Experimental and numerical investigation of CO_2 gas flow in an intermediate flow cell using a modified invasion percolation model

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Exceptional service in the national interest

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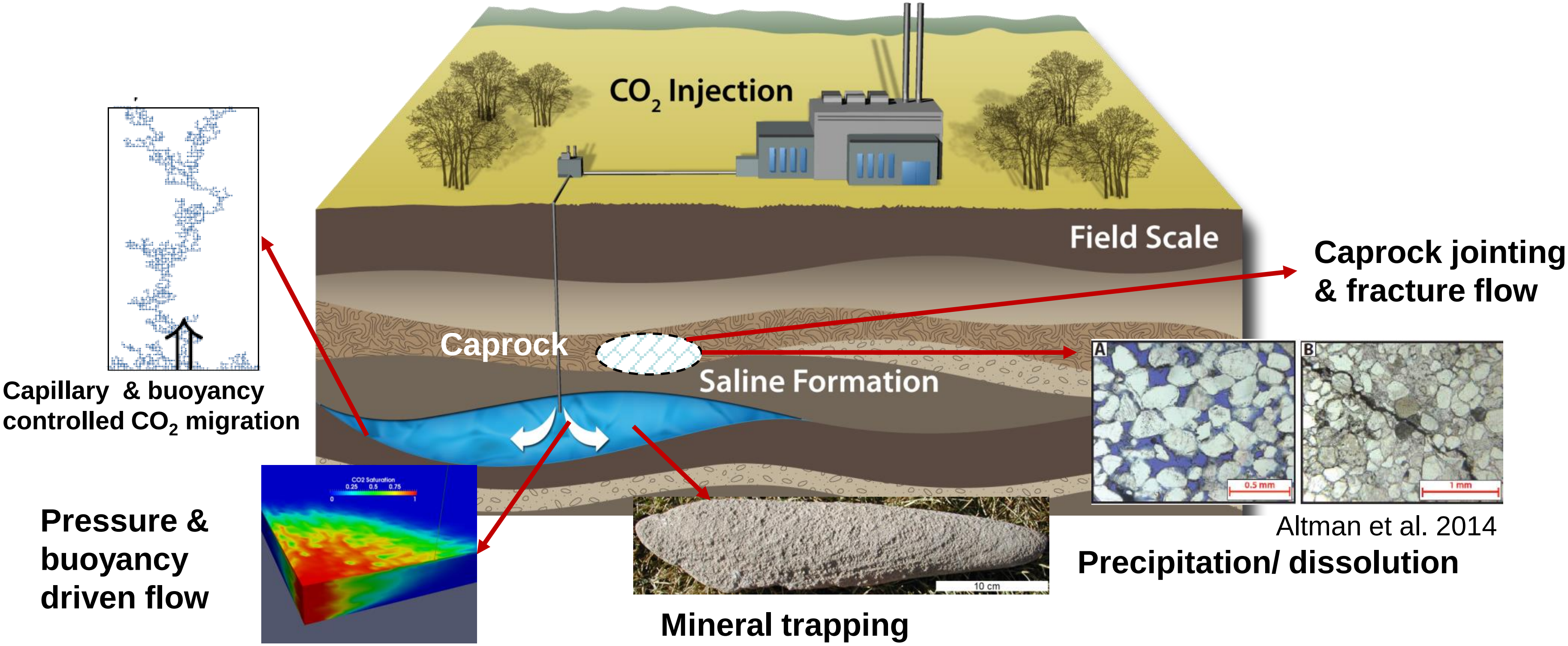
Outline

- Backgrounds
- Intermediate Scale Experiment & Modified Invasion Percolation Modeling
- CT high pressure CO_2 core flood testing and modeling
- Summary

CO2 Flow and Transport Processes during Geological Carbon Storage



► **<u>Sustaining large storage rates</u>**, of order gigatons of CO_2 per year in the US, for decades without compromising other subsurface resources and without jeopardizing the security with which the CO_2 is stored;

► **<u>Using pore space with unprecedented efficiency</u>**, i.e., placing CO_2 so that it occupies half of the reservoir volume, rather than the typical current estimate of less than five percent;

Intermediate scale experiment

1. to understand and quantify the physics of the transition from compact flow to capillary channel flow (coupled with core-scale experiments)
2. to develop new experimental-informed, physics-based models of this transition process, focused on representing cm-scale heterogeneity, with the goal of developing constitutive models suitable for reservoir-scale simulators

Light transmission system

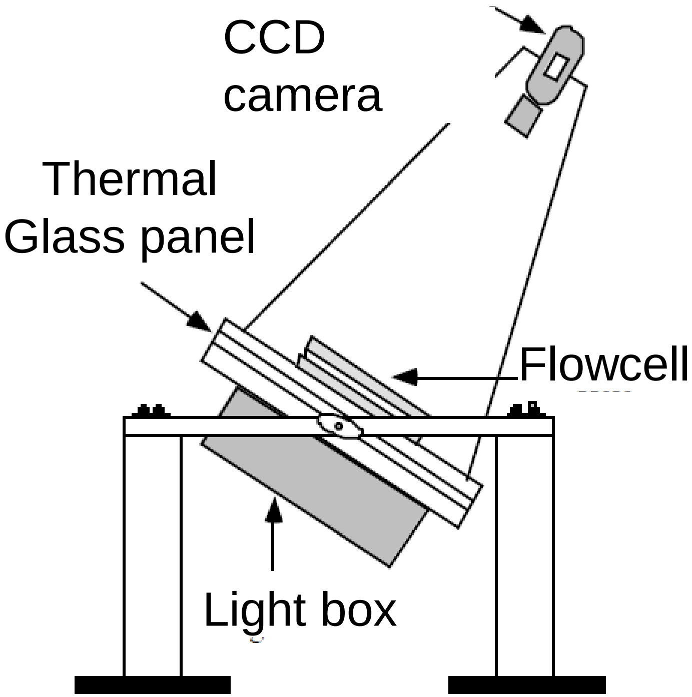
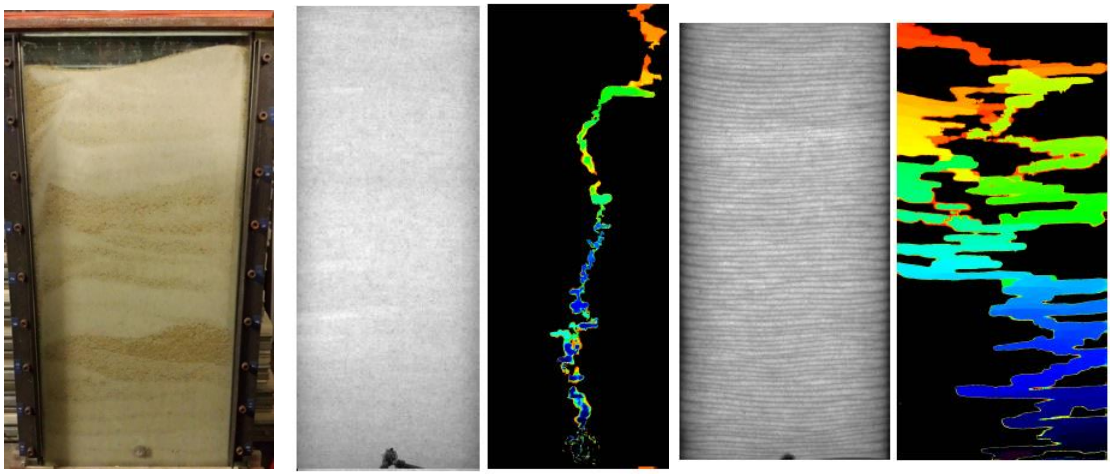


