Digital image analysis of stress-dependent granular compaction and its impact on multiphase fluid distributions

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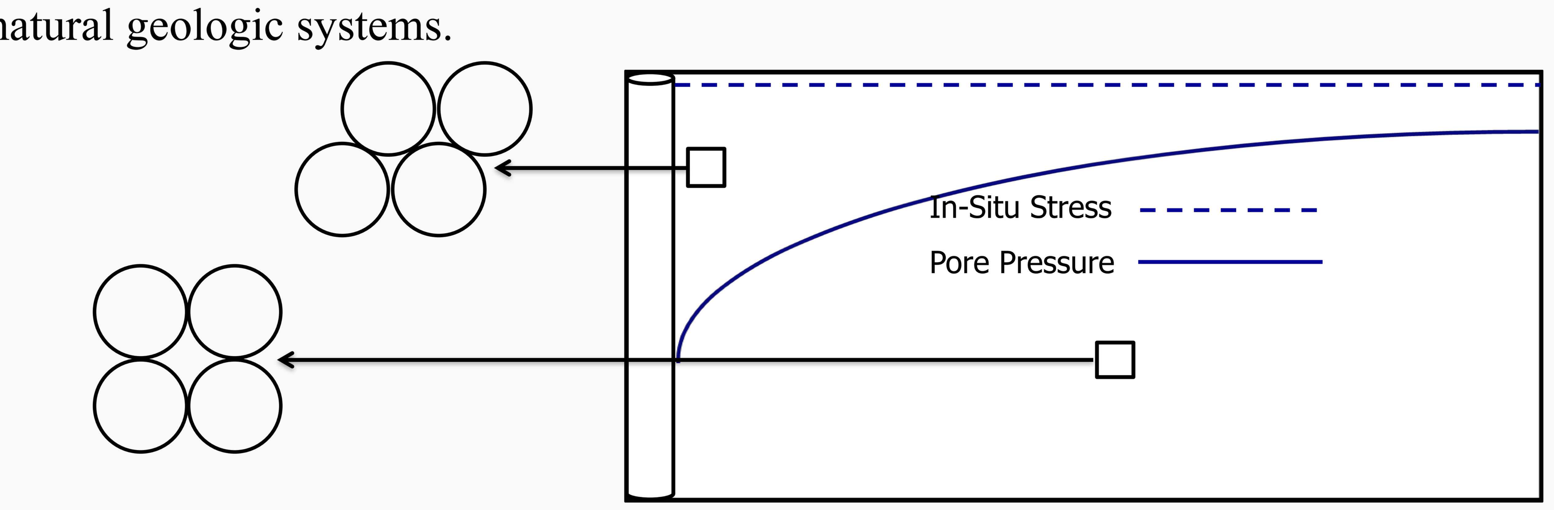
Motivation

- Pore-scale dynamics that govern multiphase flow and distributions under variable stress conditions are not well understood. This lack of fundamental understanding limits our ability to quantitatively predict multiphase flow and fluid distributions in natural geologic systems.

