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Benchmark: Modeling CO_2 gas flow in a heterogeneous sand architecture

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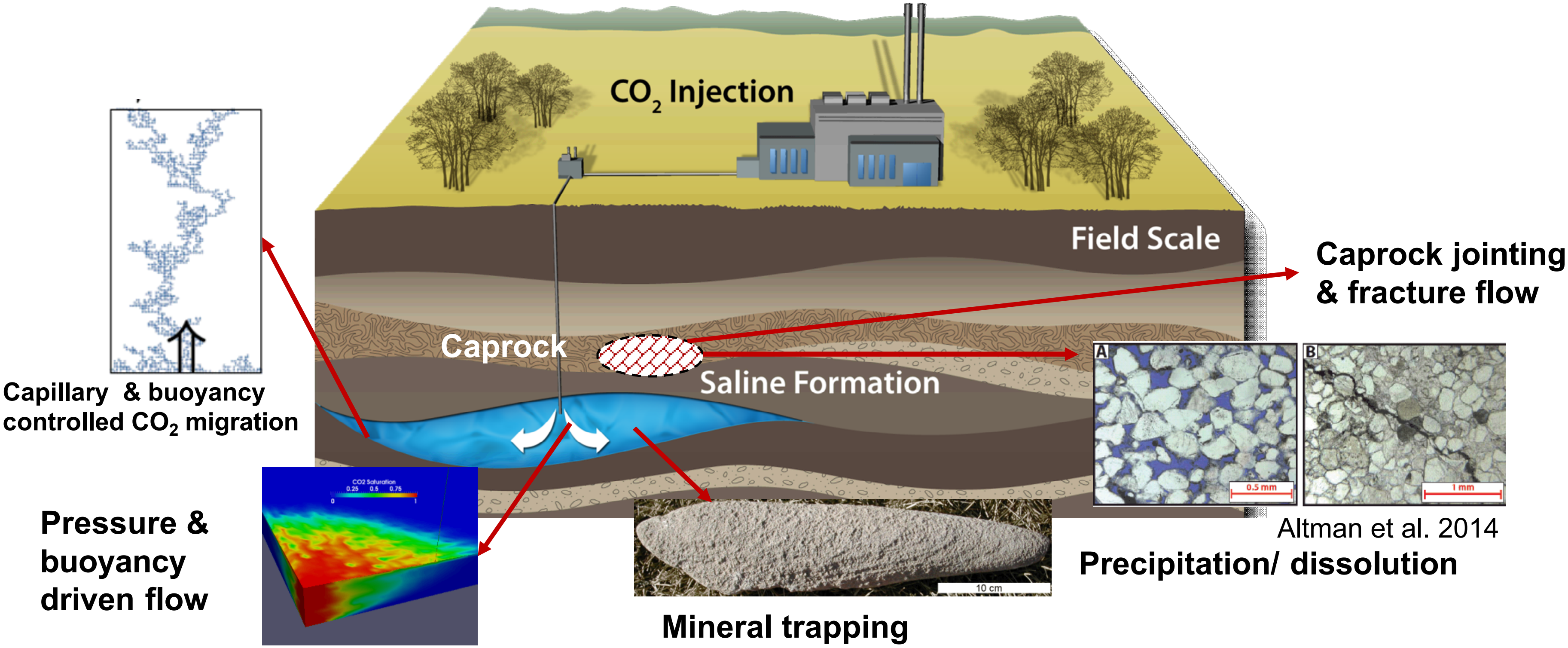
SAND2017-7230C