Image resolution: 0.1-1 mm
Data acquisition: < 1 sec

Examples with CO_2 gas flow



~30 cm **Weak layering** **Strong layering**

(Glass et al. 1998, 2000, 2001, 2003, WRR)

OPEN-MIP (Modified Invasion Percolation)

Traditional IP model

- Invading phase displaces defending phase when it overcomes the capillary resistance of neighboring pores
- Grid block with the lowest Pt connected to the growing invading front is chosen as the next invading block
- This is repeated for each growth step

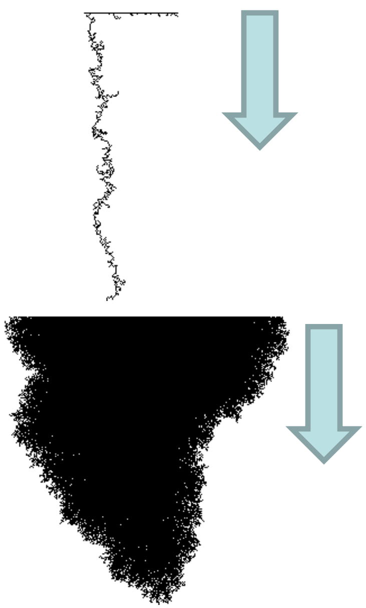
Total invasion pressure (Pt)

$$P_t = -\frac{2\sigma\cos\theta}{R} + \Delta\rho g z$$

Capillary pressure + gravity force

Modified IP model

- Traditional IP model does not account for viscous forces so that the invaded cluster is often found to be narrower and appearing as a single cluster or so-called “lightning bolt”
- Modified IP models were developed to accounts for a wider range of viscous, gravity, and capillary forces
- A modified invasion percolation (MIP) model based on Glass et al. [2001] and Glass and Yarrington [2003] was updated to incorporate stochastic invasion algorithms developed by Ewing and Berkowitz (1998)
- Examples show IP results in the same domain with different percolation growth modes (top – traditional algorithm, bottom – high randomness)



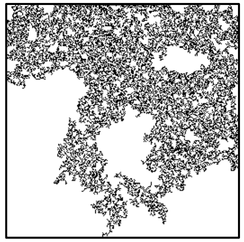
OPEN-MIP (Modified Invasion Percolation)

Steps = number of time steps
T = CPU time

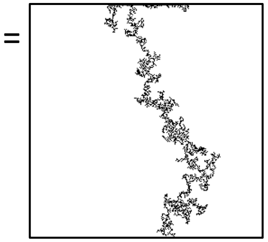
Invading nonwetting fluid

ρ = 1000 kg/m3 | ρ = 1050 kg/m3 | ρ = 1400 kg/m3

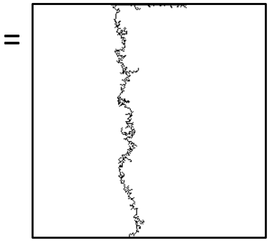
Steps = 15878
T = 224.8s



Steps = 2359
T = 12.3s

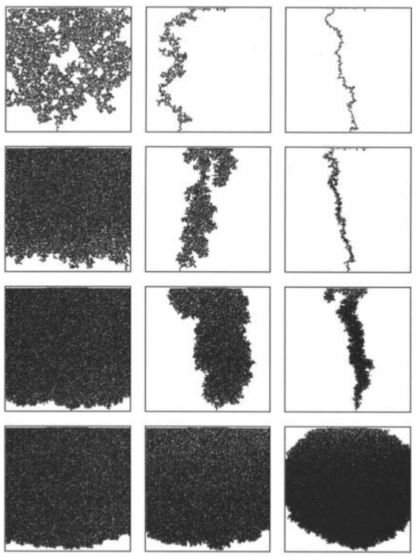


Steps = 781
T = 4.1s

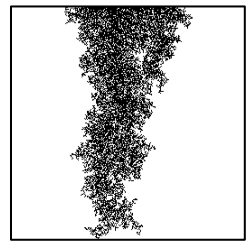


p = 0.01

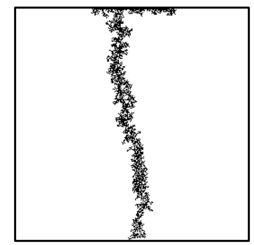
Ewing and Berkowitz (1998, WRR)



