The University of Texas at Austin
Petroleum and Geosystems Engineering
Cockrell School of Engineering

Field Scale Modeling of Local Capillary Trapping during CO_2 Injection into the Saline Aquifer

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2nd Biennial CO_2 for EOR as CCUS Conference
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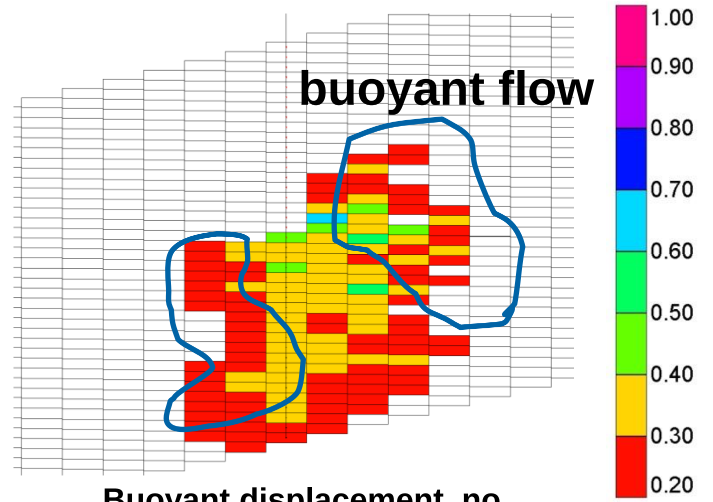
Motivation – Increased Storage Security

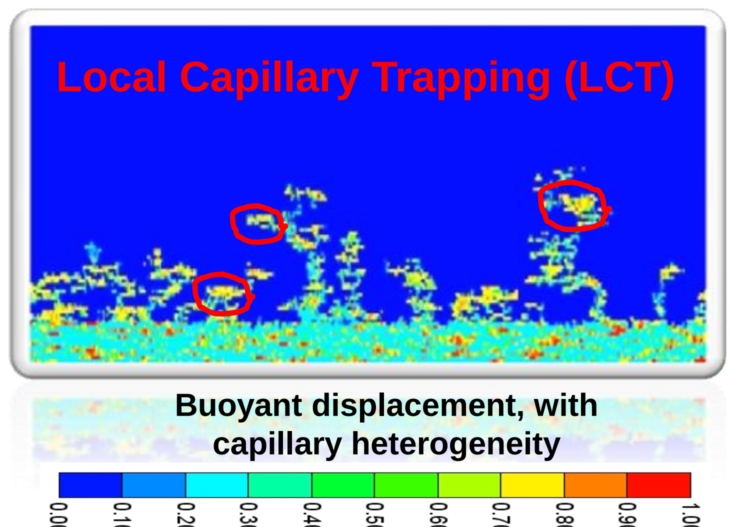
- **Maximum trapping when maximum contact of rising CO_2 plume with rock**
  - **Compact displacement front favorable.**
  - **Occurs routinely in coarse-grid simulations that neglect capillary heterogeneity.**

- **Heterogeneity of capillary entry pressure severely disrupts the displacement front**
  - **Saadatpoor et al 2009 showed that local capillary trapping occurs.**
  - **Small-scale equivalent of "fill and spill" process for charging hydrocarbon reservoirs.**
  - **Analogous to pooling of dense non-aqueous phase liquids spilled into soils.**



Buoyant displacement, no capillary heterogeneity

$$S_{g,residual} = 0.25$$

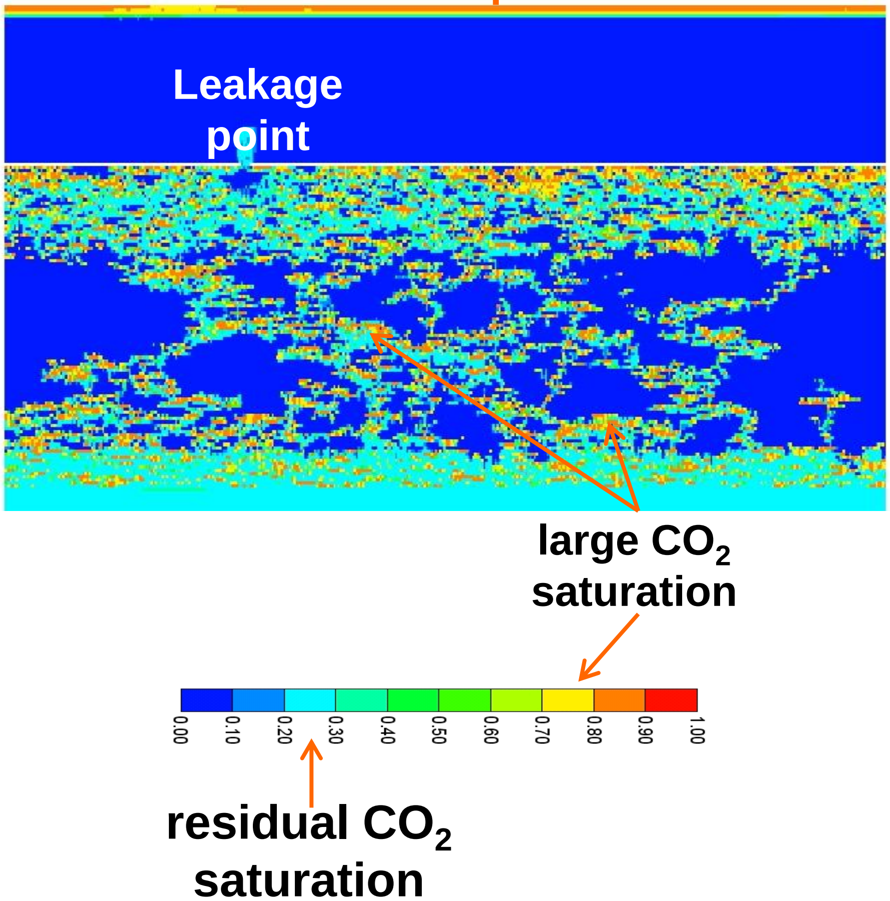


Buoyant displacement, with capillary heterogeneity

Motivation – Security Despite Compromised Seal

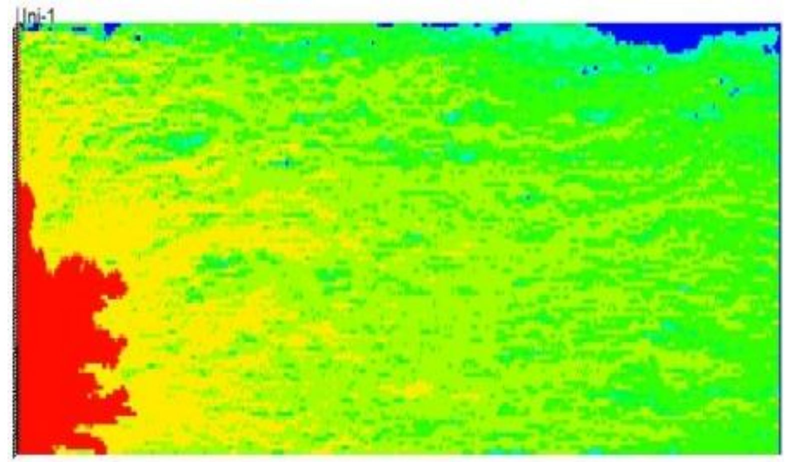
- **Existing estimates of impact of leakage assume all mobile stored CO_2 will escape.**
- **Novel concept: CO_2 that fills local (small-scale) capillary traps in heterogeneous storage formations may remain even if structural seal is compromised.**
- **Impact: reduced risk for long-term storage, achieved by considering physical implications of geological heterogeneity.**

CO_2 saturation 100 y after leak develops

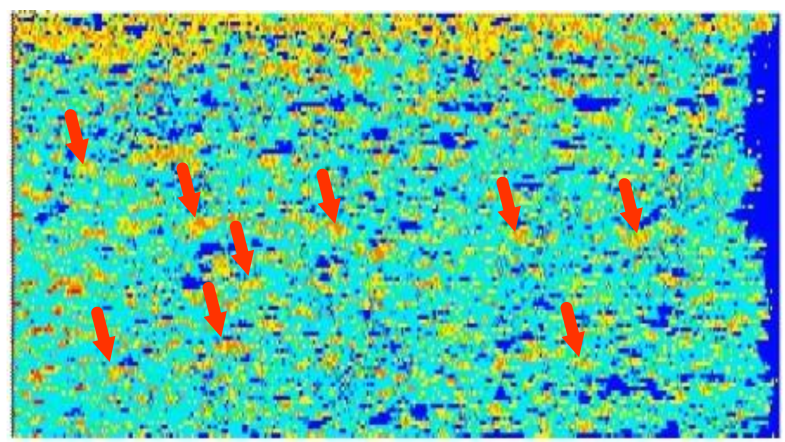


Motivation – Maximizing Safe Storage Capacity

- Local capillary traps in the near-well region can be fully filled during injection.
- They remain filled after post-injection buoyancy-driven flow ends.
- Implications: maximizing local capillary trapping would greatly enhance the safe storage capacity of CO_2.