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

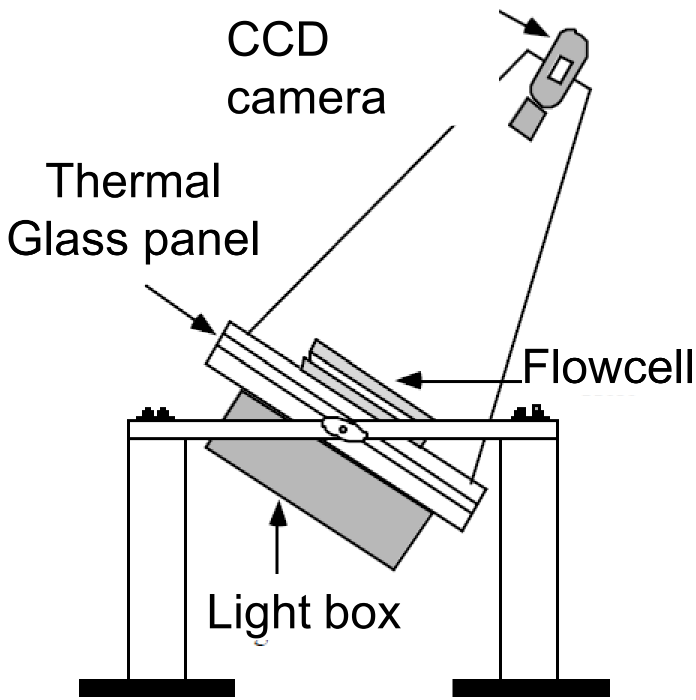
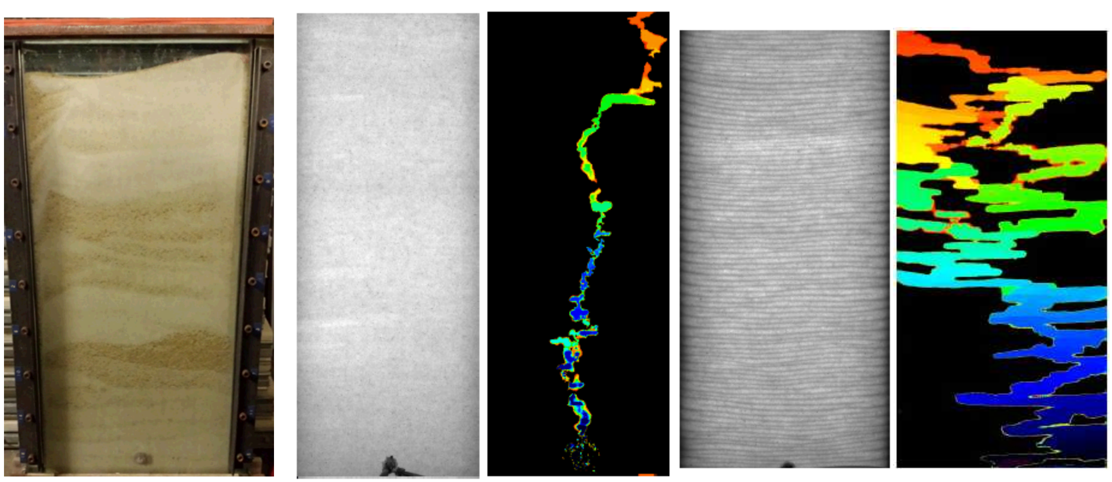