Steps = 12350
T = 123.9s

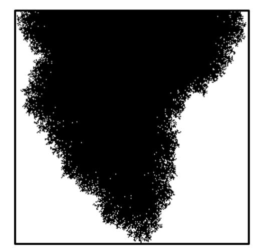


Steps = 2576
T = 12.3s

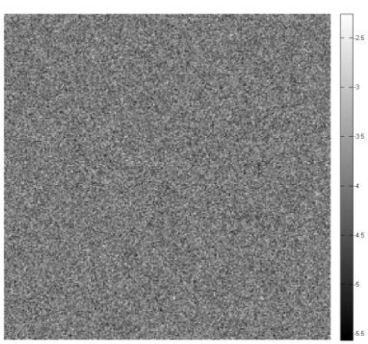


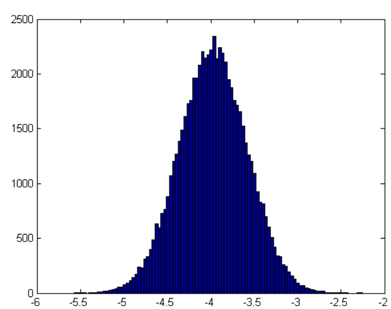
p = 0.2

Steps = 37498
T = 770.9s



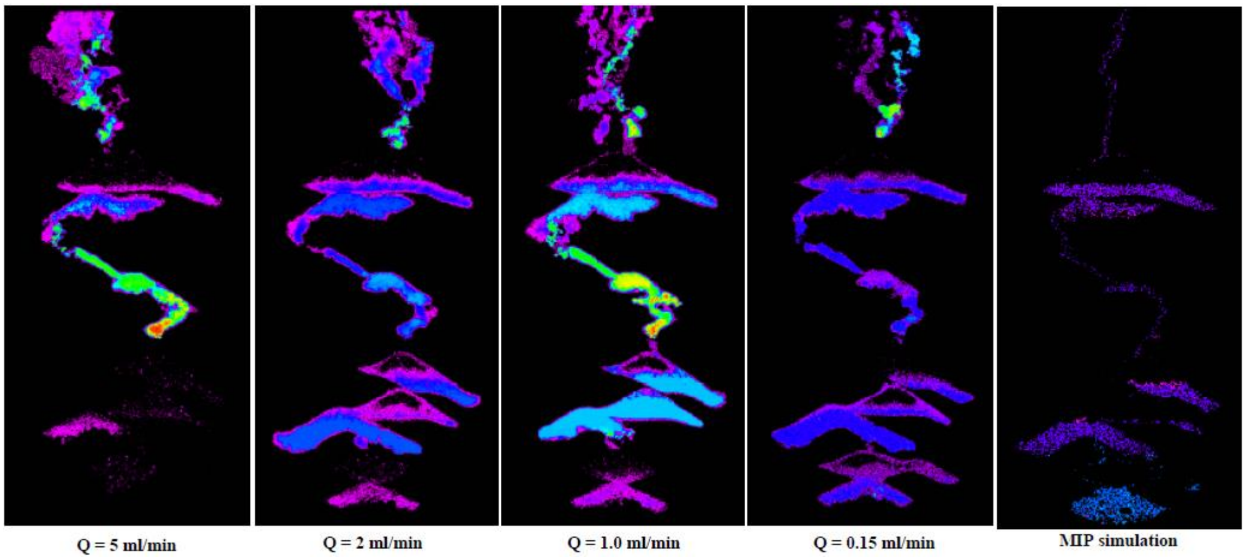
p = 0.667





Pore size distribution = lognormal
Mean pore size = 0.16 mm
Median pore size = 0.1 mm
Standard deviation of pore size = 0.18 mm
Skew of pore size = 2.6

Capillary-gravity pulsation and suppression by viscous forces

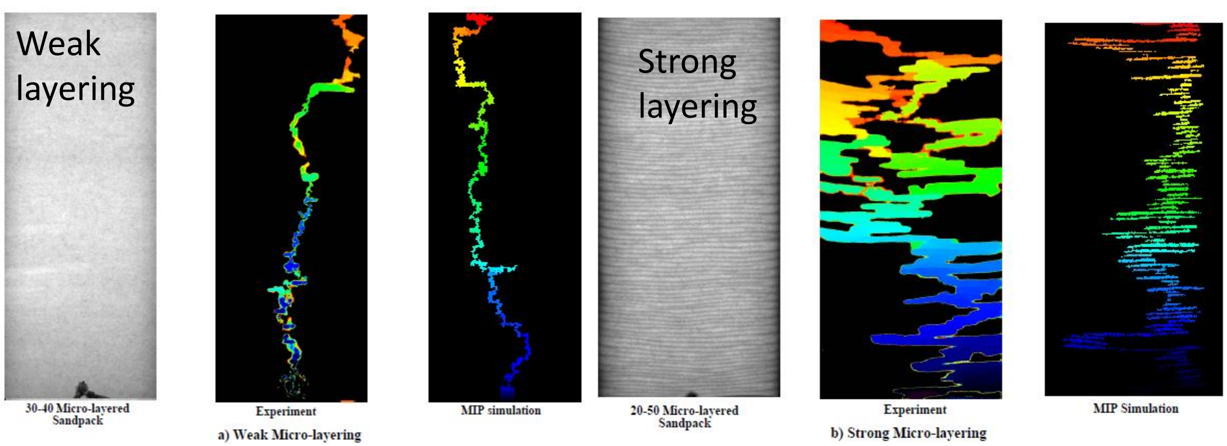


- ▶ Pulsation suppressed by a high flow rate
- ▶ MIP result similar to a low flow rate case
- ▶ Multiple pathways at the top caused by both viscous and capillary-gravity pulsation

More viscous forces (compact flow)

Capillary-Gravity Pulsation (channel flow??)