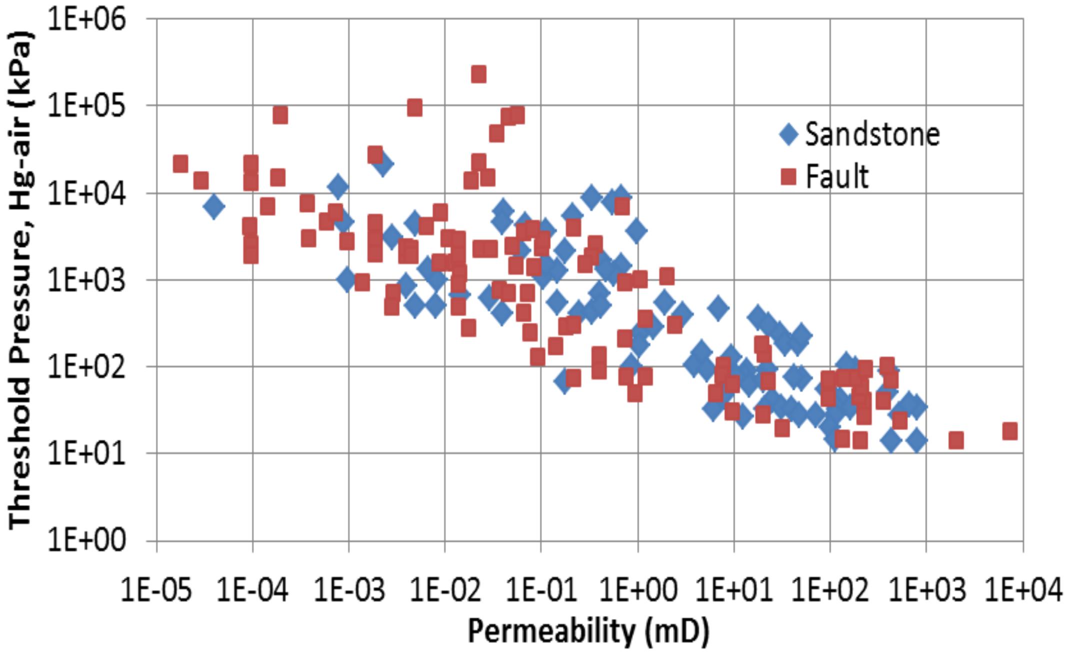
CO_2 saturation at the end of injection: perforated at the right quarter bottom, N_{gr}=0.03, right open boundary



CO_2 saturation at the steady state of buoyant flow

Introduction – Physical Basis

- In nature, sedimentary rocks typically exhibit heterogeneous, spatially correlated permeability field due to the microscopic structure variations.



Adapted from Cavanagh, 2009

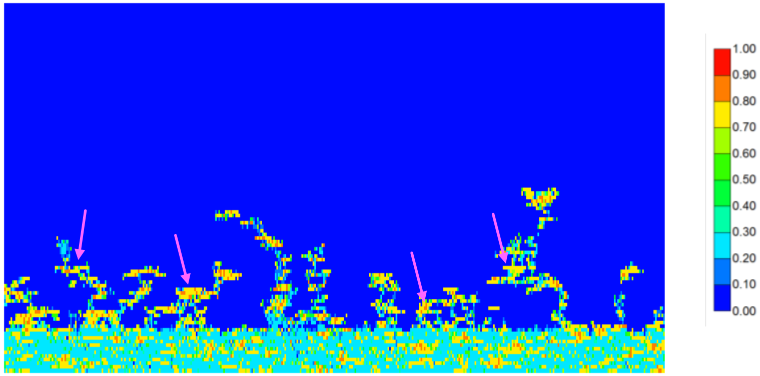
- Well established correlation exists between permeability and capillary entry pressure.

$$p_{c2}(s_w) = p_{c1}(s_w)\sqrt{\frac{k_1}{k_2}\frac{\phi_2}{\phi_1}}$$

Leverett, 1941

Introduction – Modeling Local Capillary Trapping

- **Mode of trapping occurs during buoyancy-driven flow in rocks exhibiting fine-scale capillary heterogeneity.**



Grid size: 1*1*1ft

- **Fine-scale simulations that resolve local heterogeneity have very large run times, intractable in 3D using Conventional Reservoir Simulator (e.g., CMG-GEM).**

- **Large grid blocks would smear the local capillary trapping due to upscaling.**

Identifying Local Capillary Traps from Geological Model

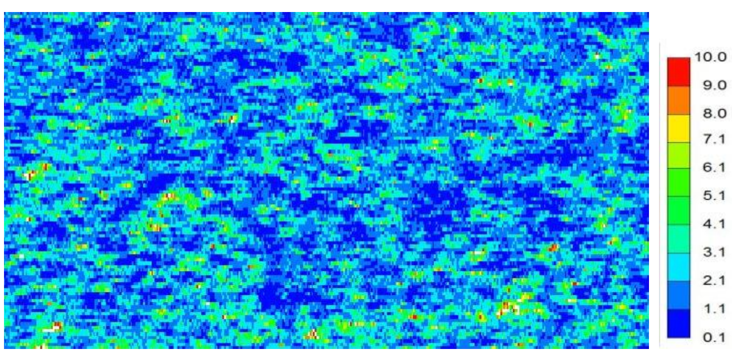
Geologic Criteria for Trapping Based on Capillary Threshold Entry Pressure

- Effectiveness of structure as local capillary trap depend on
  - Magnitude of capillary entry pressure above local traps
  - Magnitude of phase pressure in CO_2 plume
- Magnitude of entry pressure depends on
  - Microscopic: pore size distribution and connectivity
  - Macroscopic: range of permeability in the domain
- Critical capillary entry pressure
  - Assume single value characterize all local capillary trapping structures
  - Enable very rapid assessment of potential local traps

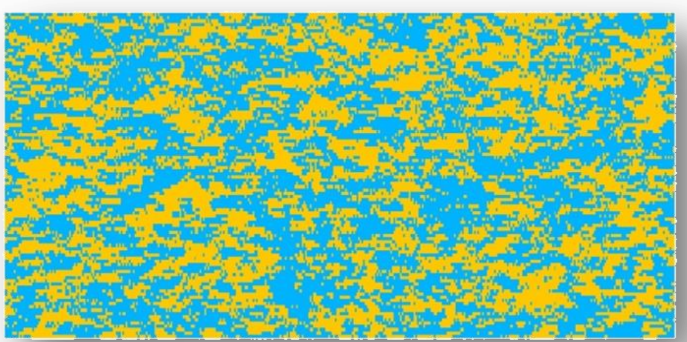
Algorithm for Geologic Criteria Method of Identifying Local Capillary Traps

- **Set of subroutines applied to 3D domain of values 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 (P_c^{crit}).**



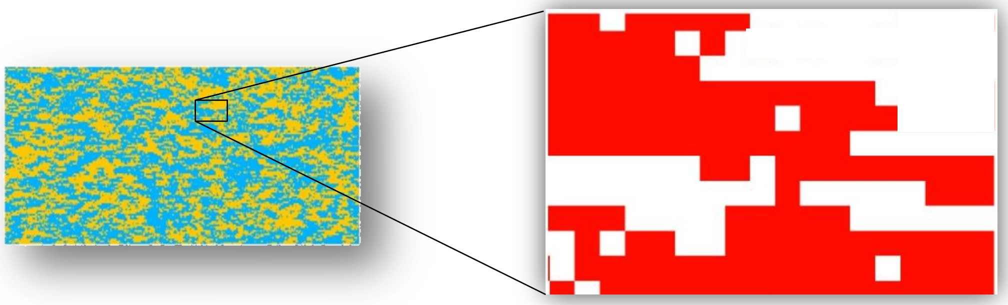
Heterogeneous capillary entry pressure



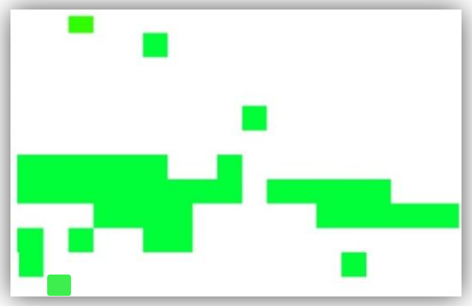
Orange cells have $P_{c,entry} > P_c^{crit}$

Algorithm for Geologic Criteria Method of Identifying Local Capillary Traps

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 (local capillary traps)**

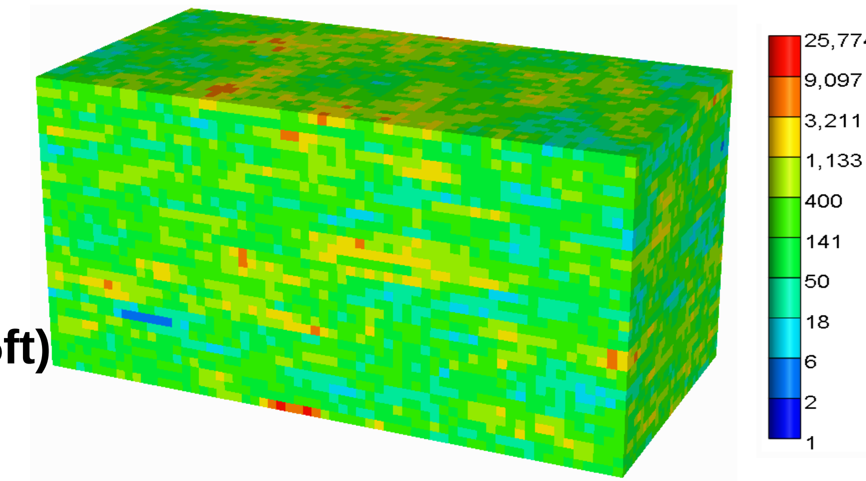


Results from Geologic Criteria

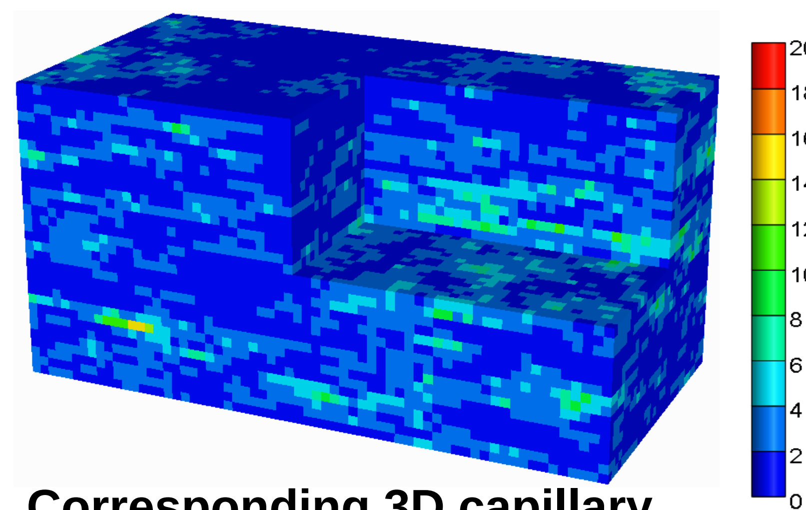
- **3D**

- **64 x 32 X 32 ft**
- **1 x 1 x 1 ft grid block**
- **Correlated in x and y direction (5 x 5ft)**
- **Uncorrelated in vertical direction**
- **Perm_avg = 403 mD**