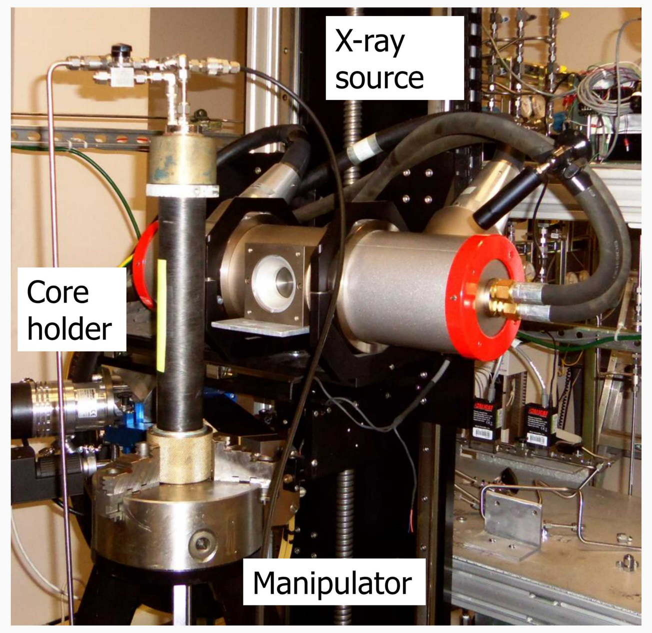


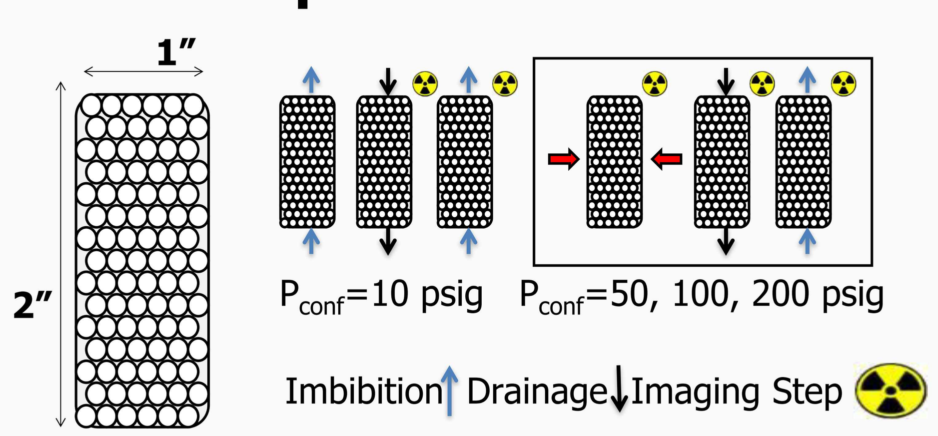
A schematic of pressure profile in a well cross section. Variable effective stress conditions may create different compaction configurations in geologic formations.

Objectives

- Study the impact of varying confining conditions on compaction and its impact on multiphase distribution in porous media using X-ray microtomography (micro-CT)
- Develop a new 3D contact angle algorithm to automatically measure in-situ contact angles and apply the algorithm to multiphase flow experiments imaged by micro-CT under different wettability conditions

Multiphase flow experiments





Soda-lime glass beads (0.75mm)

Wetting phase - 6% w/w NaI solution
Non-wetting phase -kerosene.
The inlet flow rate ~ a 2ml/min.

Voxel resolution: ~28.8^3 μm^3

Permeability (k) and Tortuosity (τ) Estimations

▶ **Lattice Boltzmann simulations with segmented data**

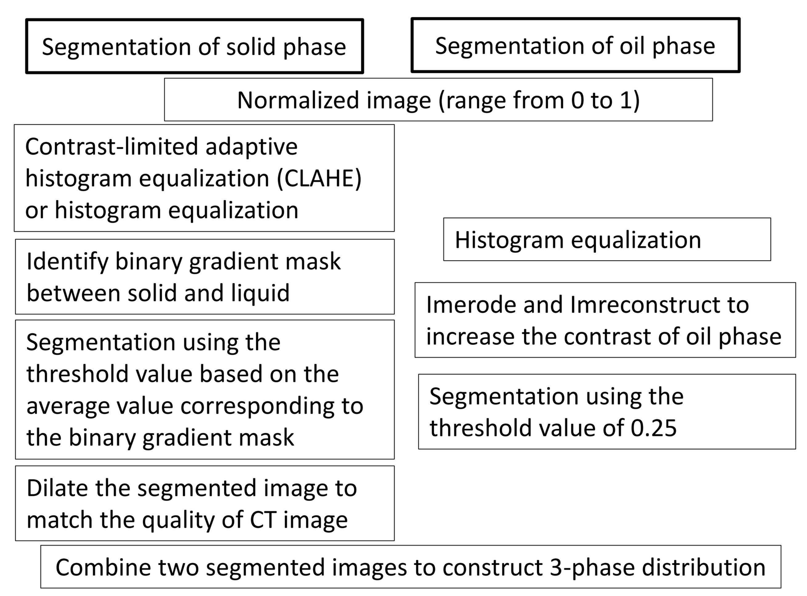
- LB solver (Palabos, 2013) with a 3-D, 19 velocity (D3Q19) model & multiple relaxation time (MRT)
- Segmented image stack to establish internal boundaries (walls of porous medium) where simple bounce-back boundary conditions were used
- Fixed pressure at inlet and outlet boundaries and no flux over the rest of boundaries

