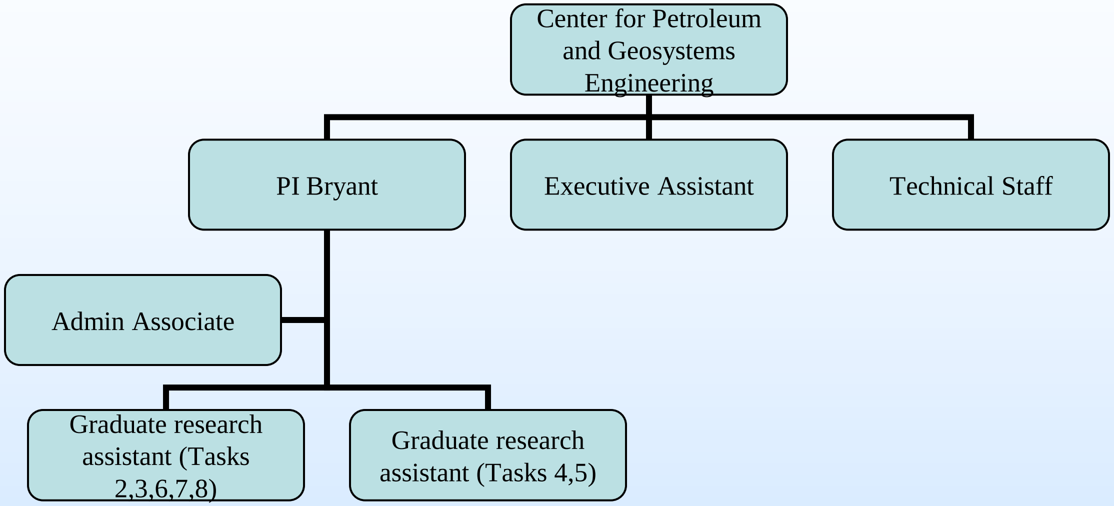
- Developed algorithms to estimate volume of local capillary traps from geologic model
- Tested algorithms against full-physics simulations
- Evaluated influence of “critical capillary entry pressure” on potential capillary traps
- Designed, built, operated apparatus to study role of heterogeneity on buoyancy-driven flow
- Redesigned apparatus currently under construction

Summary

- Key Findings
  - Critical capillary entry pressure adequate for finding potential traps
  - Computationally efficient algorithm determines upper bound on extent of local capillary trapping: 10% to 30% of pore volume
  - Trapping during buoyant migration simulations less than upper bound
- Lessons Learned
  - Hydrophobic apparatus too cumbersome
  - Critical capillary entry pressure alone cannot explain actual trapping
- Future Plans
  - Experimental validation in hydrophilic apparatus
  - Seek simple proxy for influence of displacement physics on actual trapping

Appendix

Organization Chart



- Organization
  - Center for Petroleum and Geosystems Engineering
  - Cockrell School of Engineering
  - The University of Texas at Austin
- Team
  - PI Steven Bryant
  - GRAs
    - Ehsan Saadatpoor (PhD 2012)
    - Angelica Hernandez (MS, 2011)
    - Yuhao Sun

Gantt Chart

Phase	Task	Milestone	YEAR 1				YEAR 2				YEAR 3				Interdependencies
			1	2	3	4	1	2	3	4	1	2	3	4	
1	1														Project management
	2.1														Identify structures for local traps from geostatistical and petrophysical data; feeds Tasks 3, 6 and 7
	2.2														
	2.3	1.A				X									
	2.4														
	3	1.B						X							Effect of geologic setting on distribution of structures
	4	1.C			X										Experimental validation of simulations of Tasks 6, 7
2	5	2.A										X			
	6.1	2.B								X					Influence of operating conditions on filling traps identified in Tasks 2, 3
	6.2														
	6.3	2.C									X				
	7	2.D										X			Effect of loss of seal integrity on CO_2 escape from traps filled in Task 6
	8	2.E											X		Method to upscale results of Task 7
			Phase 1						Phase 2						

Milestone Description
1.A Set of model storage formations with fine scale assignments of petrophysical properties relevant to local capillary trapping ($k, \phi, S_{w,irr}, S_{gr}, P_c^{entry}$ and drainage/imbibition curves)
1.B Estimate maximum pore volume in local structures as a fraction of total pore volume in typical storage formations, and hence the potential importance of local capillary trapping.
1.C Method for observing accumulation of buoyant nonwetting phase beneath local capillary barriers at the bench scale.
2.A Validation of concept of local capillary trapping in heterogeneous 2D model porous media.
2.B Preliminary assessment of filling of local capillary traps for buoyancy-dominated displacement.
2.C Trend of the fraction of potential local capillary traps filled as a function of primary controls including the effect of the injection period for a range of gravity numbers and different CO_2 volumes
2.D Preliminary assessment of trend of the fraction of CO_2 above residual that remains trapped after seal rupture for range of operating conditions in a representative set of storage formations.
2.E Preliminary version of a function or effective property that that accounts for the amount of local capillary trapping in terms of geologic and petrophysical and operating parameters.

Bibliography

- Publications:

  - Saadatpoor, E. "Local Capillary Trapping in Geological Carbon Storage", Ph. D. dissertation, The University of Texas at Austin, 2012.
  - Hernandez, A. MS thesis, The University of Texas at Austin, 2011.