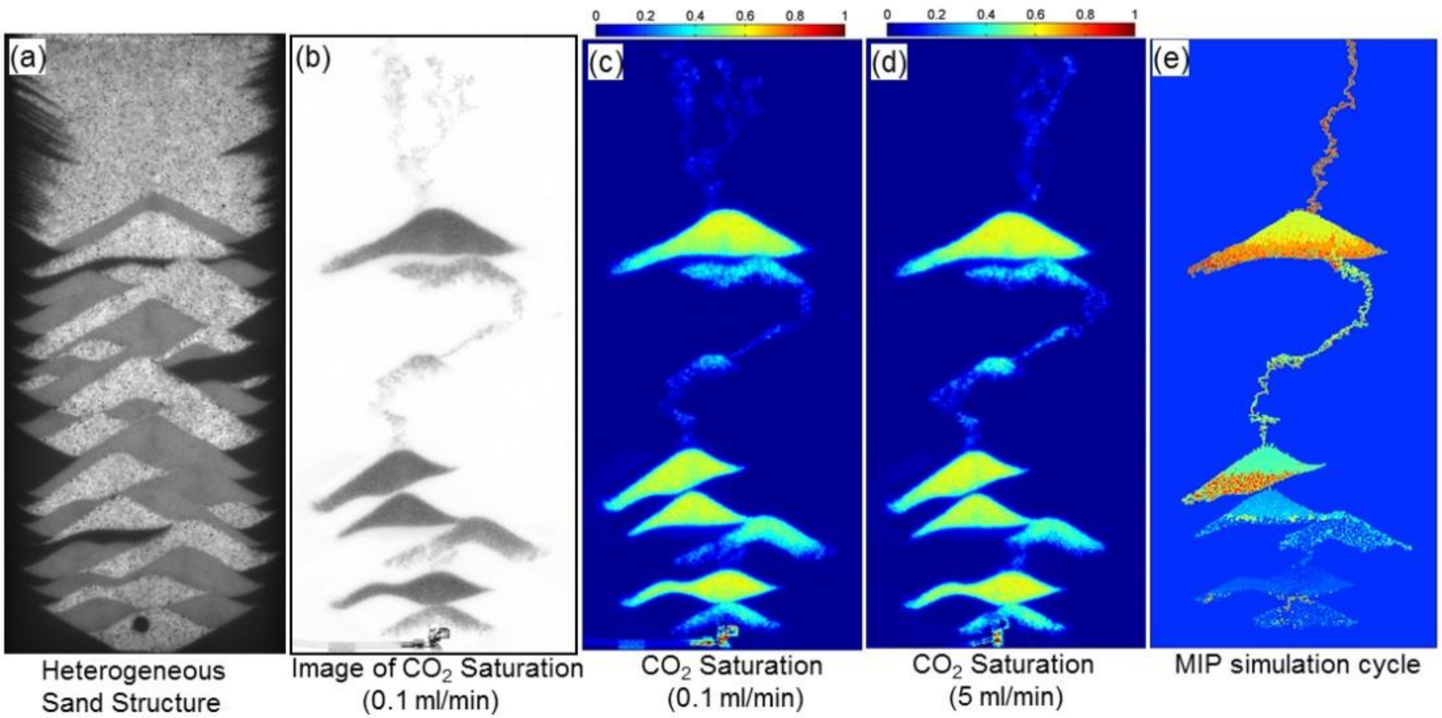
Influence of micro-layering within sedimentary deposit



- ▶ CO_2 invasion from a point
- ▶ Capillary-gravity pulsation led to the bifurcation of pathway
- ▶ MIP requires a mapping of micro-scale layering

Conrad and Glass (SAND2001)

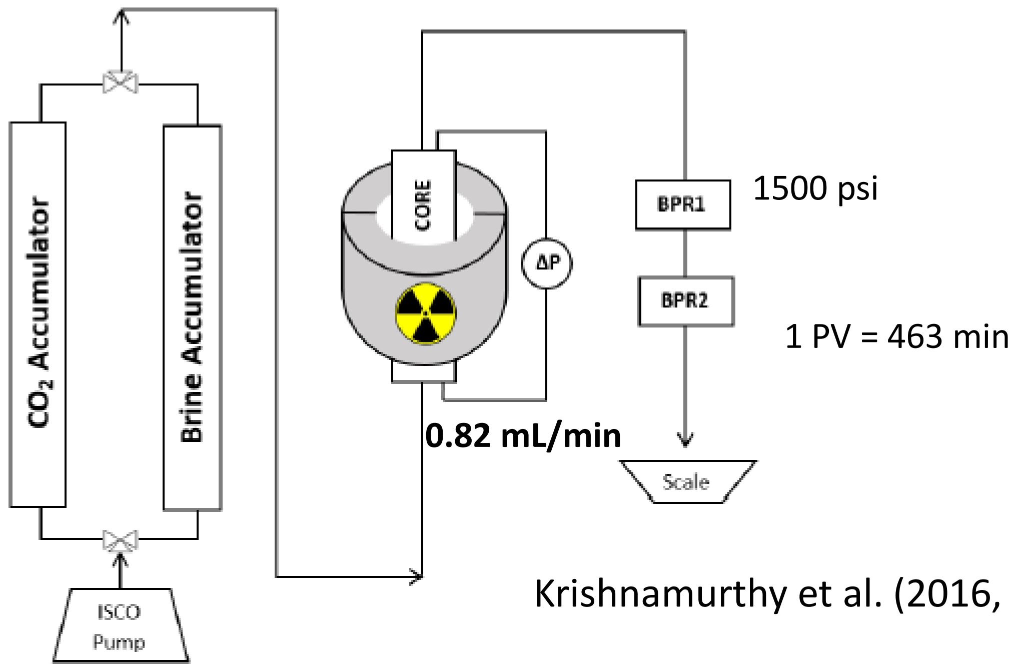
OPEN-MIP Case



(a) Experimental heterogeneous sand structure (26 cm wide, 55.5 cm tall) of Glass et al. showing the find sand (dark, #50-70), medium sand (gray, #30-40), and coarse sand (light, 12-20) units.
(b) CO_2 saturation image at a CO_2 gas injection rate of 0.1 ml/min.
(c-d) Experimental CO_2 saturations just after CO_2 gas reached the top of the chamber at 0.1 mL/min and 5 ml/min, respectively.
(e) MIP simulation cycle with cold color for early and warm color for late filling cycles.