- **Choose critical entry pressure to be equal to 1.2 psi.**



Sample 3D permeability field



Corresponding 3D capillary entry pressure field

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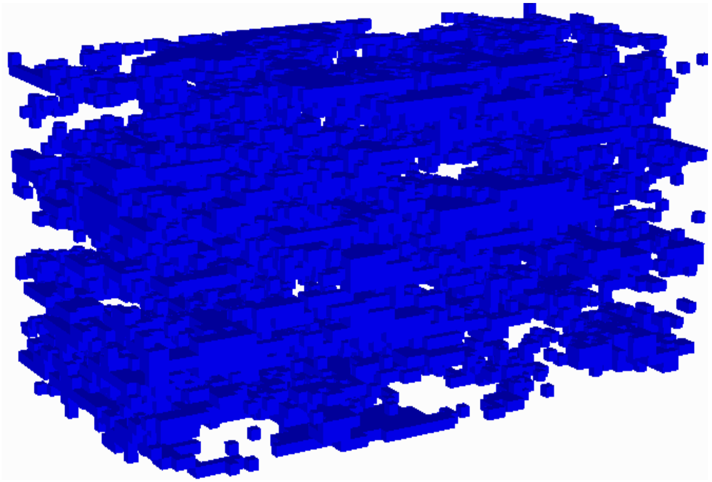
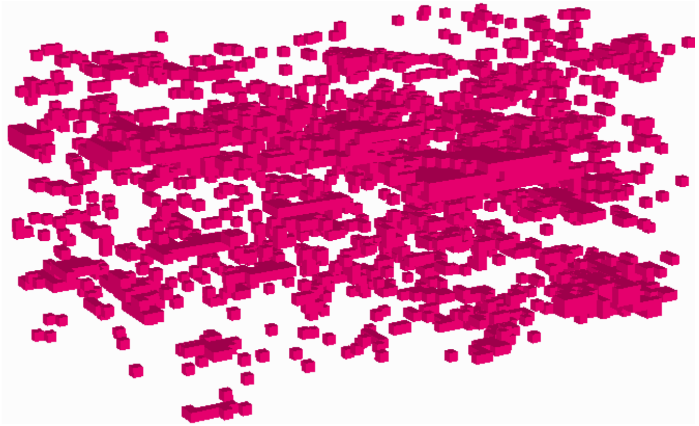
Results from Geologic Criteria

- **Step 2: non-barrier grid blocks in the blue color**



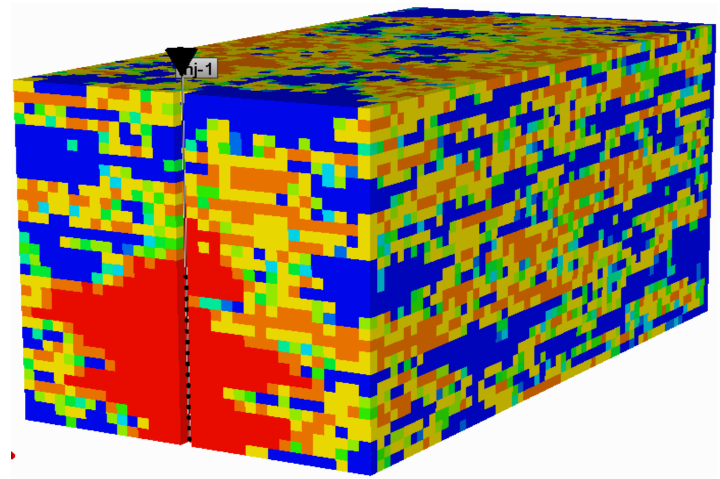
- **Step3: local capillary traps predicated from the geologic method account for 6% of the total pore volume.**



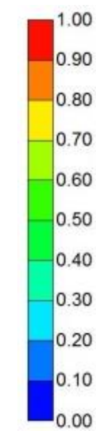
Results from CMG-GEM Simulator

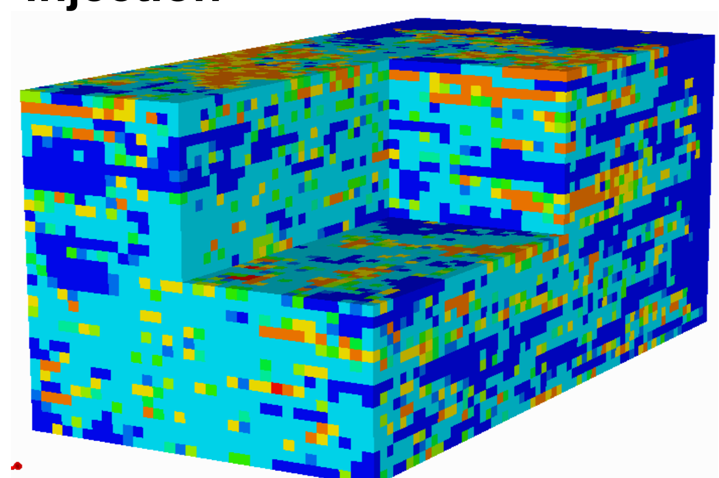
- ## CO_2 Injection Simulation
  - Vertical injector perforated at left bottom (16 ft)
  - Injection rate: 3E+5 Scf/d
  - Injection period: 70 day
  - Simulation period: 50 yr
  - Boundary: flowing boundary on right

  - Scattered accumulations of high CO_2 saturation (yellow to red) are local capillary trapping.



CO_2 saturation at the end of injection

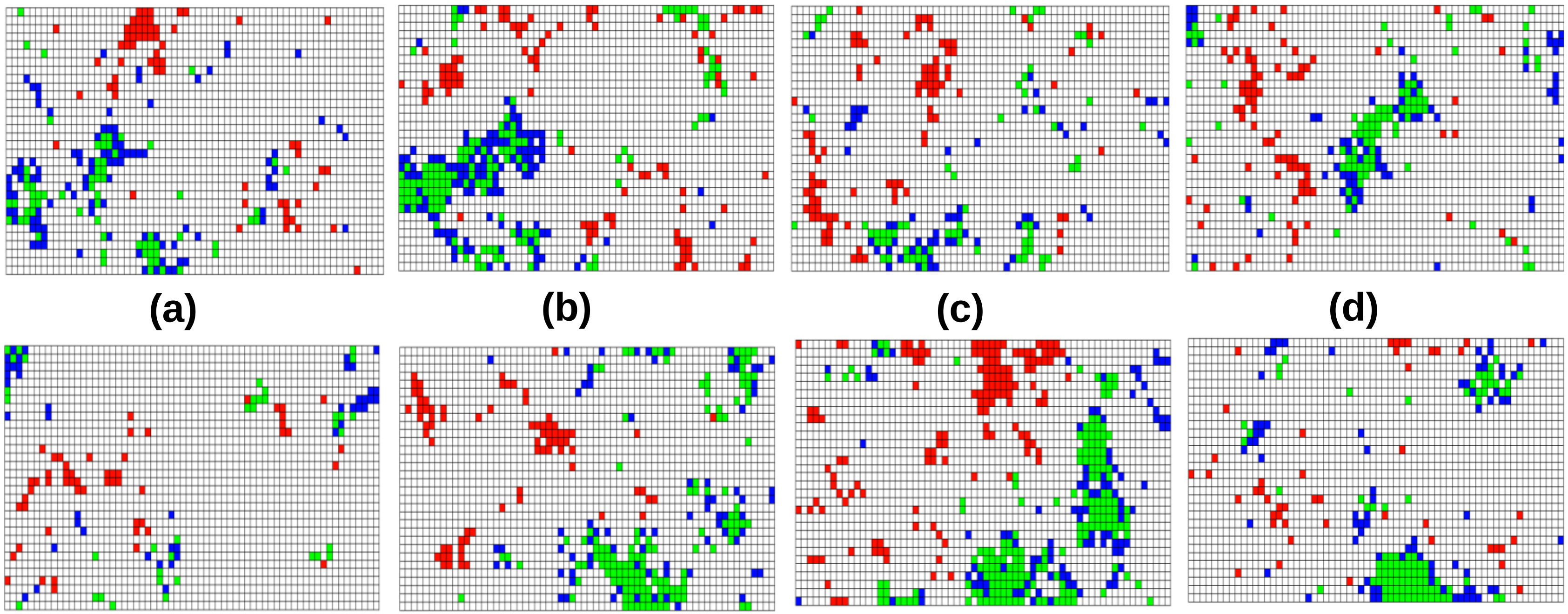




CO_2 saturation at the steady state of buoyant flow (50 yr)

Comparison of Local Capillary Traps Predicted by Simulation Method and Geologic Criteria

- **Top areal view of local capillary traps predicted by the two methods.**



(a) (b) (c) (d)

(e) (f) (g) (h)

- **Figures (a) through (h) show layer 7 through 14, respectively.**

Simulation Only
Simulation and Geologic Criteria
Geologic Criteria only

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Incorporating CO_2 Flow Dynamics into the Geologic Criteria

Using Connectivity Analysis to Approximate CO_2 Plume Behavior during injection.