Image resolution: 0.1-1 mm
Data acquisition: < 1 sec

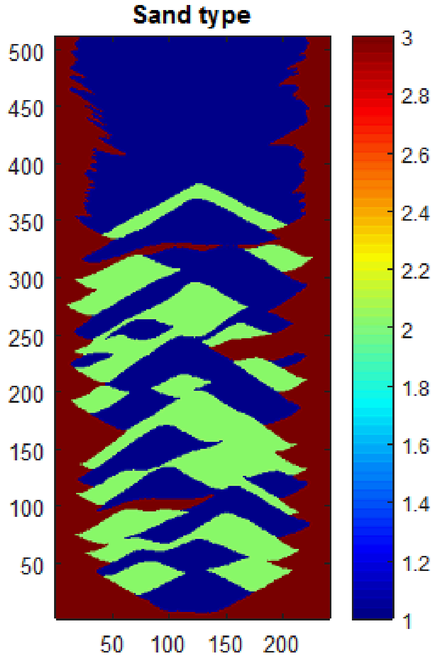
Examples with CO_2 gas flow

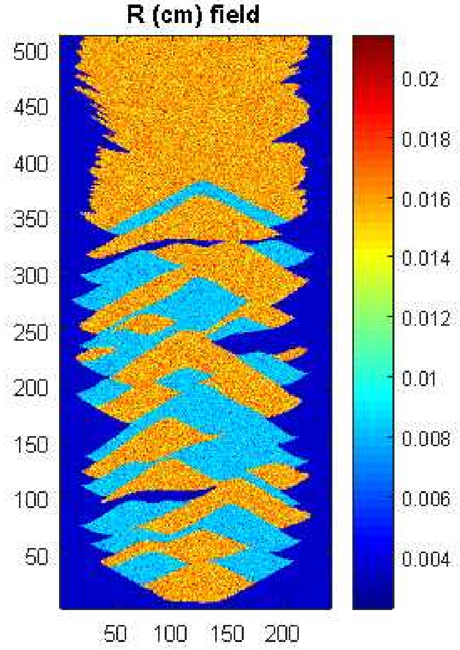


~30 cm **Weak layering** **Strong layering**

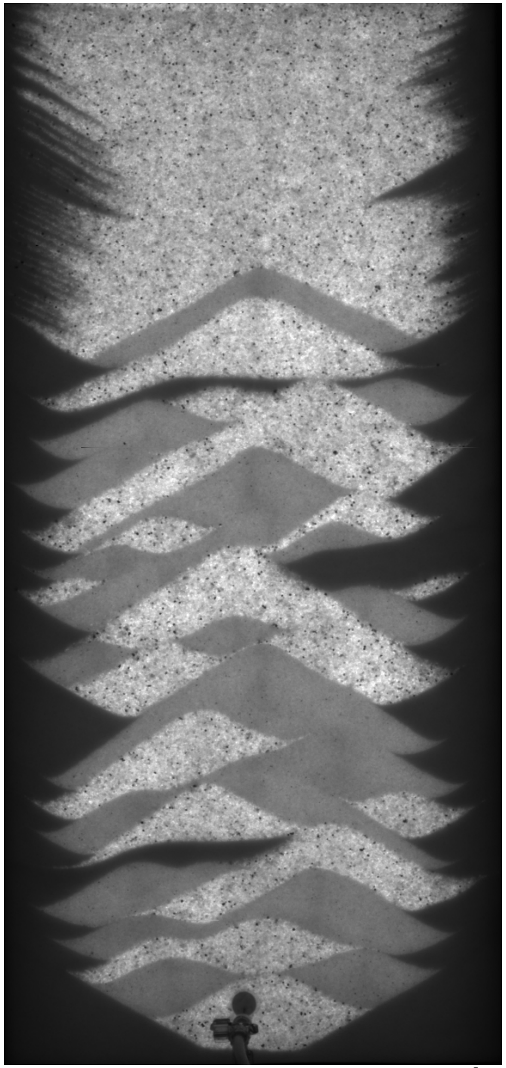
(Glass et al. 1998, 2000, 2001, 2003, WRR)

Overview Bob Glass Experiments





Experimental image

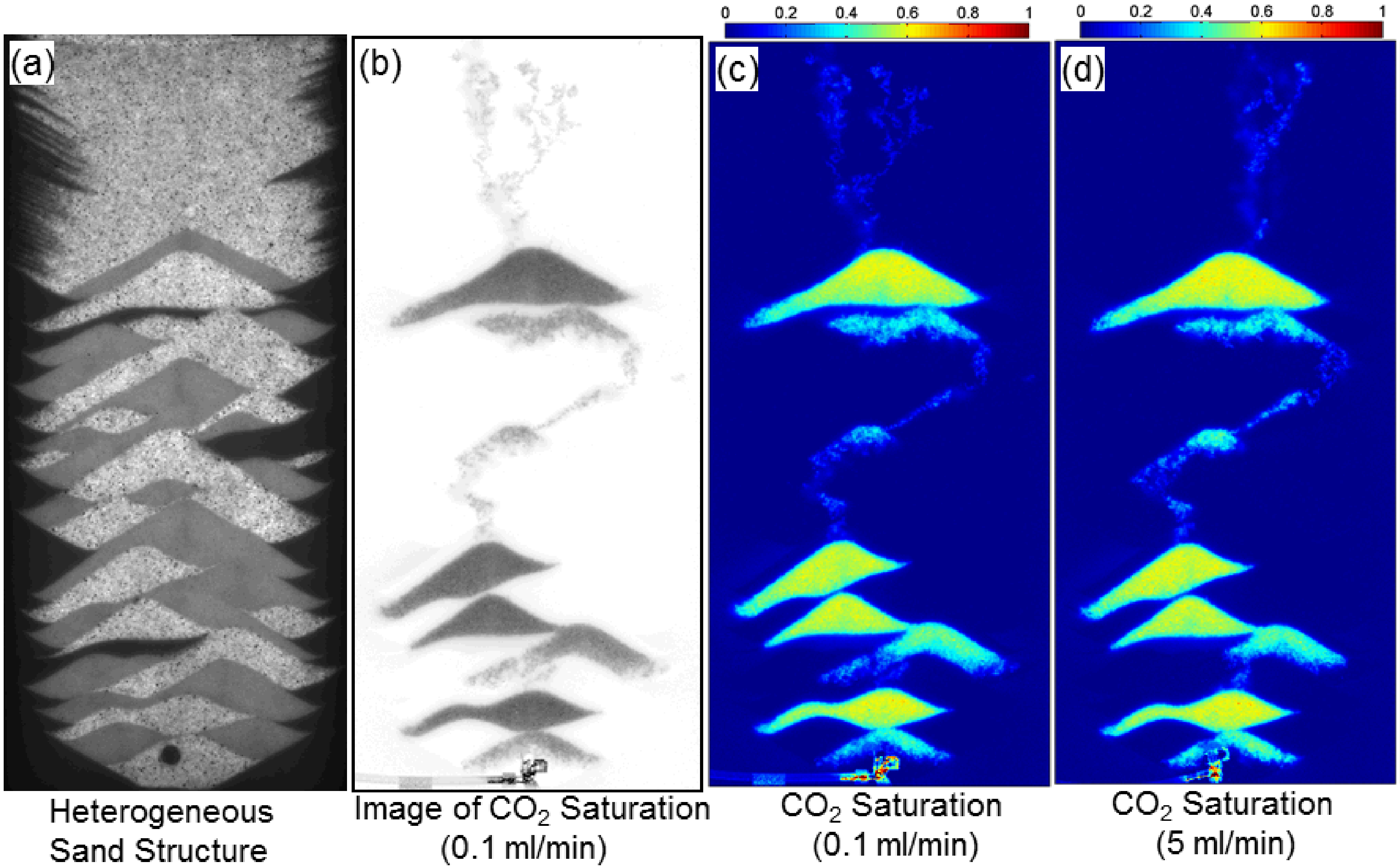


Sand 1: Accusand 12-20
Sand 2: Accusand 30-40
Sand 3: Accusand 50-70

Grid: 240 x 511 (dx=dy=0.1087cm)
Origin: lower left corner in figures

Dimension: 26.088cm x 55.55cm x 1cm
Injection hole: Diameter=11 pixels at (110.5, 35.5) in [240 x 511] grid system
Injection rates: 0.1, 0.5, 1, 2, 5 mL/min

Experimental Data Analysis



(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.