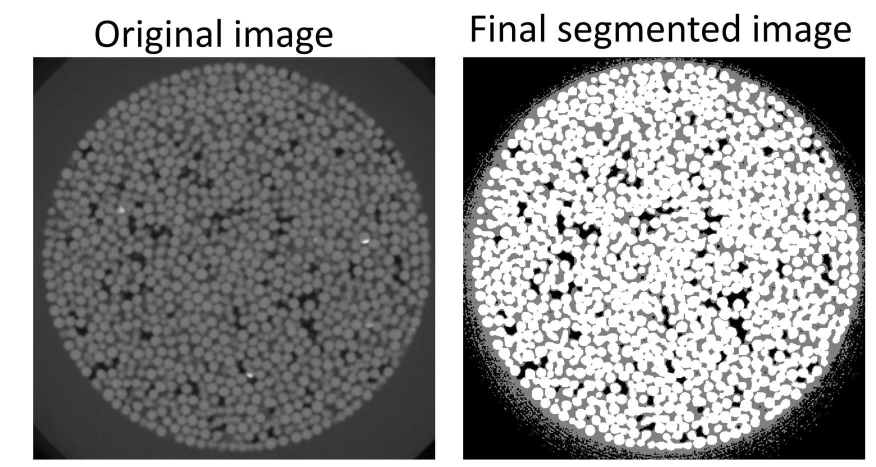
▸ **Permeability & tortuosity** (Darcy's law under the laminar flow regime)

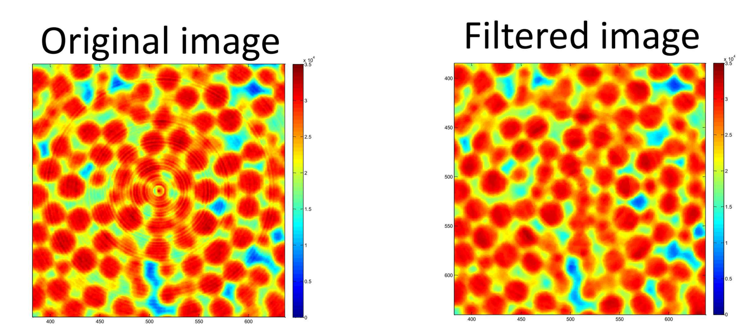
$$k = \frac{U\mu L}{\Delta P}, \tau = \frac{\langle|\mathbf{v}|\rangle}{\langle v_x\rangle}$$

- U = average velocity; μ = fluid viscosity (=$\rho\nu$)
- L = length in the main flow dir.; ΔP = pressure gradient
- $|\mathbf{v}|$= absolute value of the local flow velocity
- v_x = velocity in the main flow direction
- < > = spatial average over the sample volume