Hirsch and Schuette (1999): The grid blocks are connected with edges and the edges are weighted by reservoir parameters that impact connectivity such as porosity and permeability.

$$\textbf{Edge weight} = \frac{\sqrt{Vp_i * Vp_j}}{T_{ij}}$$ **[-] unit less**

Time needed to fill the given pore volume with a fluid of unit viscosity under a unit pressure gradient.

Vp = pore volume;

$i.j$ = indexs of grid blocks;

$T_{i,j}$ = transmissivity between grid blocks $\left(T = K\frac{A}{L}\right)$;

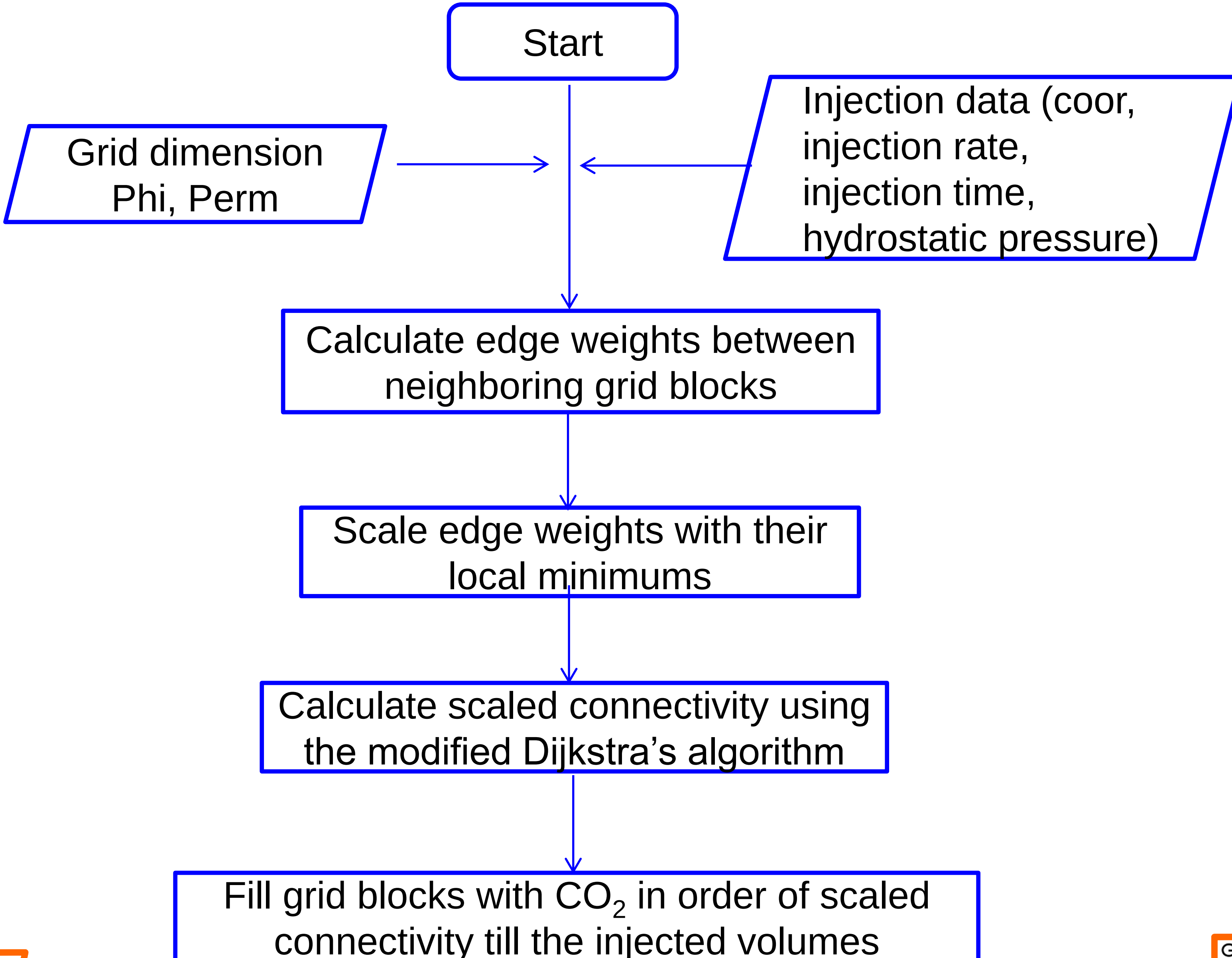
$$\textbf{Modified Edge weight} = \mu_{CO2} * \frac{\overline{S_{Co2}} * \sqrt{Vp_i * Vp_j}}{T_{ij} * \overline{k_{r,CO2}} * (\Delta P_{ij} + \Delta(\rho g h)_{ij})}$$ **[Sec]**

$\overline{S_{Co2}}$ = average CO_2 saturation determined from fractional flow curve;

$\overline{k_{r,CO2}}$ = CO_2 relative perm at the end point;

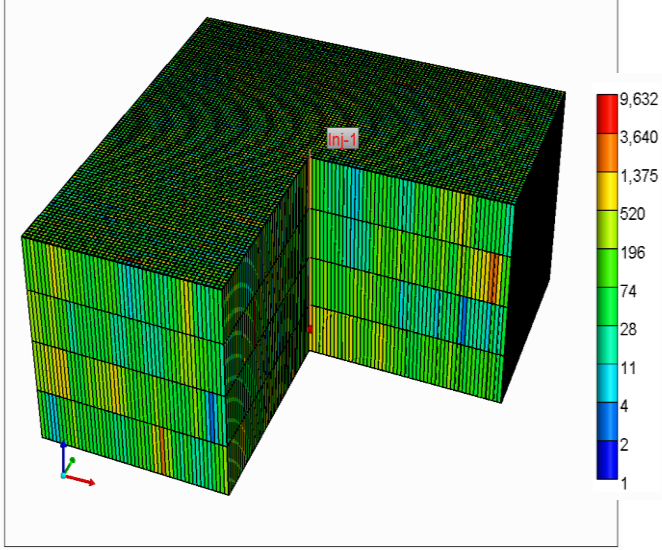
ΔP_{ij} = pressure difference between grids i and j, use the steady state radial flow in the homogenous media to calculate it.

Flow Chart of Connectivity Analysis



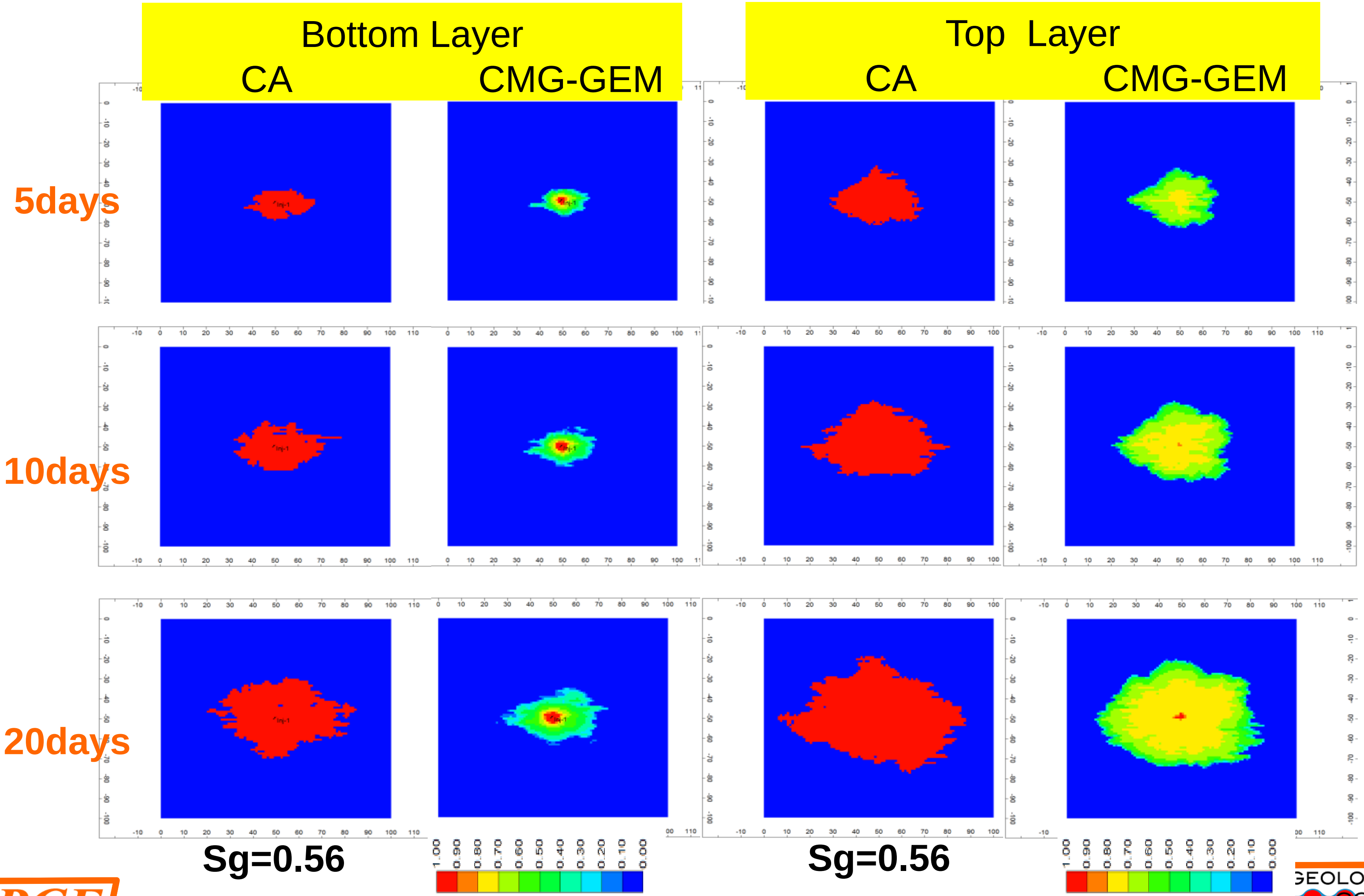
Verification Connectivity Analysis (CA) using CMG-GEM: 3D Case