Overview of Model – Aria

- Solve Darcy equations for two-phase immiscible fluid flow using thermal/fluids finite-element code Aria (SNL code)

$$\frac{\partial}{\partial t}(\rho_w \phi(1 - S_n)) = \boldsymbol{\nabla} \cdot \left(\rho_w \frac{k_{rw}}{\mu_w} \boldsymbol{K} \cdot (\boldsymbol{\nabla} p - \rho_w \boldsymbol{g}) \right) + Q_w$$

$$\frac{\partial}{\partial t}(\rho_n \phi S_n) = \boldsymbol{\nabla} \cdot \left(\rho_n \frac{k_{rn}}{\mu_n} \boldsymbol{K} \cdot (\boldsymbol{\nabla} p + \boldsymbol{\nabla} p_c - \rho_n \boldsymbol{g}) \right) + Q_n$$

$$p_c = p_n - p_w$$

$$S_w + S_n = 1$$

Overview of Model – Aria (cont.)

- Capillary Pressure use van Genuchten function:

$$p_c = p_{c0}\left(s^{-\frac{1}{\lambda}} - 1\right)^{\frac{1}{\beta}}$$

$$\lambda = 1 - \frac{1}{\beta} \quad , \qquad \beta > 1$$

$$s = (S_w - S_{w,r})/\left(\left(1 - S_{nw,r}\right) - S_{w,r}\right)$$

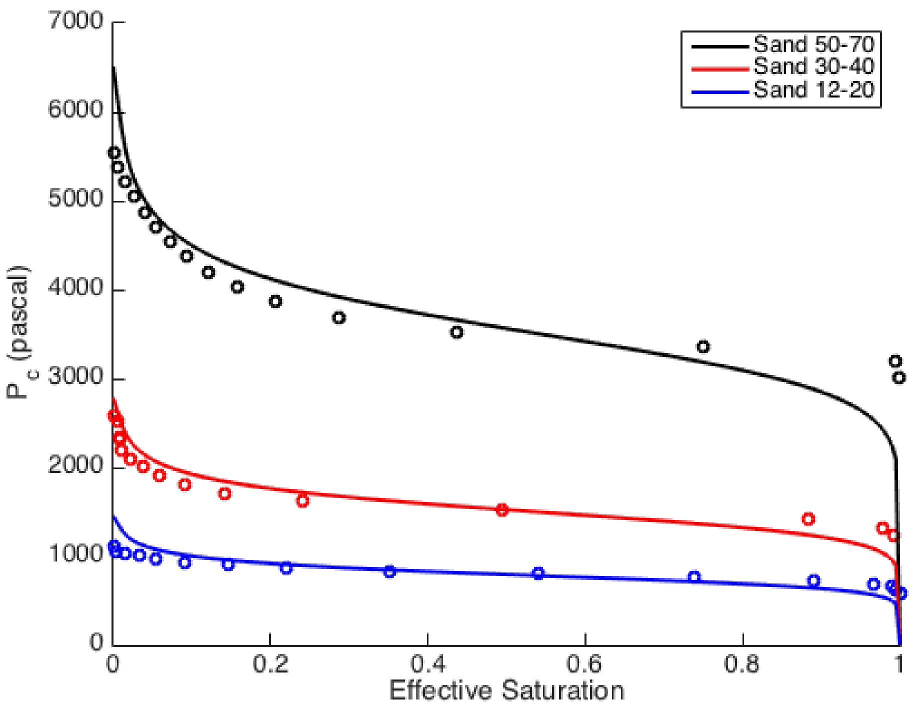
- Relative perm use van Genuchten function:

$$k_{rl} = \sqrt{s}\left[1 - \left(1 - s^{\frac{1}{\lambda}}\right)^{\lambda}\right]^2$$

$$k_{rg} = \sqrt{1 - s}\left[1 - s^{\frac{1}{\lambda}}\right]^{2\lambda}$$

Capillary Pressure Curves

- Fit data to provided capillary pressure curves measured for the three sand-types using van Ganuchten model $\beta = 10$