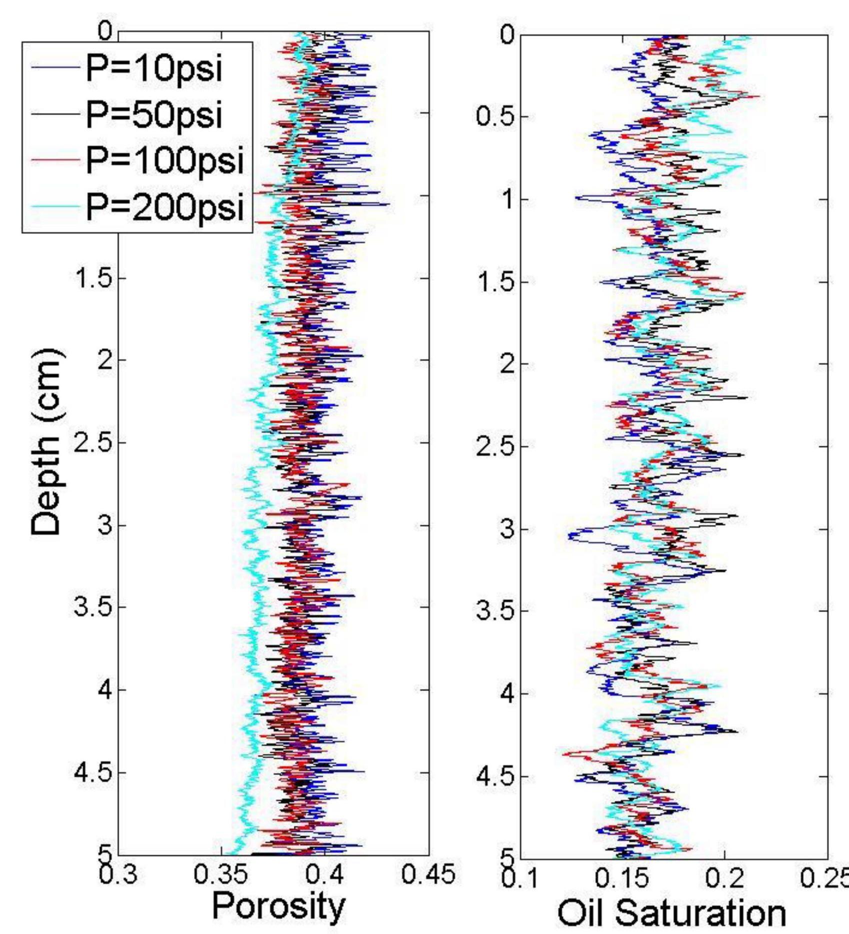
Image Analysis and Granular Compaction



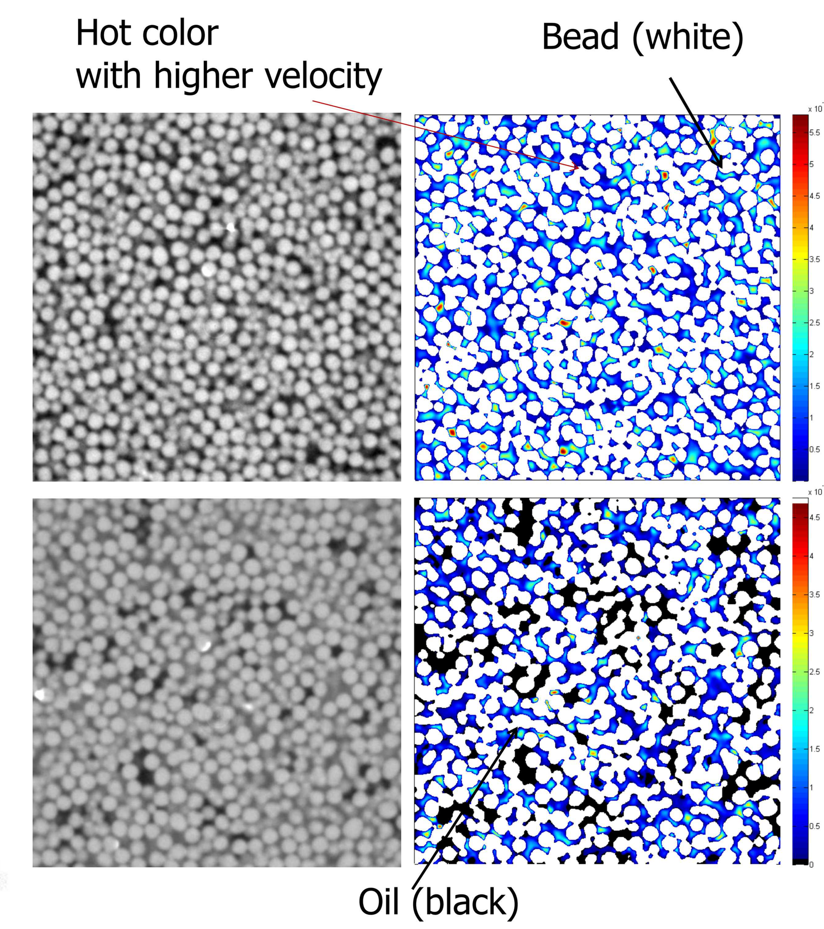




- Ring artifact removal – Wavelet-FFT filtering followed by additional filtering (median, convolution, sharpening filters)