Permeability Field



Grid Dimension	100*100*4
Grid Size, ft	1*1*1
Well type	Vertical injector
Injection rate (RC ft^3/d)	60
Injection time, day	20
Perforation grid	(50,50,4)
Fluid property	
CO_2 volume ratio RC/SC	3.02E-3
CO_2 viscosity (RC, cp)	8.61E-2
CO_2 density (RC, kg/m^3)	618.70
Water density (RC, kg/m^3)	1024.60
CA input parameters	
Average CO_2 saturation	0.56
Endpoint CO_2 relative perm	0.86

Comparison of CO_2 Saturation between Connectivity Analysis (CA) and CMG-GEM



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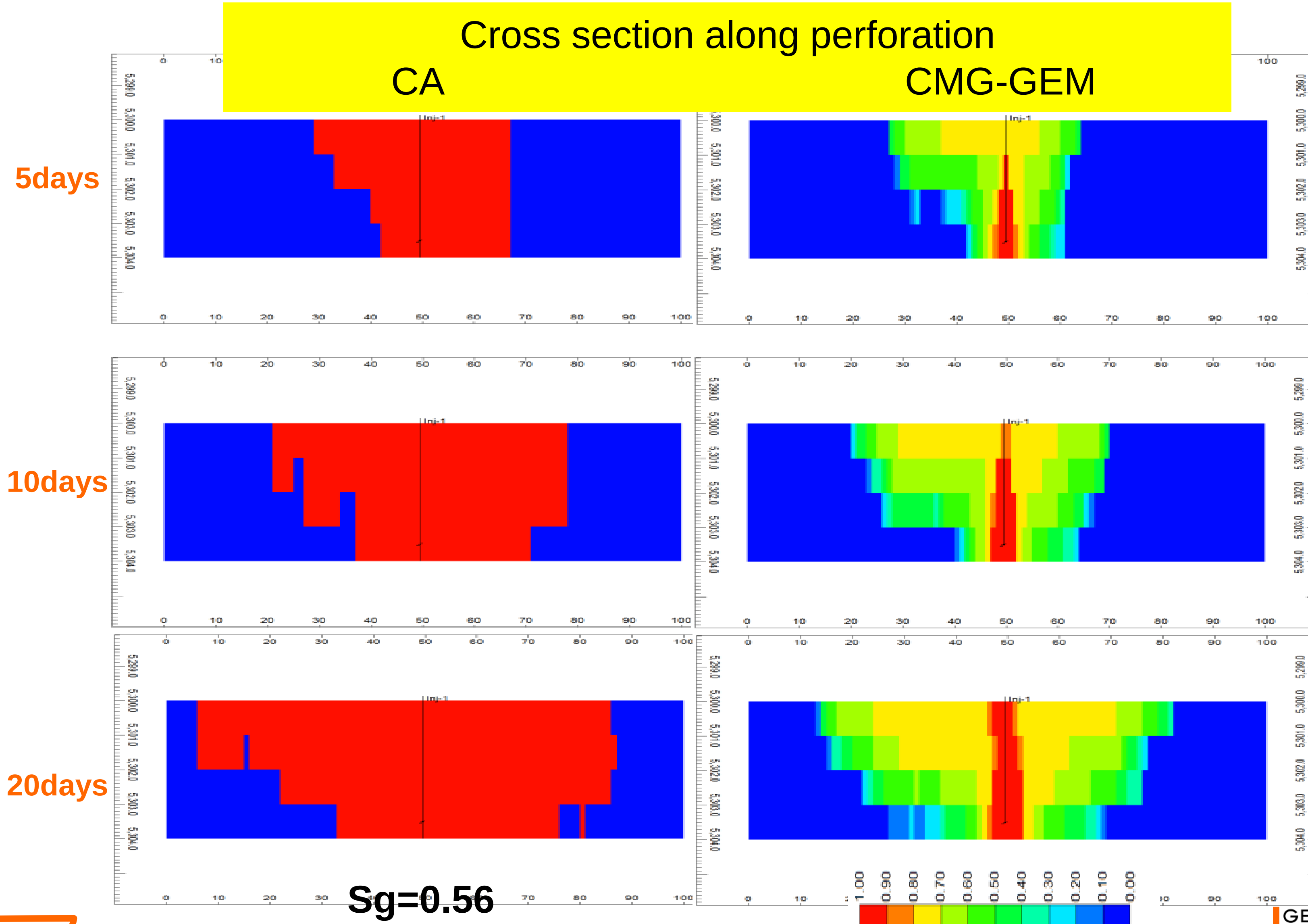
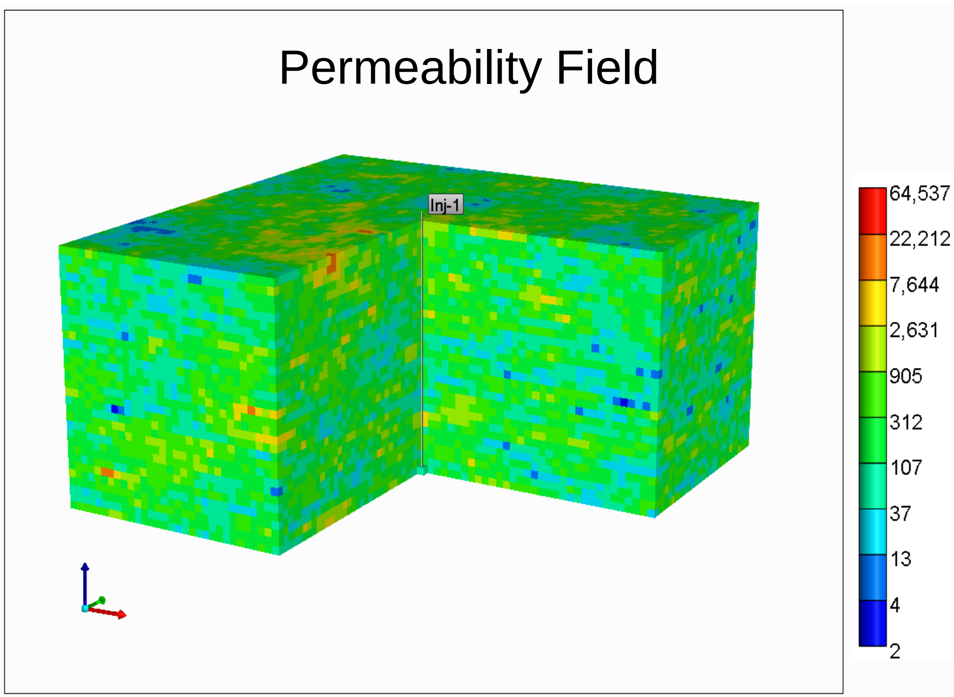
Comparison of CO_2 Saturation between Connectivity Analysis (CA) and CMG-GEM



Using Connectivity Analysis + Geologic Criteria to Predict the Local Capillary Trapping Under the Real Injection Scenarios in the Different Heterogeneous Storage Domains