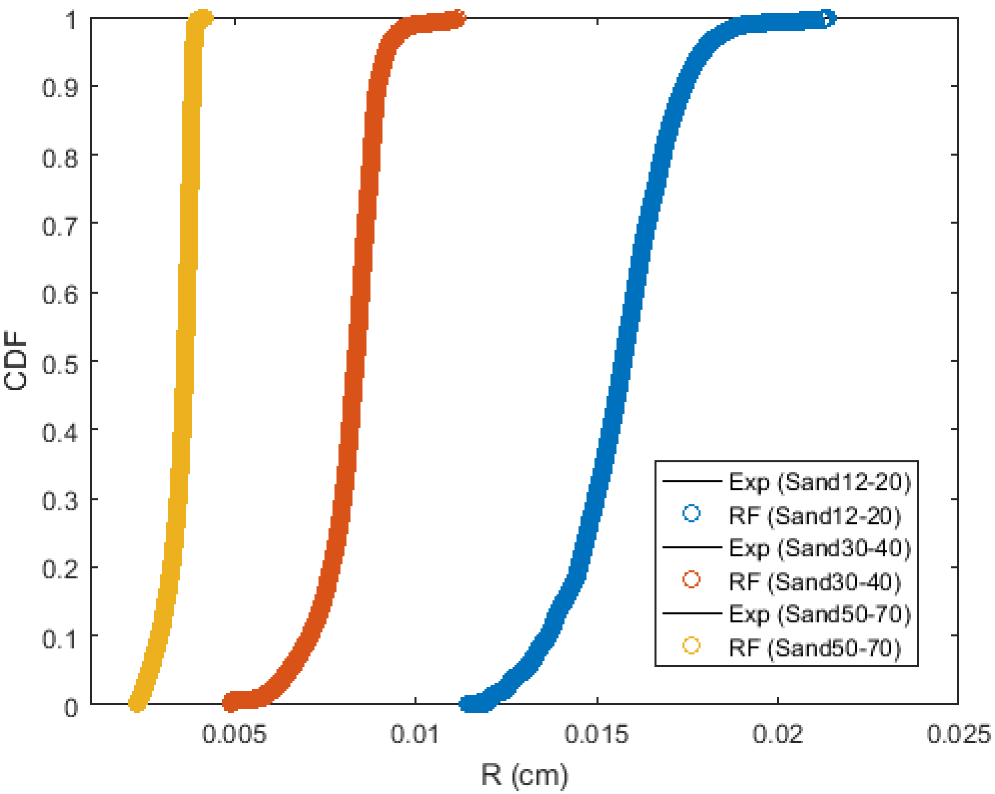
Overview of Model - Permeability

- Take provided radius field (r_p) generated from probability density function.
- Generate single-phase permeability using Carman-Kozeny relationship:

$$\kappa = \frac{a\phi^3 r_p^2}{4(1-\phi)^2}$$

- Porosity based on sand-type $\phi \approx 0.35$ for all sands

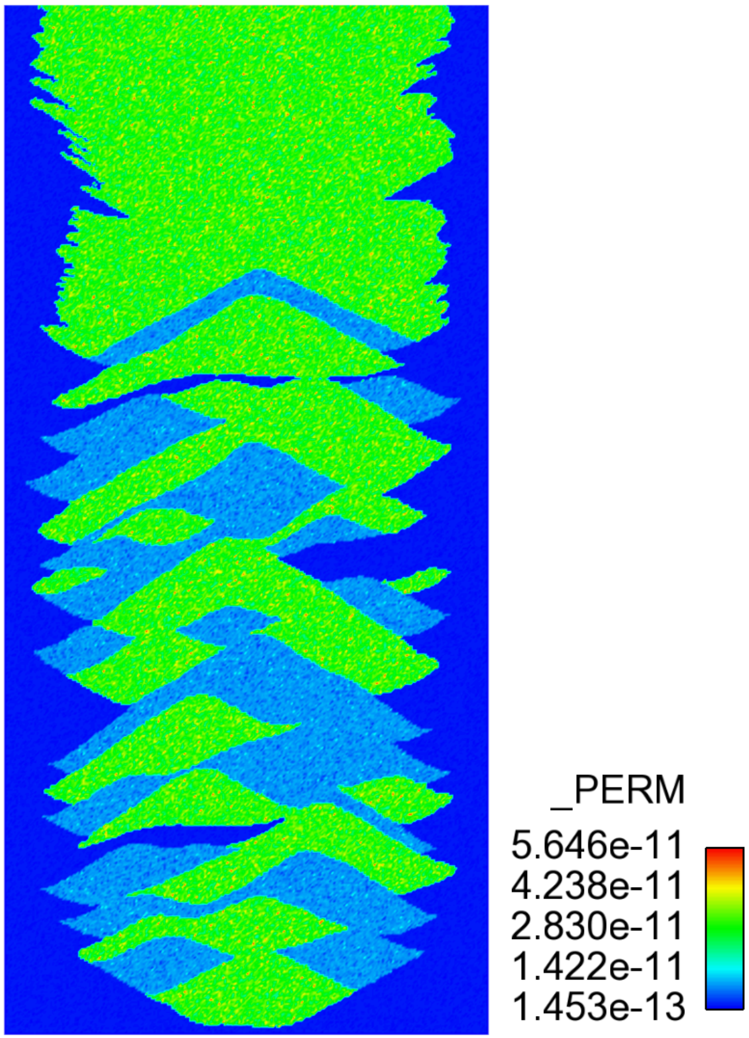
R (cm) field generation



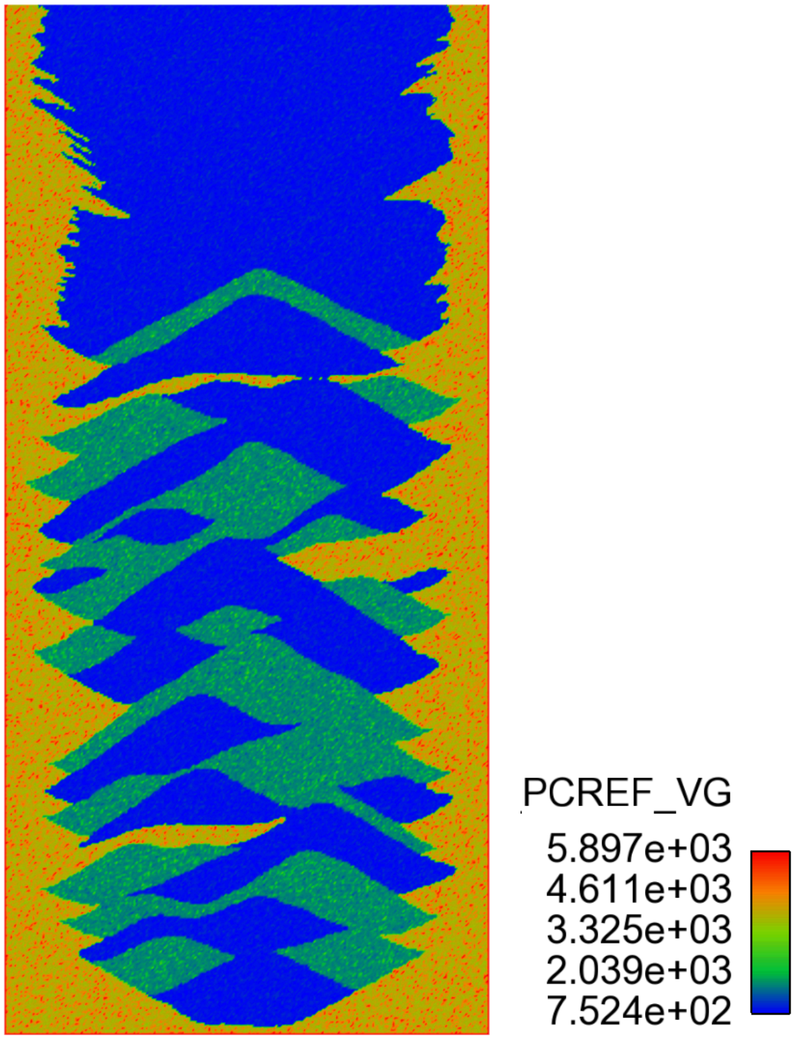
Inverse transform sampling from experimental data