- Porosity and oil saturation profiles along the column depth under different confining pressures (10psi to 200psi)



- CT images (left) and cross-sectional velocity fields with segmented data (right) after single-phase brine injection (top) and the first imbibition of multiphase cycles (bottom)

- Major Achievement

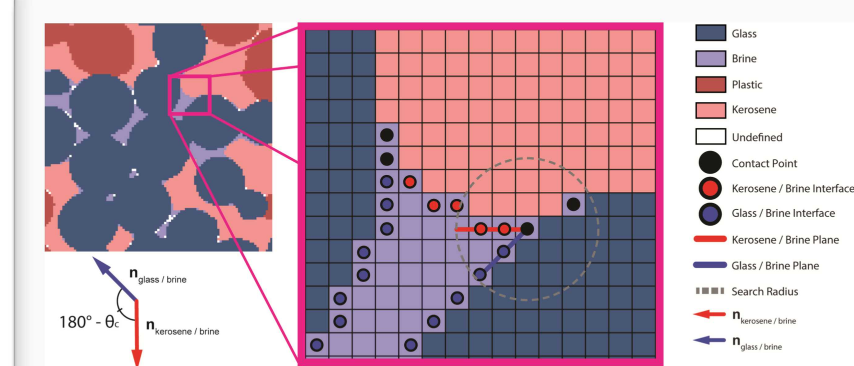
Observing multiphase flow at the pore scale reveals the effects of wettability and confining pressure on sweep efficiency and residual oil and water distributions in porous materials

- Significance and Impact

Different wettabilities lead to different displacement mechanisms at the pore scale, resulting in different contact angles. Understanding residual trapping in reservoirs under varying confining pressures has significant implications for emerging geoscience problems (CO_2 sequestration, EOR)

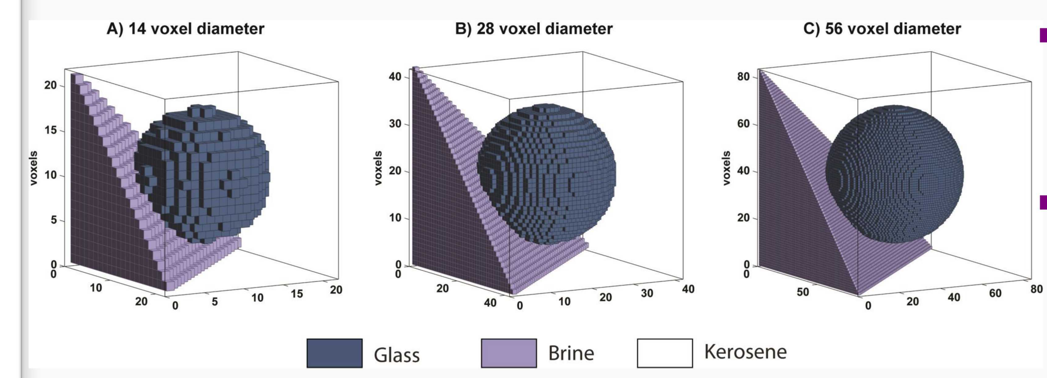
- Research Details
  - X-ray microtomography (CT) reveals pore-level details of wettability and the distribution of oil and water phases after imbibition and drainage
  - In four different wettability conditions, in-situ contact angle hysteresis was observed using a newly developed 3-D contact angle analysis algorithm
  - A notable compaction is observed by porosity change at 200 psi and residual oil saturation becomes more homogeneous after multiple drainage and imbibition cycles