High pressure CO_2 core flood experiment

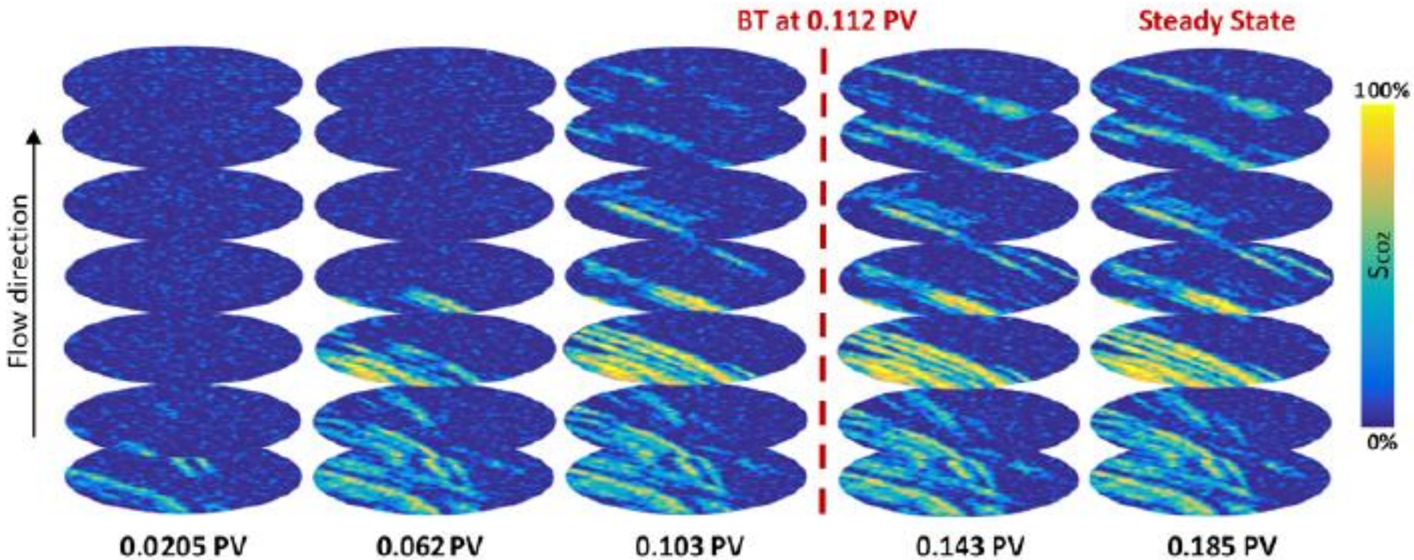
Boise sandstone
k =3.75 x 10^{-12} m^2
Porosity = 0.308
Brine = 1010 kg/m^3
CO2 = 818 kg/m^3

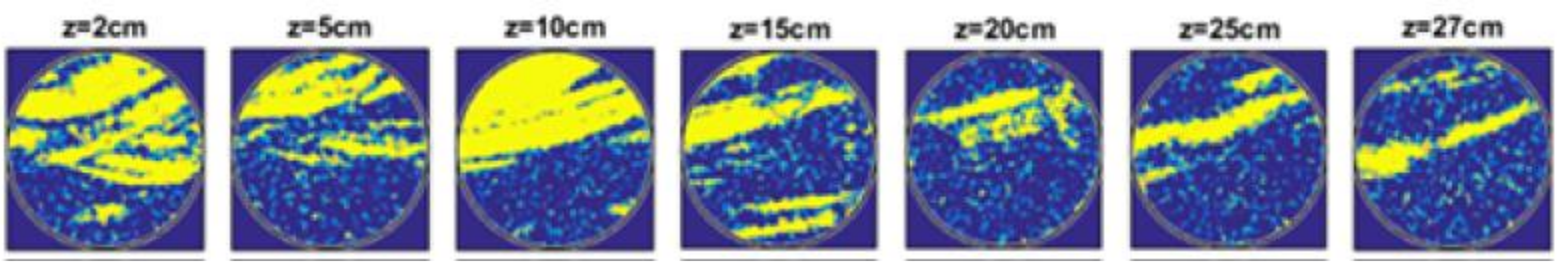


Krishnamurthy et al. (2016, in review)

- Boise sandstone (30 cm long and 7.2 cm diameter core)
- X-ray CT scanning
  - 1cm scanning thickness for 30 cm long core (also 0.2 cm thickness)
  - CT images at 0.257 cm x 0.257 cm pixel resolution
  - Images are taken at an interval of ~0.02 to 0.05 PV