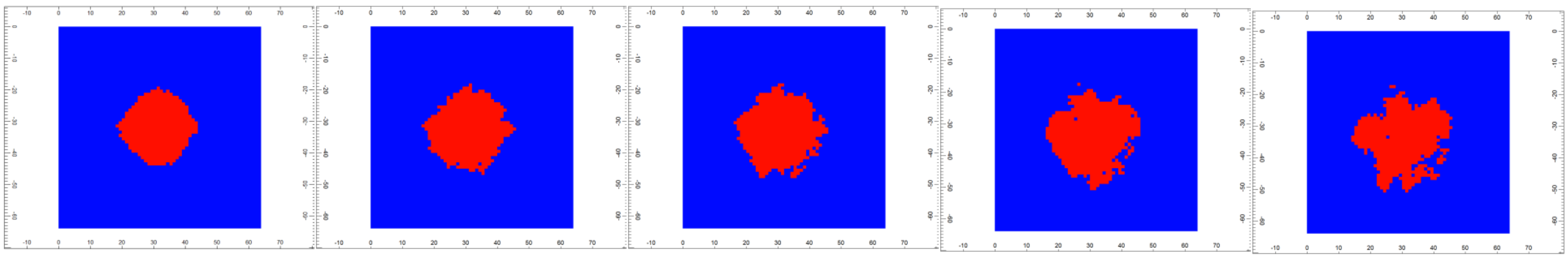
3D Model: Base Case



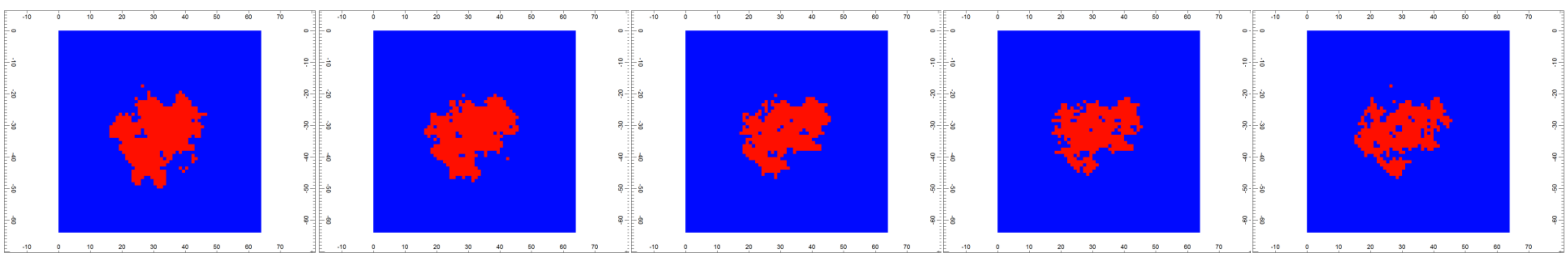
3D Model (base case)	
Grid Dimension	64*64*32
Grid Size, ft	1*1*1
Permeability correlation, ft	4x4x1
Ln(perm),avg	5.27
Ln(perm),std	1.2 0
Dykstra Parsons Coe (V_dp)	0.70
Porosity	0.27
Injection configuration	
Well type	Vertical injector
Injection rate (MM Scf^3/d)	0.10
Injection time, day	10
Perforation grid	(32,32,32)
Fluid property	
CO_2 volume ratio RC/SC	3.02E-3
CO_2 viscosity (RC, cp)	8.61E-2
CO_2 density (RC, kg/m^3)	618.70
Water density (RC, kg/m^3)	1024.60
Connectivity Analysis parameters	
Average CO_2 saturation	0.56
Endpoint CO_2 relative perm	0.86

CO_2 Plume in the Top layer at the End of Injection from Connectivity Analysis: Effect of Dykstra Parsons Coefficient (V_{dp})

V_{dp}=0.2603 V_{dp}=0.4528 V_{dp}=0.5952 V_{dp}=0.7005 V_{dp}=0.7785



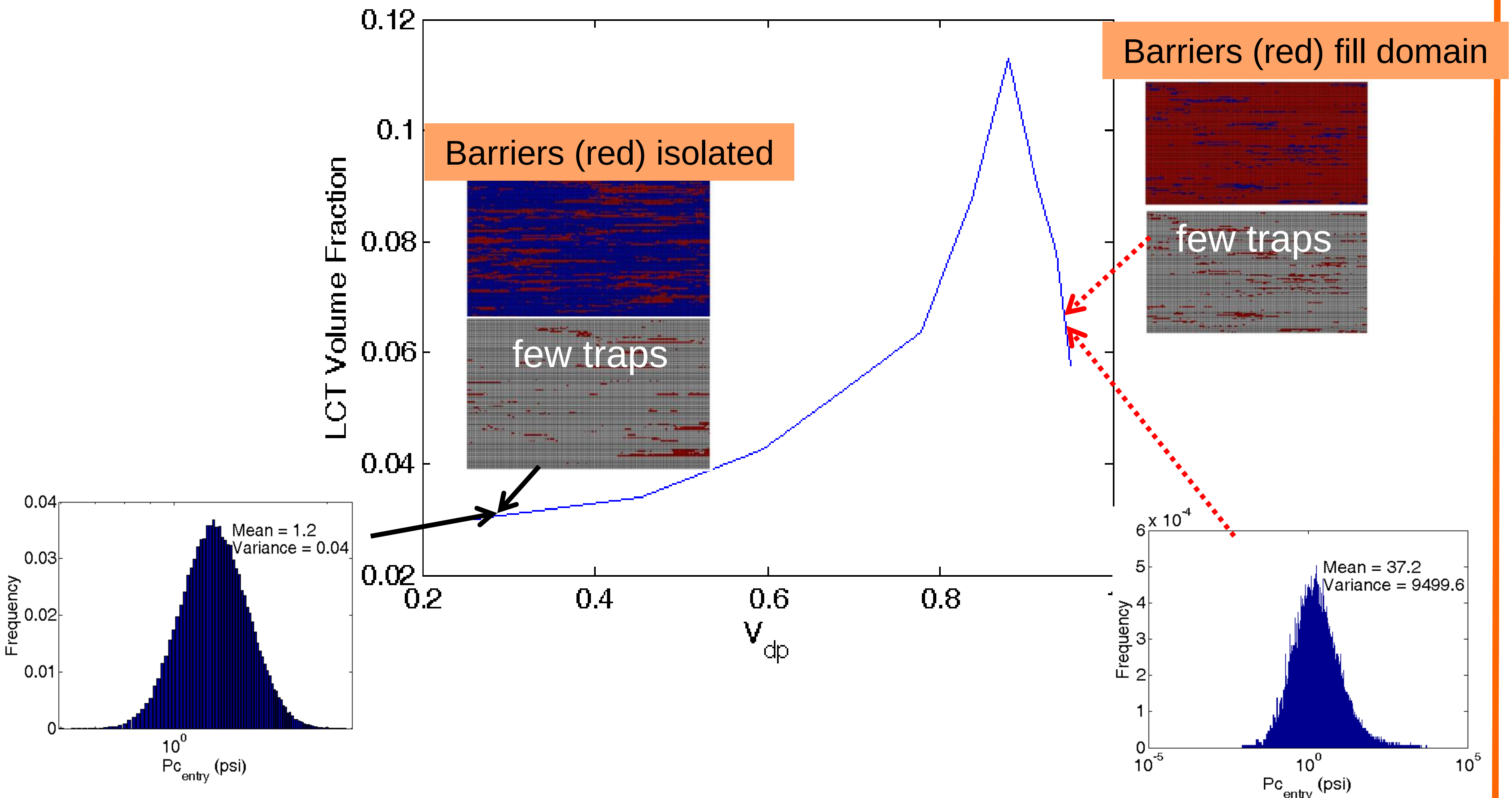
V_{dp}=0.8361 V_{dp}=0.8788 V_{dp}=0.9103 V_{dp}=0.9337 V_{dp}=0.9509



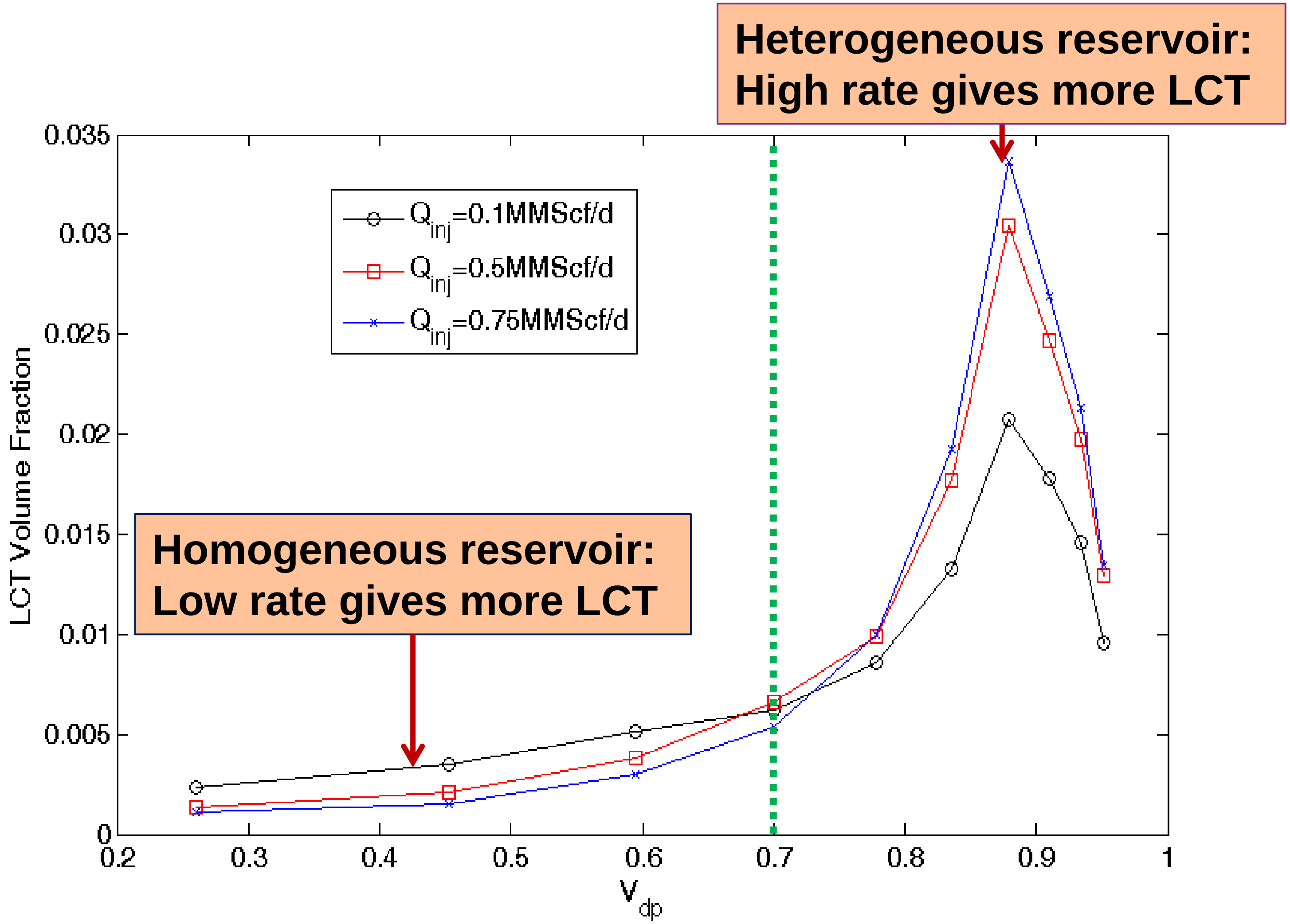
Connectivity Analysis is effective in predicting CO_2 plume behavior in the geologic fields with different level of heterogeneity (V_{dp}).