Automated 3-D Contact Angle Analysis

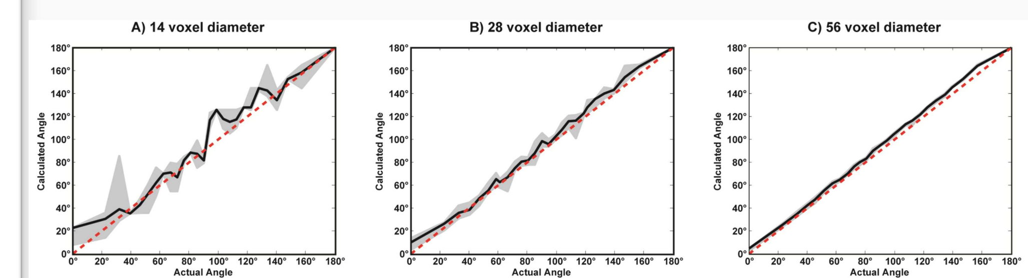


1. Define the interface along with contact points
2. Fit a plane to each interface within a search volume (SV: a sphere with a radius of 3 voxels)
3. Compute contact angle by taking dot product of the normal vectors to each plane

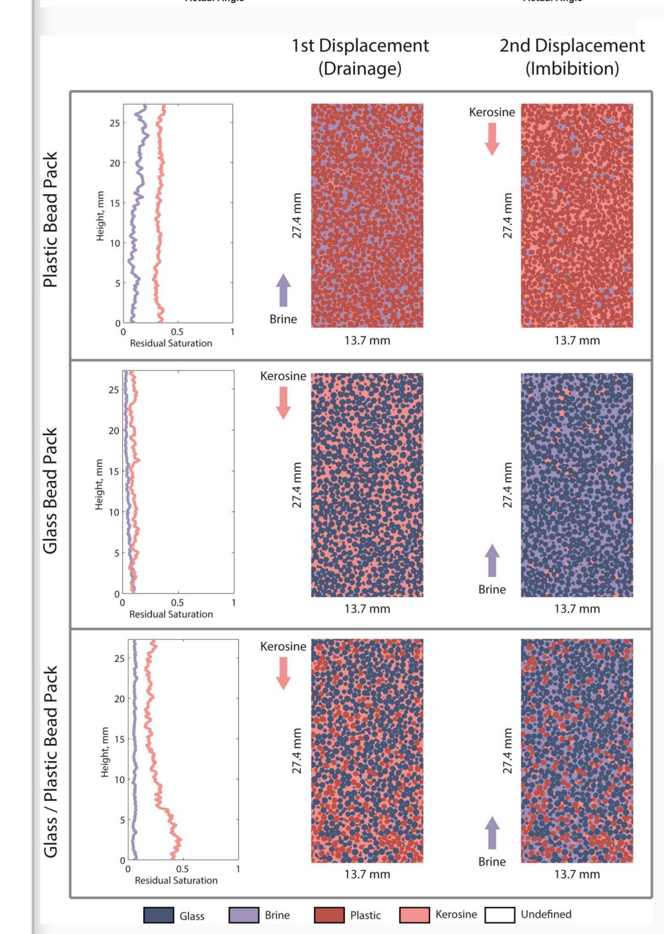
- Two-dimensional view of interface identification, contact points and contact angle calculation

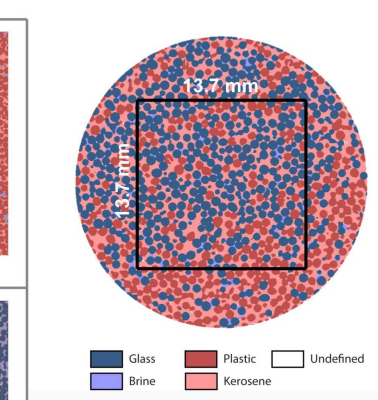


- Test cases with spherical bead at three different voxel resolutions: 14, 28, 56 voxel diameters.
- Diagonal plane represents the brine phase, at a theoretical contact angle of approximately 160°