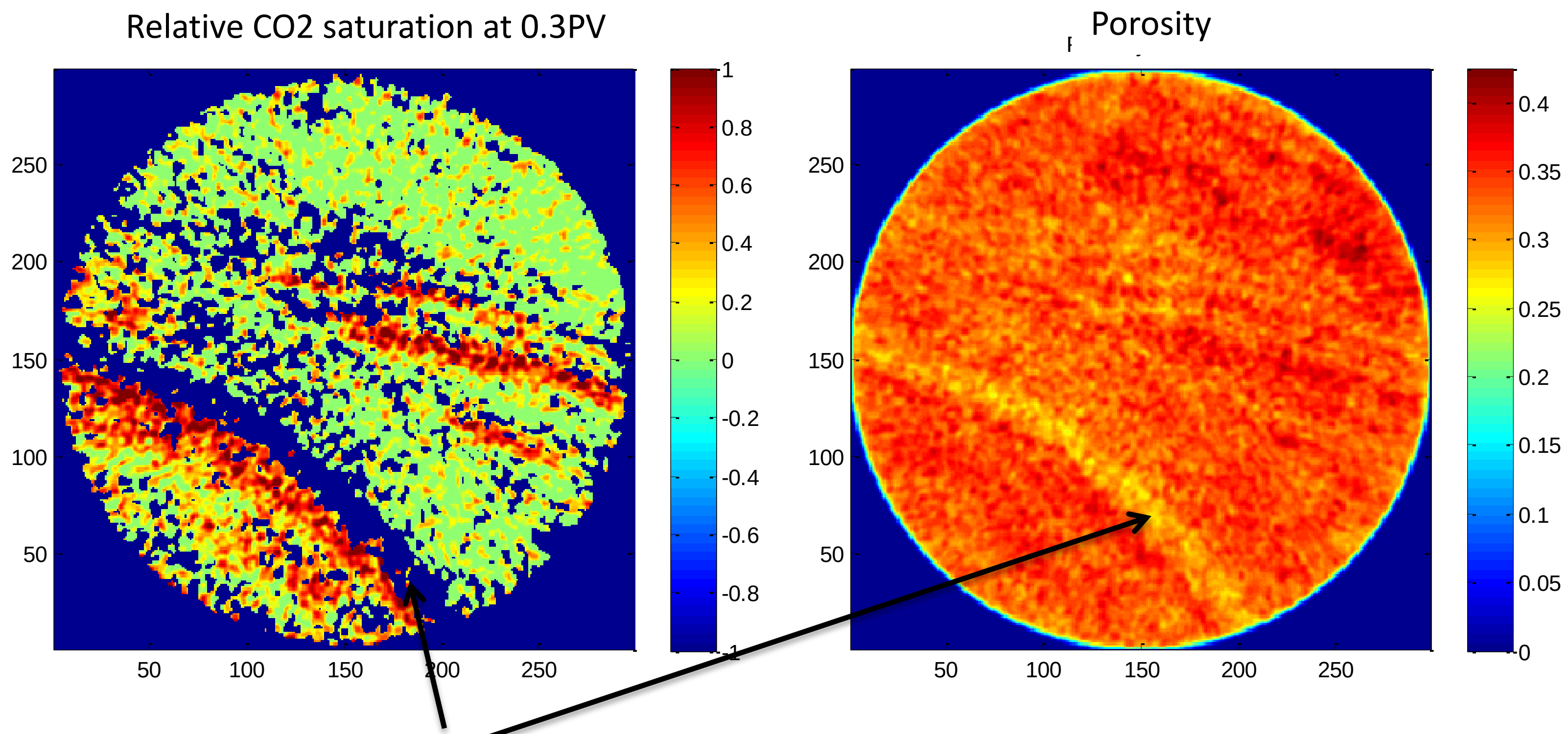
CO_2 Saturation Profiles from CT data





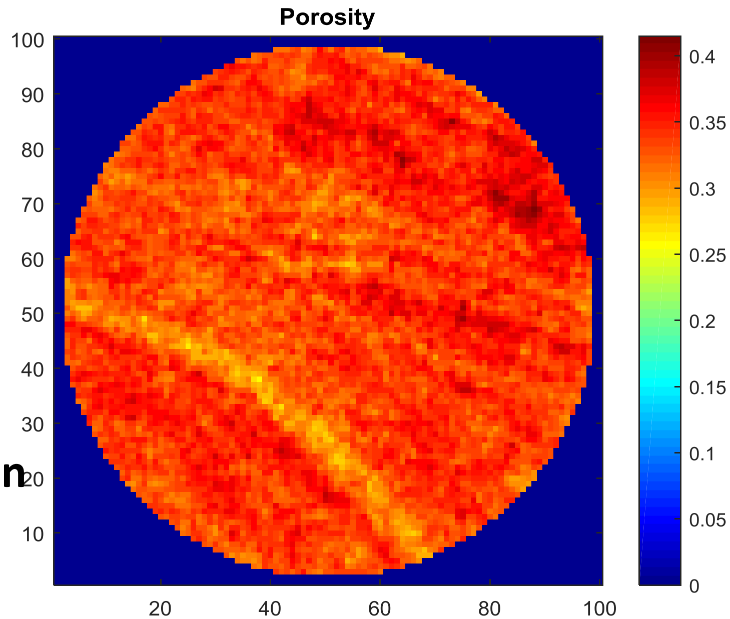
0.185 PV

CO2 flooding and porosity relationship



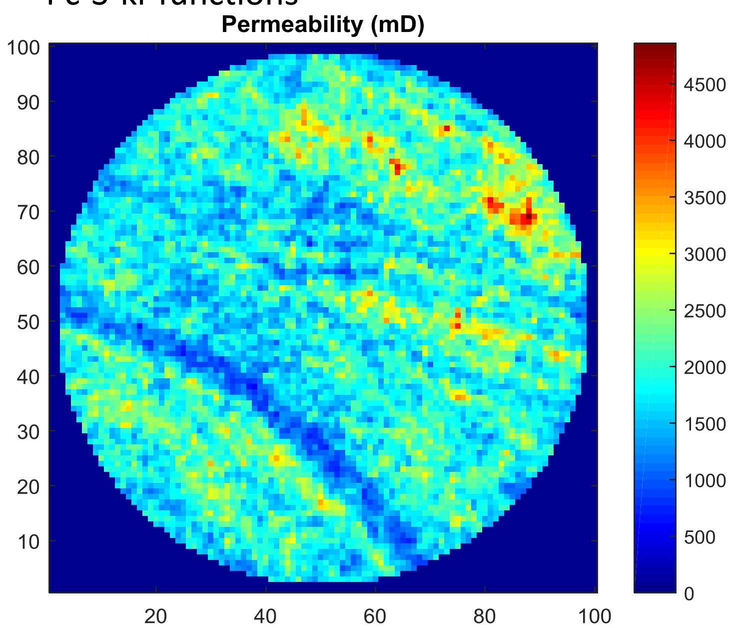
Mask area with porosity < 0.325

Summary