Effect of Dykstra Parsons Coefficient (V_{dp}) on LCT from Geologic Criteria

Choose critical capillary entry pressure to be equal to 1.2 psi.



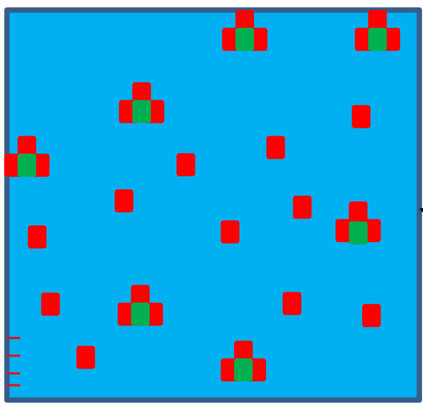
Effect of Injection Rate on LCT for Different Heterogeneous (V_{dp}) Models



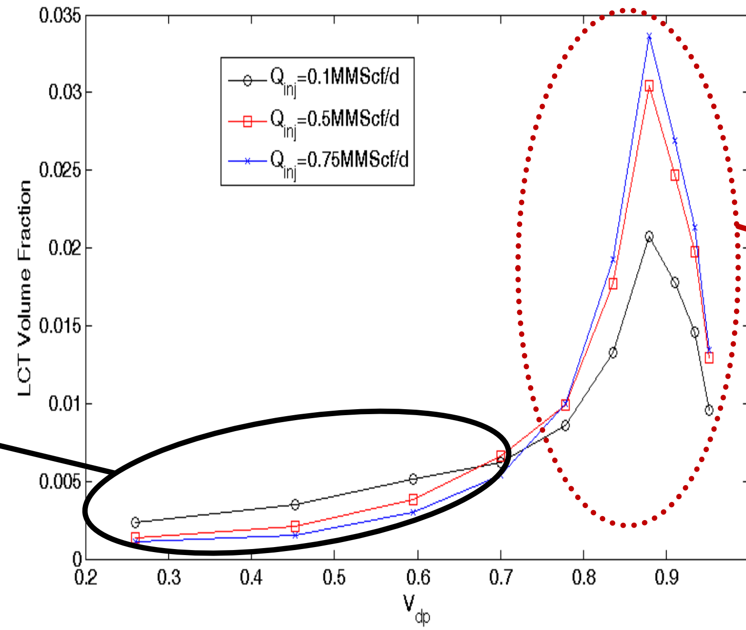
Combine Geologic Criteria with Connectivity Analysis

Effect of Injection Rate on LCT for Different Heterogeneous (V_{dp}) Models(Schematic Explanation)

Flow path fill the domain



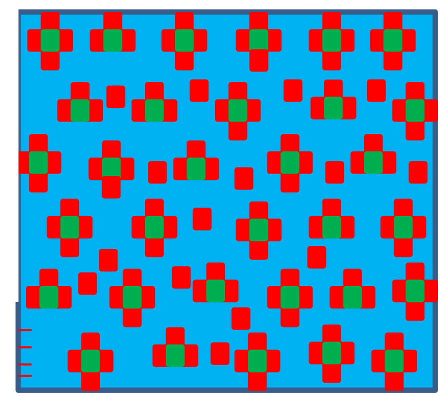
Small rate avoids the barriers and flow farther, thus gives rise to more likely of filling the local capillary traps.



Legend

- Barrier grid
- LCT grid
- Flow path grid
- Perforation grid

Barrier fill the domain



High rate could sweep the barriers and fill the traps surrounded by barriers.

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Summary and Conclusions

- **local capillary traps in the near-well region can be fully filled during injection. Moreover, they remain filled after post-injection buoyancy-driven flow ends.**
- **Final CO_2 distribution is controlled by local capillary traps intrinsic to the capillary pressure heterogeneity .**
- **Geologic Criteria gives fast and good prediction of local capillary traps in the CO_2 swept zone during injection.**
- **The extended connectivity analysis shows a good match of CO_2 plume computed by the full-physics simulation (CMG-GEM).**
- **There exists a threshold Dykstra-Parsons coefficient, below which low injection rate gives rise to more LCT; whereas higher injection rate increases LCT in heterogeneous reservoirs.**
- **Both the geologic criteria and connectivity analysis are very fast; therefore, the integrated methodologies can be used as a quick tool to estimate local capillary trapping at the field scale.**

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Thank you very much!

Q&A

Email: boren@utexas.edu

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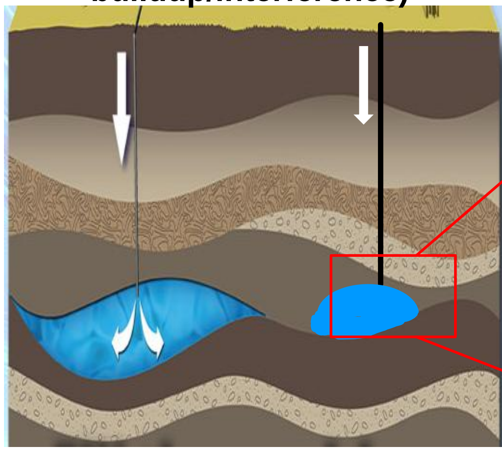
Back-up Slides

Spatial Scales in Geological Carbon Sequestration

Basin Scale
(10~100 km pressure buildup/interference)

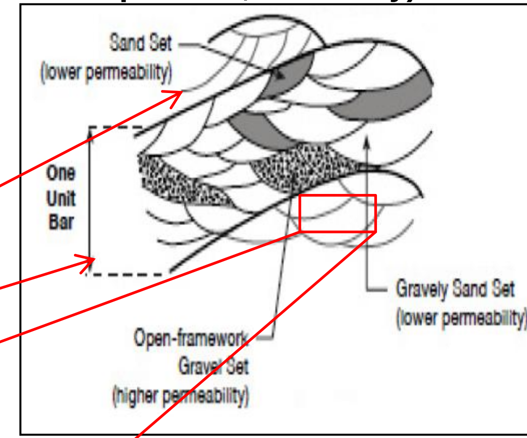


Adapted from http://www.utefrc.org/

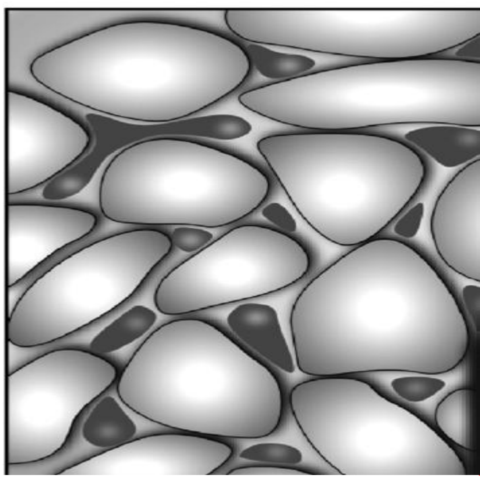
Stratum Scale
(~ km plume shape, secondary seal)

(e.g., Zhou et al., 2010)

Depositional Unit Scale
(~m, lithoface scale, CO_2 trapping process, efficiency)

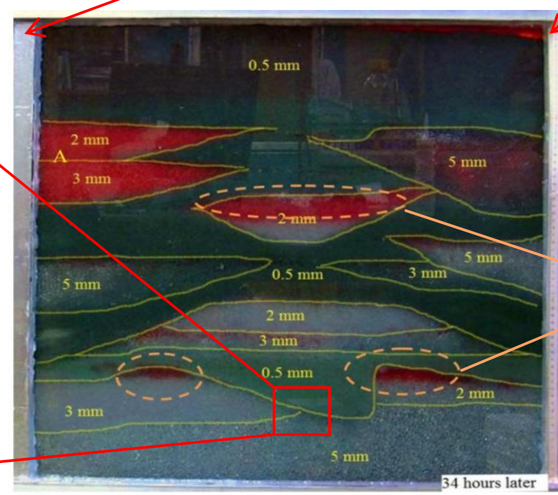


(Gershenzon et al., 2015)



(Bachu, 2008)

Pore/Grain Scale
(μm ~ cm, coordination number, residual trapping)



(Sun, 2014)

Local Capillary Trapping

Bench Scale
(cm~m, grain size variation, distribution of small heterogeneity, final CO2 distribution)