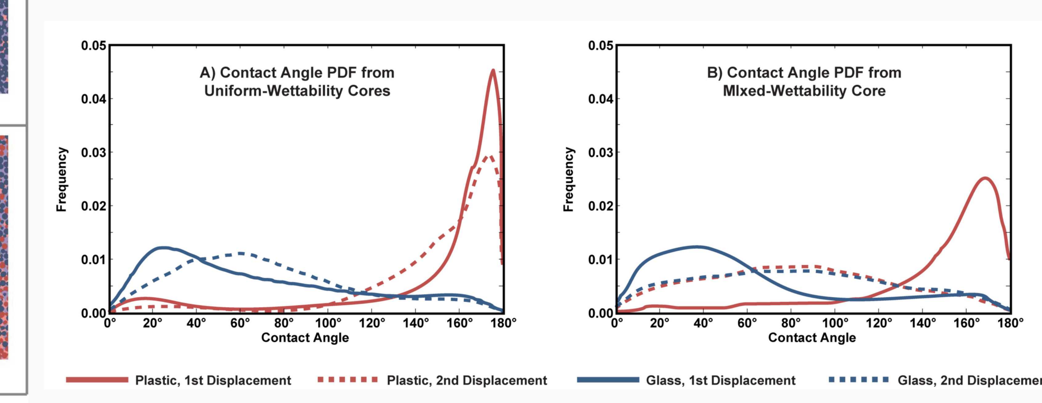


- Theoretical contact angle compared to the calculated contact angle.
- Mean contact angle – black line
- STD - gray region.





- Residual saturations and vertical cross-sections for each bead pack..
- The displacement direction is represented by arrows to the left of each cross-section
- Modified from Celauro et al. (2014)



- Uniform wetting

Bead Type	Plastic		Glass	
Displacement	1st	2nd	1st	2nd
Contact Points	2.95×10^6	2.84×10^5	9.05×10^5	3.94×10^5
Invalid Points	1.72×10^6	1.42×10^5	5.84×10^5	1.16×10^5
Contact Angles	1.22×10^6	1.42×10^5	3.22×10^5	2.78×10^5
75th Percentile	173.2°	170.3°	97.1°	95.5°
50th Percentile	165.1°	158.6°	54.8°	66.0°
25th Percentile	141.5°	139.1°	29.2°	42.4°
Average	144.8°	148.4°	66.6°	72.1°
Standard Dev.	46.4°	33.5°	45.5°	39.4°
Mode	176°	175°	22°	60°

- Mixed wetting

Bead Type	Plastic		Glass	
Displacement	1st	2nd	1st	2nd
Contact Points	1.49×10^4	2.23×10^5	1.45×10^6	3.53×10^5
Invalid Points	1.30×10^4	3.66×10^4	1.18×10^6	5.64×10^4
Contact Angles	1.95×10^3	1.87×10^5	2.75×10^5	2.97×10^5
75th Percentile	169.5°	114.0°	88.3°	116.0°
50th Percentile	159.1°	82.1°	50.1°	81.4°
25th Percentile	136.5°	50.9°	29.2°	47.9°
Average	144.7°	83.3°	63.8°	83.1°
Standard Dev.	37.4°	41.9°	45.9°	44.1°
Mode	171°	90°	37°	90°

Publications

- V. A. Torrealba, Z.T. Karpyn, Yoon, H., K. Klise, and D. Crandall (2014, in review, Geofluids), Pore-scale investigation on stress-dependent characteristics of granular packs and the impact of pore deformation on fluid distribution
- J. G. Celauro, V. A. Torrealba , Z. T. Karpyn, K. A. Klise, S. A. McKenna (2014). Pore-Scale Multiphase Flow Experiments in Bead Packs of Variable Wettability. Geofluids.
- Palabos (2013), PArallel LAttice BOltzmann Solver, www.palabos.org
- Klise, K. D. Moriarty, H. Yoon, and Z. Karpyn (2014, in review, AWR), Automated contact angle estimation for three-dimensional X-ray microtomography data

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