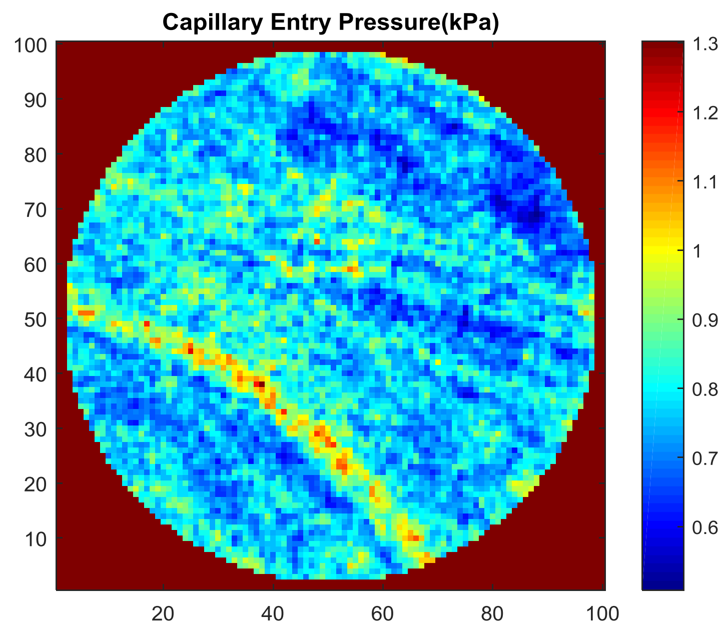


Estimated based on
CT images with dry and wet core

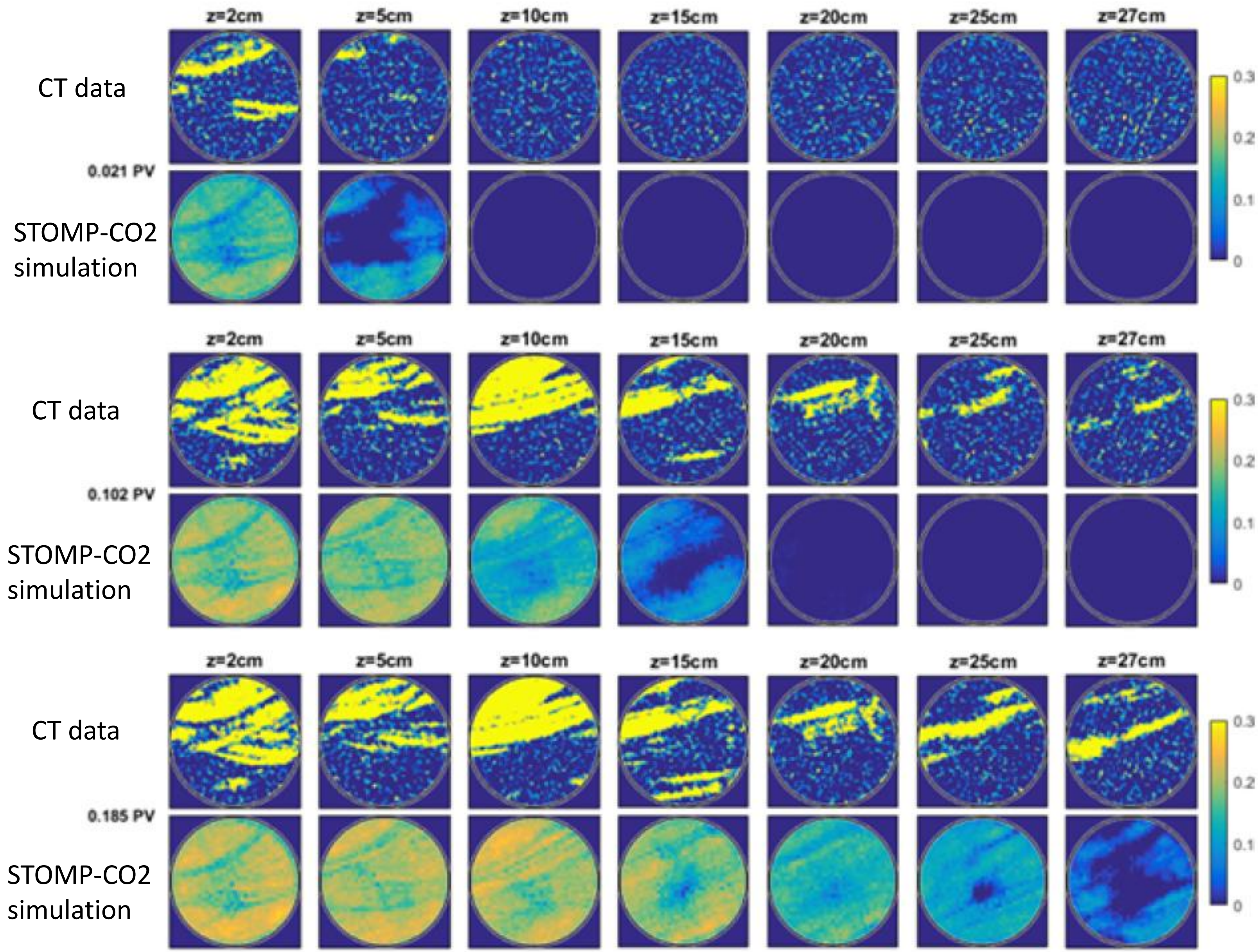
Multiphase flow simulation (STOMP)
- Permeability
- Pc-S-kr functions



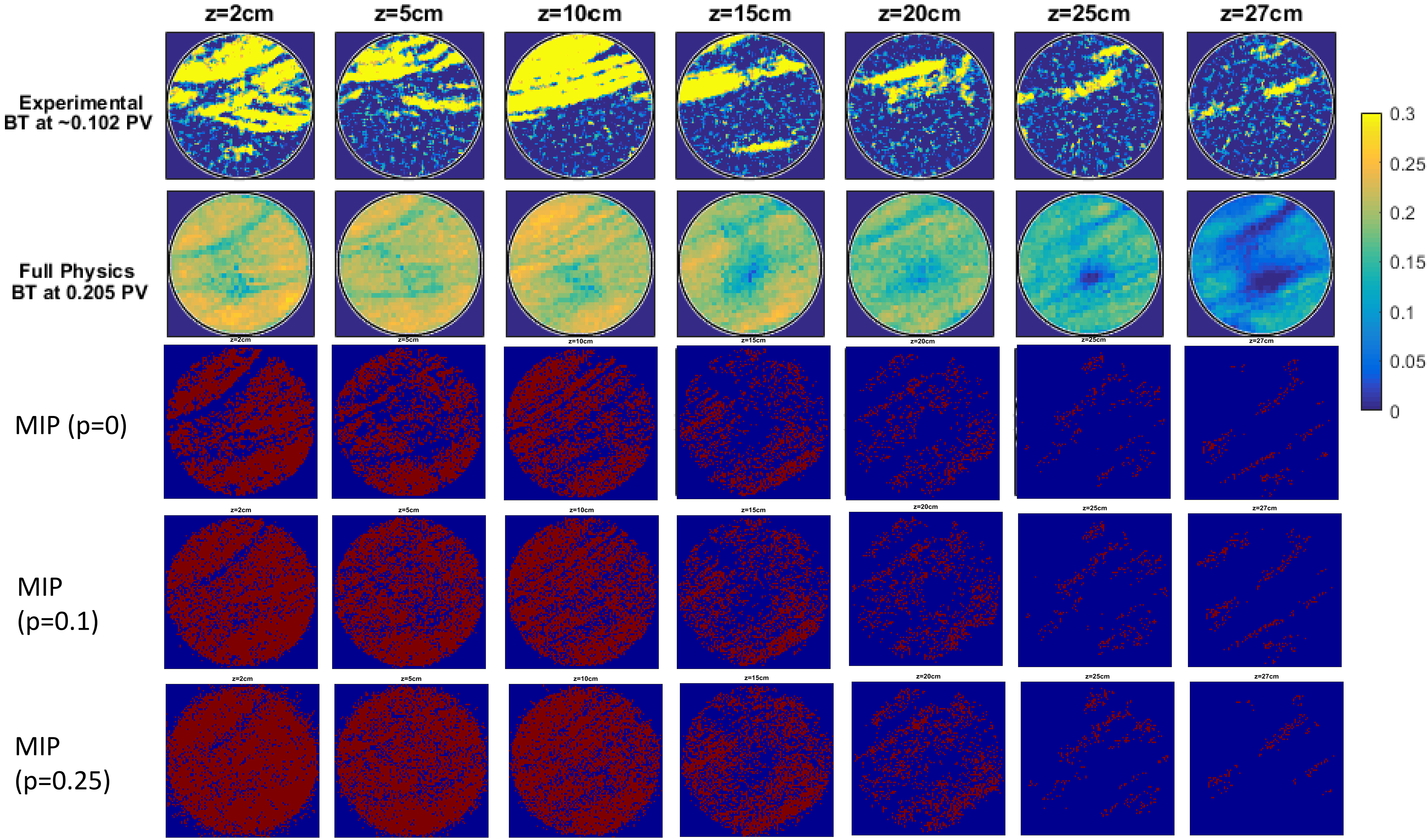
MIP simulation
Permeability
Pc-S-kr functions