Permeability and Pressure Fields

Permeability Field κ

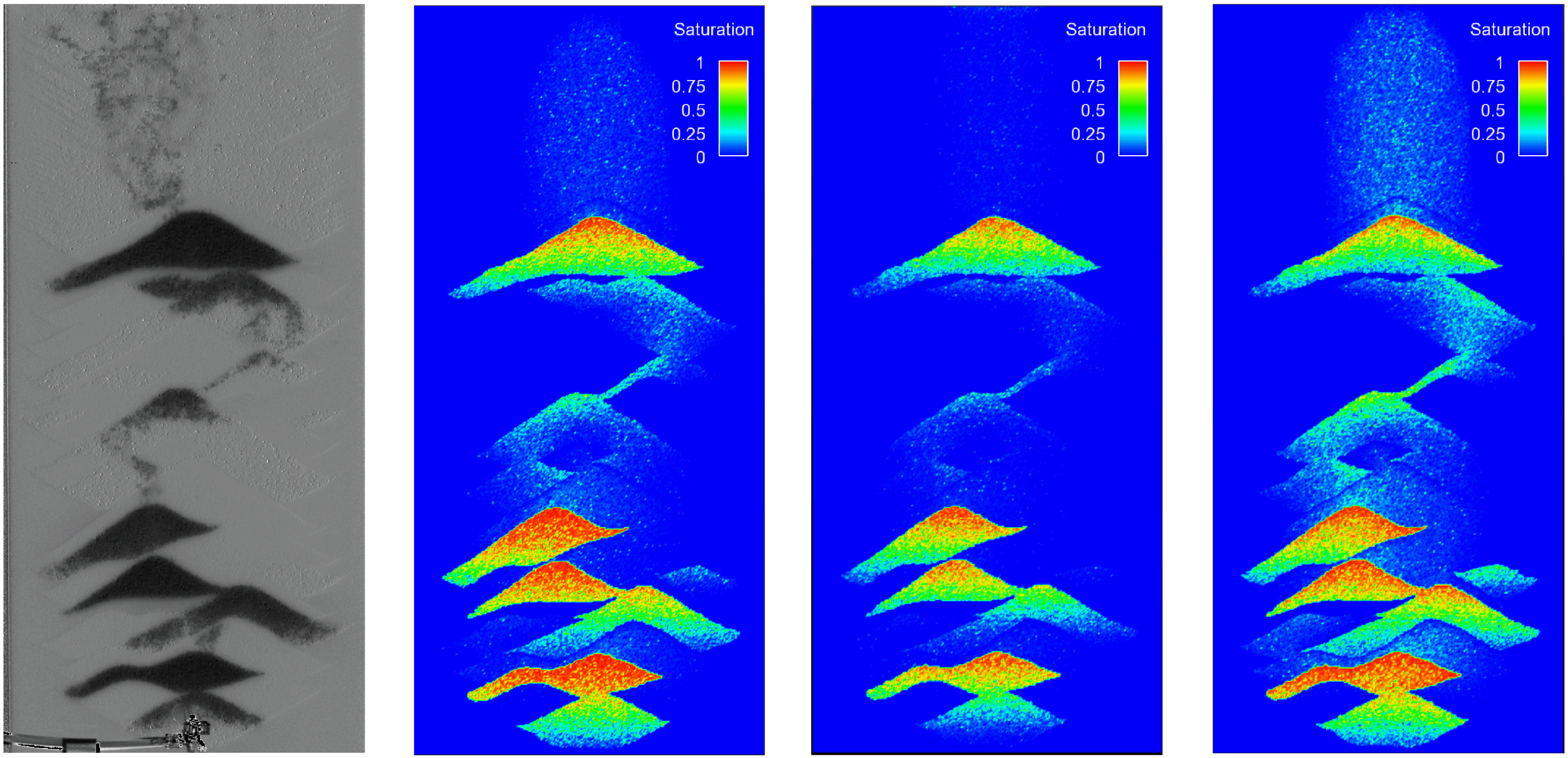


Capillary Pressure Field p_{c0}



Results – Saturation Profiles (Aria)

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



(a) Flow Rate = 1.2 mL/min
Break through time = 42.3 min
Break through vol = 50.8 mL

(b) Flow Rate = 1.0 mL/min
Break through time = 46.4 min
Break through vol = 46.4 mL

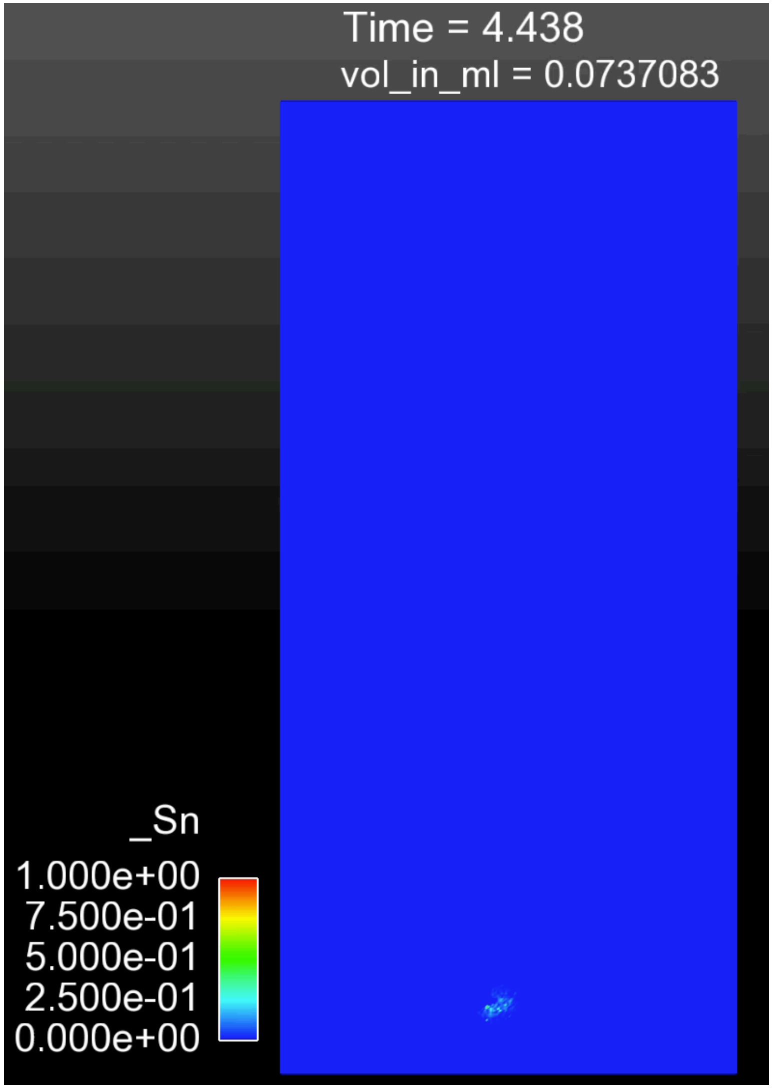
(c) Flow Rate = 0.1 mL/min
Break through time = 296 min
Break through vol = 29.6 mL

