CO_2 Migration and Trapping in Heterogeneous Porous Media

Prasanna G. Krishnamurthy
Tip Meckel
David DiCarlo

UTCCS-5

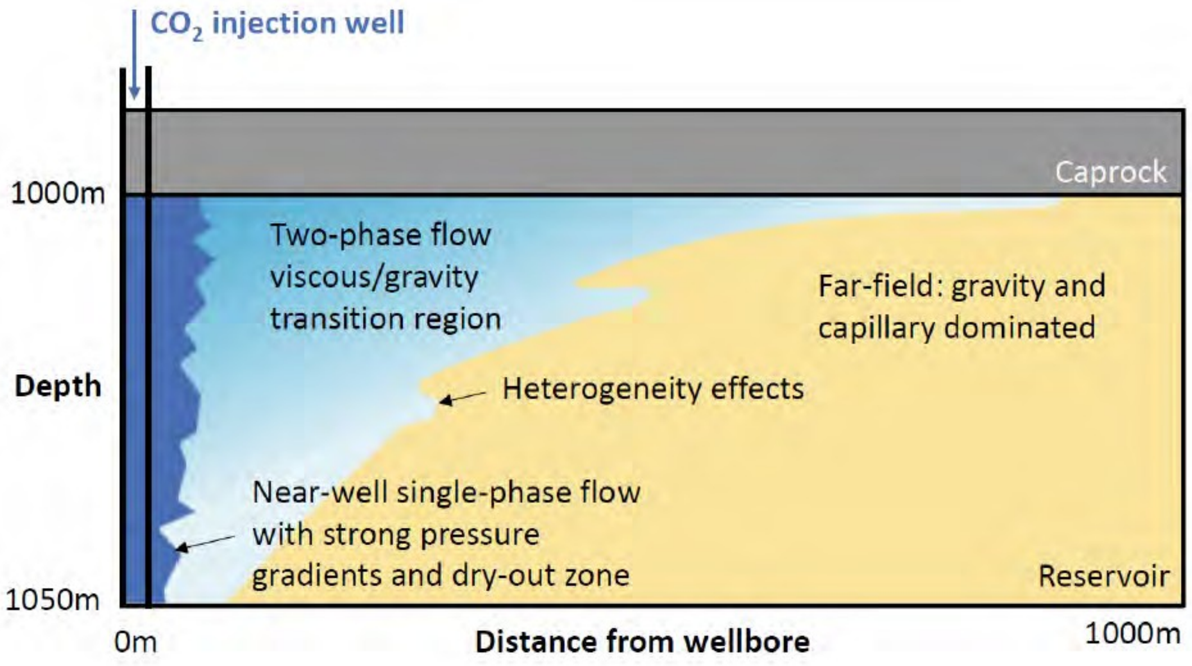
29th January 2020

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

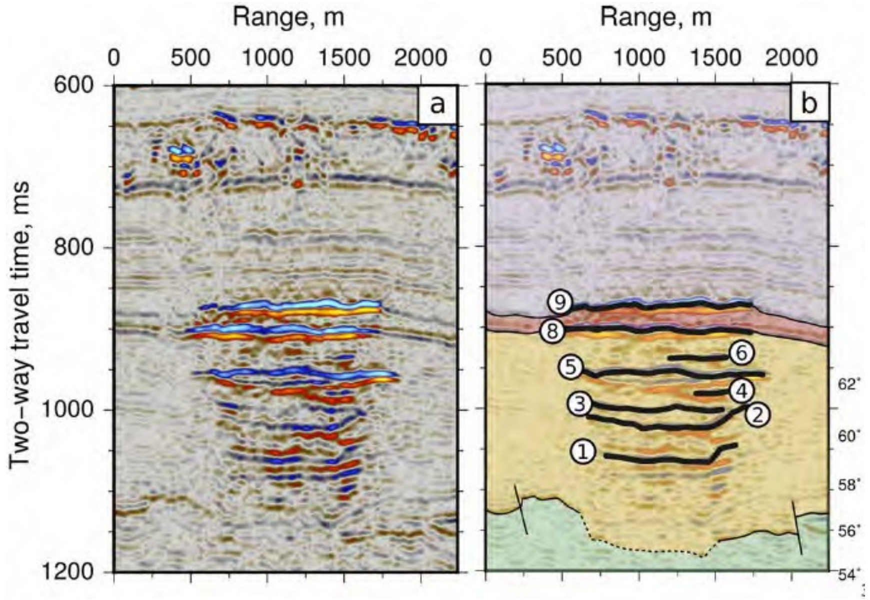
CFSES
CENTER FOR FRONTIERS OF SUBSURFACE ENERGY SECURITY

BUREAU OF ECONOMIC GEOLOGY

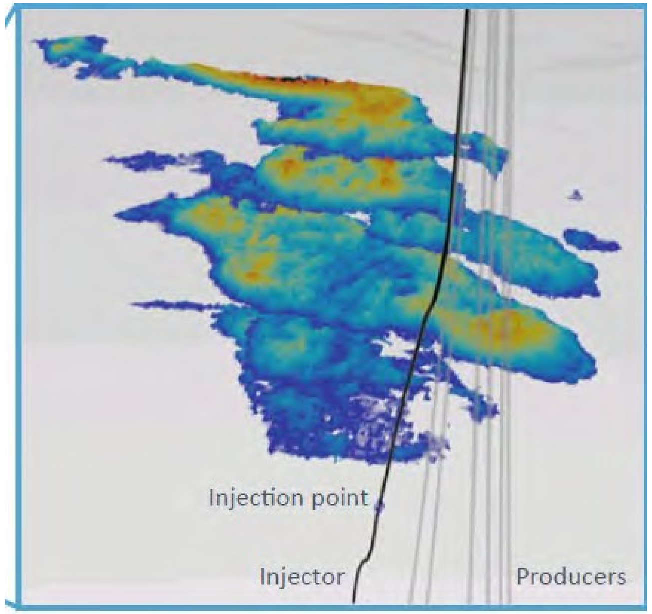
Problem Conceptualization



Ringrose 2020



Cowton et al. 2018



Ringrose 2020

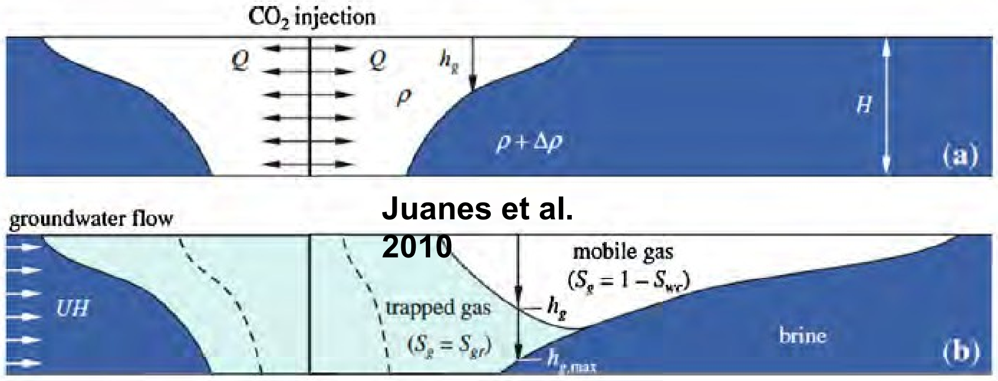