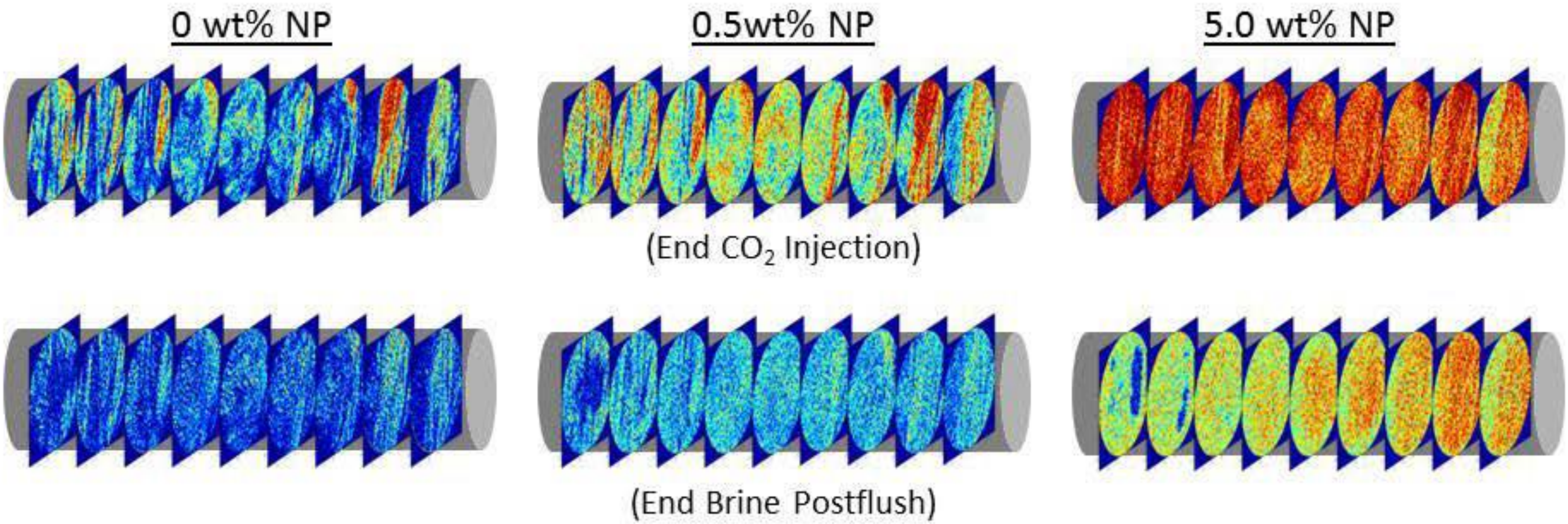
Experimental vs. Darcy's law based CO_2



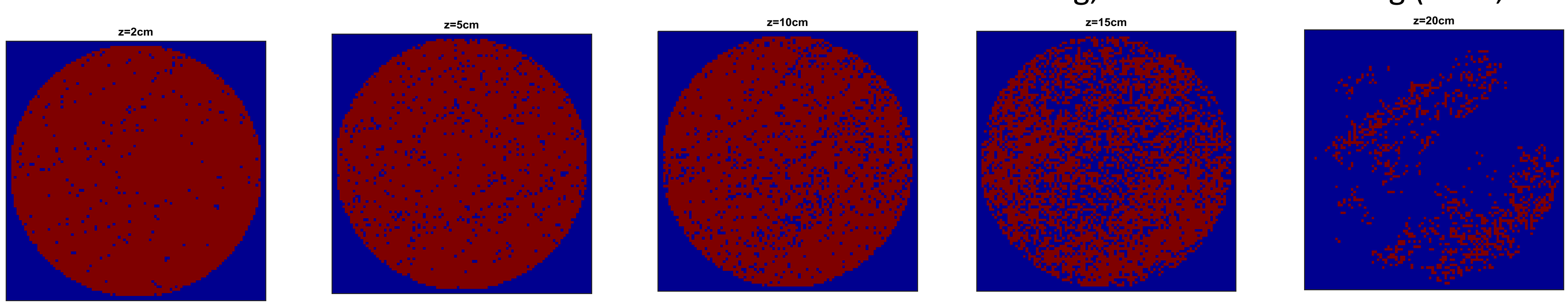
MIP Results


z=2cm
z=5cm
z=10cm
z=15cm
z=20cm
z=25cm
z=27cm
Experimental BT at ~0.102 PV
Full Physics BT at 0.205 PV
MIP (p=0)
MIP (p=0.1)
MIP (p=0.25)
0.3
0.25
0.2
0.15
0.1
0.05
0

CO_2 core flood experiments with nano-particles



CFSES 2016 Meeting, modified from Wung (2015, MS thesis)



MIP (p=0.5)

Summary

1. Modified Invasion percolation model has been developed and tested to understand and quantify the physics of the transition from compact flow to capillary channel flow
2. Intermediate flow cell and core-scale experiments with in-situ visualization provided new experimental-informed, physics-based models of this transition process
3. MIP can be used to focus on representing cm-scale heterogeneity, with the goal of developing constitutive models suitable for reservoir-scale simulators (e.g., relative permeability functions)
4. Validated MIP will be released to the public domain with examples to facilitate collaborations on multiphase flow at multiple scales