(d) Flow Rate = 5.0 mL/min
Break through time = 10.1 min
Break through vol = 50.5 mL

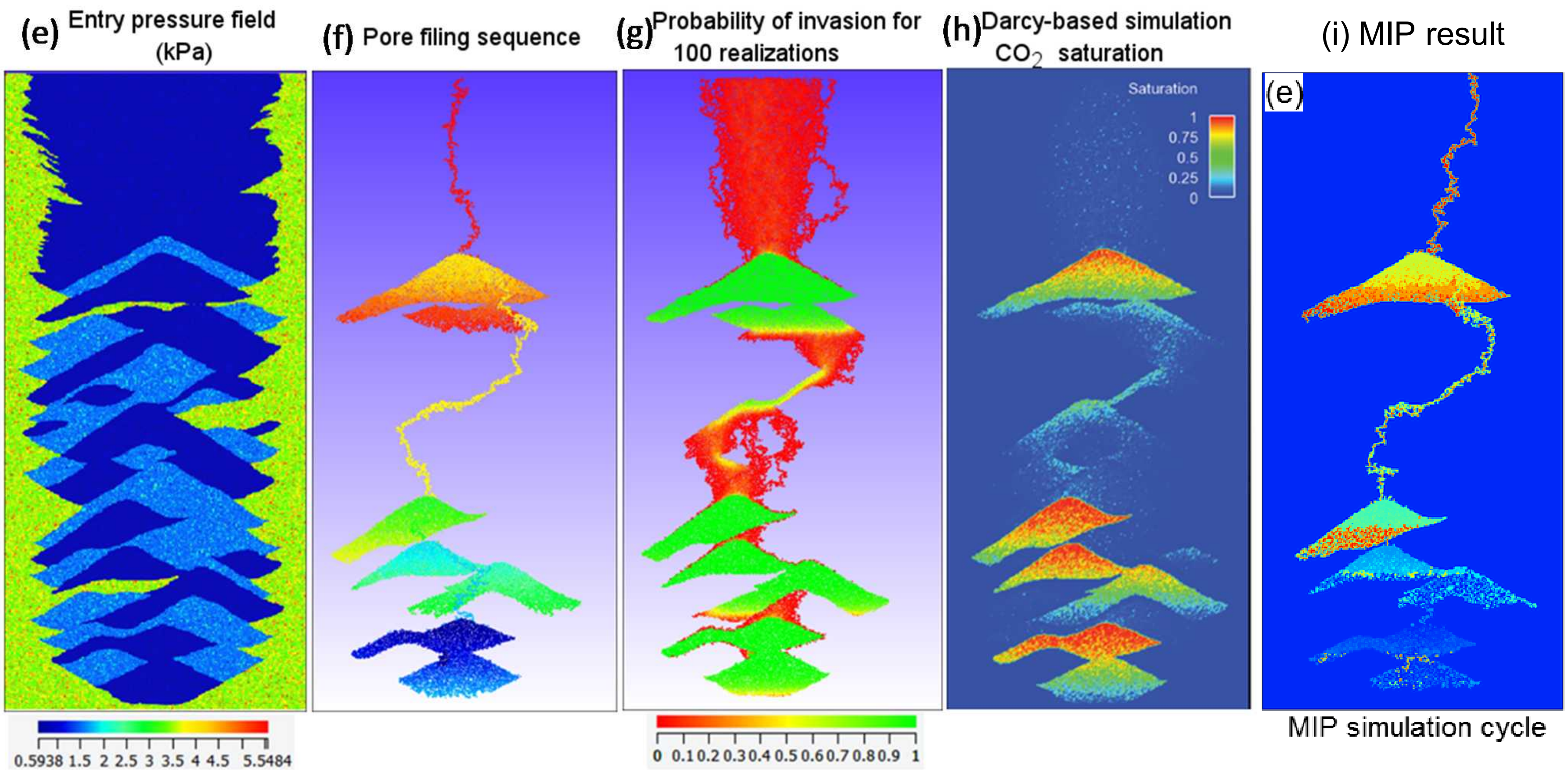
Results – Saturation Profiles (cont.)

Experiment

Simulation (Aria)



Results – IP Simulations



(e) Entry pressure (kPa) field for invasion percolation models corresponding to sand packing architecture shown in (a). A total of 100 realizations are employed. (f) Invasion (pore filling) percolation result in one realization. Cool and hot colors are early and late filling order, respectively. (g) Probability of invasion per each pixel for 100 realizations. (h) CO2 saturation based on Darcy-based continuum model in the random field domain in (e), (i) Modified invasion percolation cycle with cold color for early and warm color for late filling cycles.

Summary & Conclusions

- Modeled the heterogeneous sandbox experiments of Bob Glass
  - Darcy Flow
    - Aria
    - PFLOTRAN
  - Invasion Percolation (IP)

- Good agreement with experiment
  - Breakthrough times
  - Saturation profiles
  - Plume at top of sandbox