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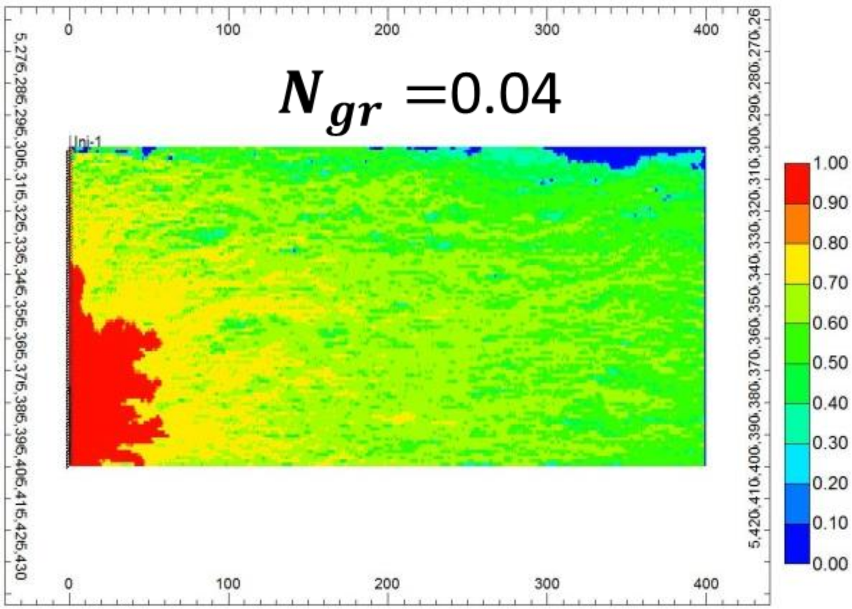
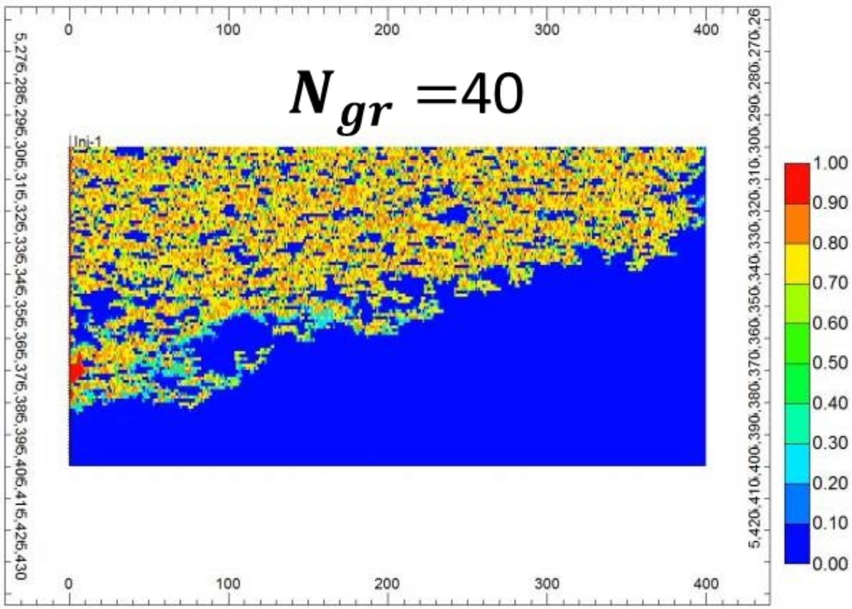
As gravity number increases, flow changes from compact displacement to capillary-channeling



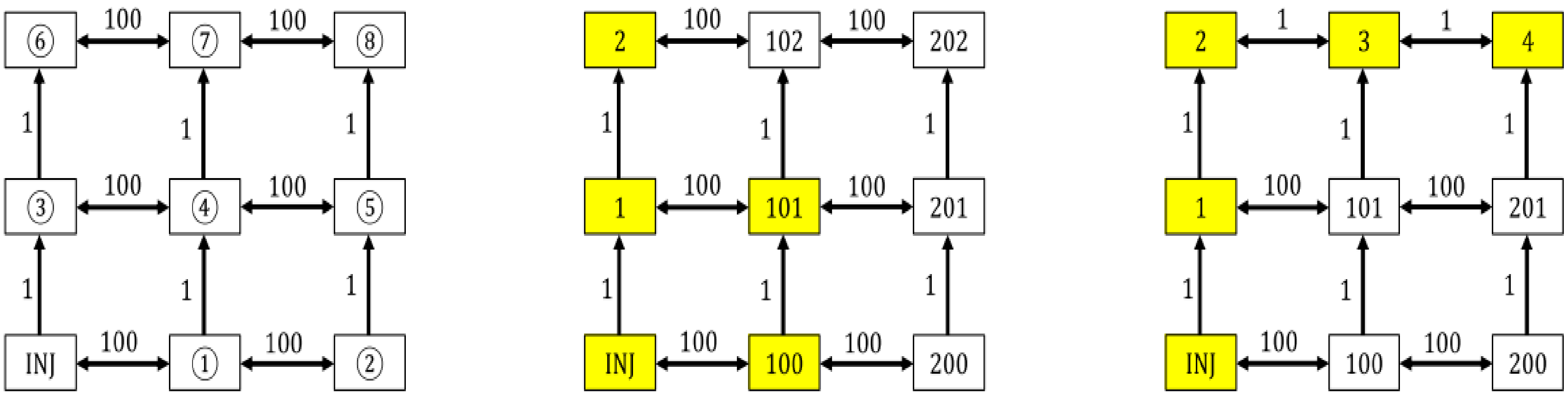


CO_2 saturation at the end of injection.

Difference between Local Capillary Trapping and Residual Trapping

Difference	Local Capillary Trapping	Residual Gas Trapping
Origin	Intra-reservoir capillary barriers	Snap-off
Porous Media	Heterogeneous	Homo/heterogeneous
Displacement Type	Drainage	Imbibition
Trapped CO_2 Saturation	$S_{gr,max} < S_{LCT} < 1 - S_{wr}$	$S_{gr} \leq S_{gr,max}$
Scale of Trapping	$10^{-2} \sim 10^{+1}\, m$	$\sim \mu m$
Influential Factor	Gas column height Entry capillary pressure, correlation length	Wettability, porosity, pore connectivity and et al
Interplay	Residual and LCT compete with each other	

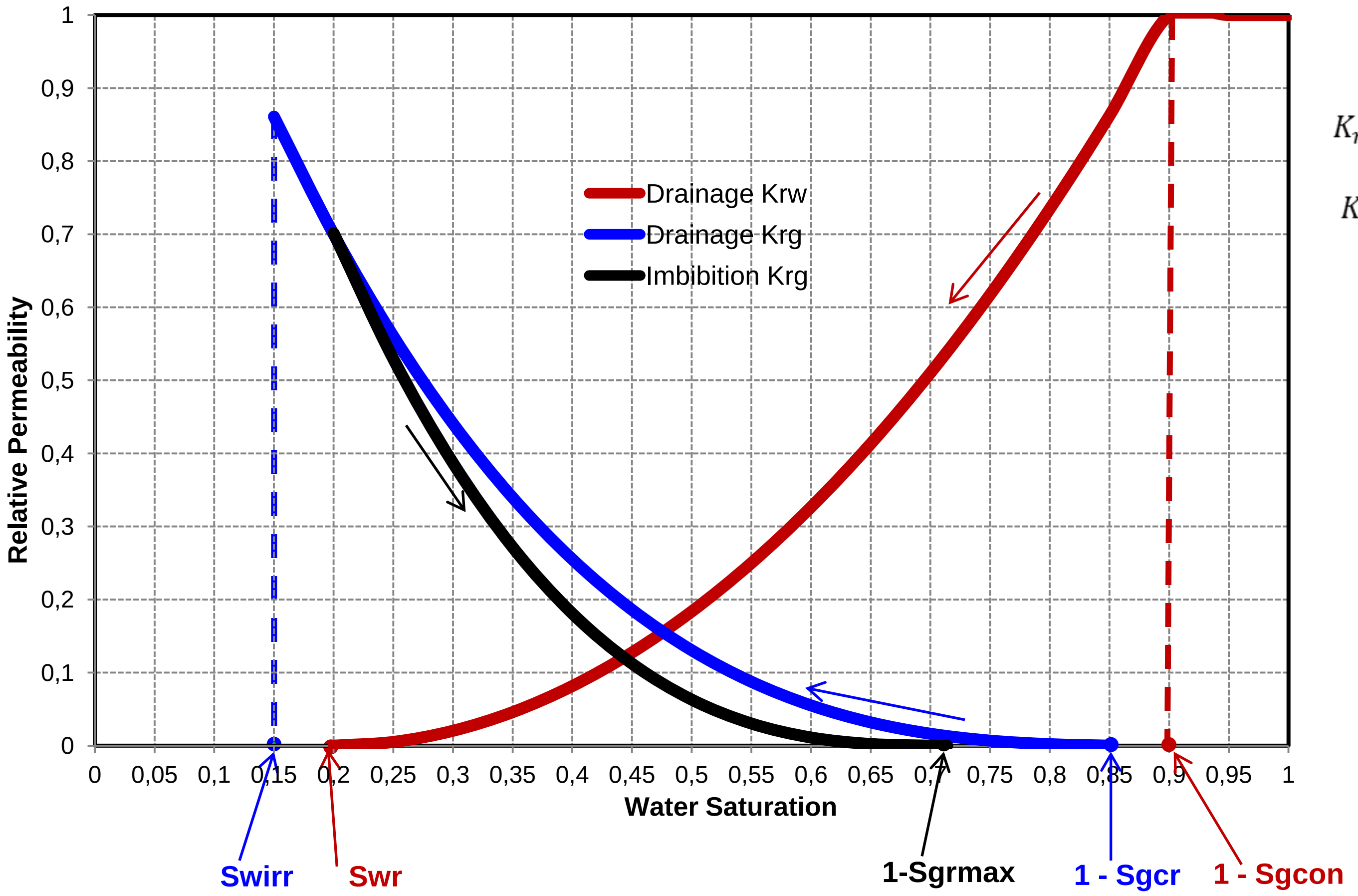
Scaled Connectivity Analysis



(a) a graph (b) original connectivity analysis (c) scaled connectivity analysis

Scaled connectivity analysis is used to enhanced the influence of buoyancy on the CO_2 plume behavior.

Relative Permeability with the Maximum Residual Gas Saturation equal to 0.286.



$$K_{rg} = K_{rg}^0 \left(\frac{S_g - S_{gcr}}{1 - S_{wirr} - S_{gcr}}\right)^{N_g}$$

$$K_{rw} = K_{rw}^0 \left(\frac{S_w - S_{wr}}{1 - S_{gcon} - S_{gwr}}\right)^{N_w}$$

Krg0	0.86
Sgcon	0.10
Sgcr	0.15
Ng	2.75
Krw0	1.00
Swirr	0.15
Swr	0.20
Nw	2.00

Capillary Pressure Curve