Sub-meter scale barriers can determine migration pathways and speed of plume movement

WHAT SATURATIONS?

Implications for: capacity, monitoring, imaging.

Expected Outcomes

Trapping Capacity Prediction

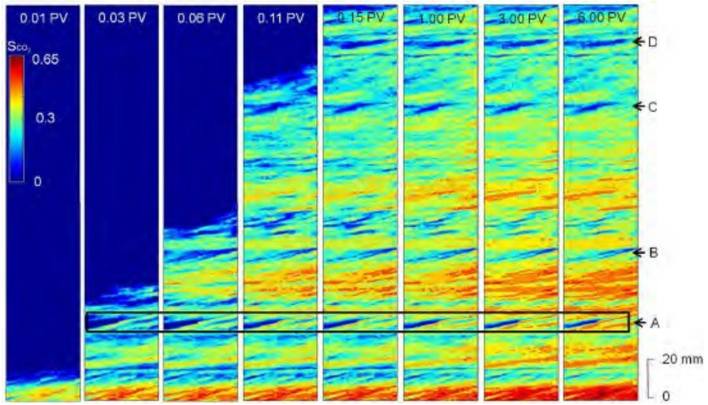


Juanes et al. 2010

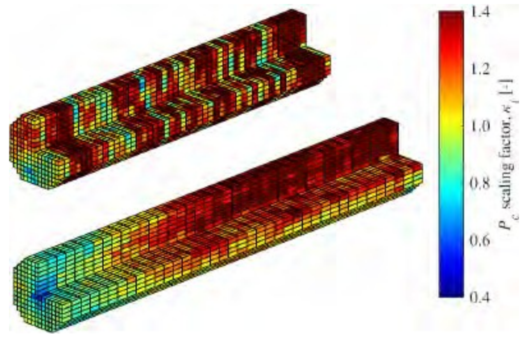
$$E_{saline} = E_{An/At}\, E_{hn/hg}\, E_{\phi e/\phi tot}\, E_A\, E_L\, E_g\, E_d$$

USGS 2010

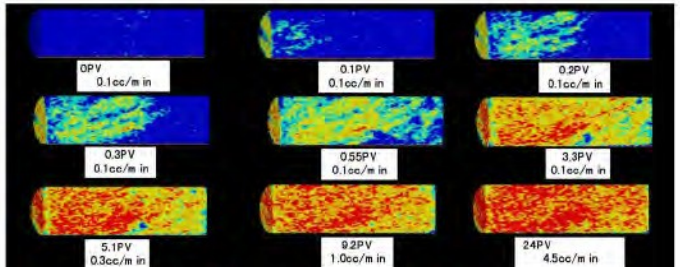
Visualizing Flow through Heterogeneous Media



Oh et al. 2015

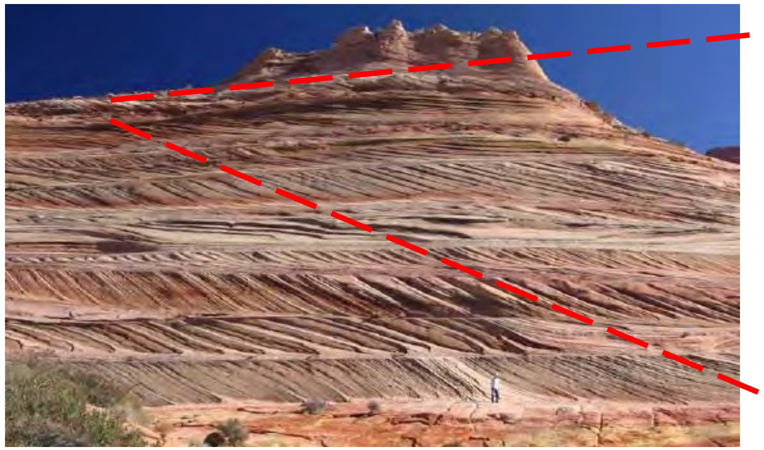


Jackson et al. 2018



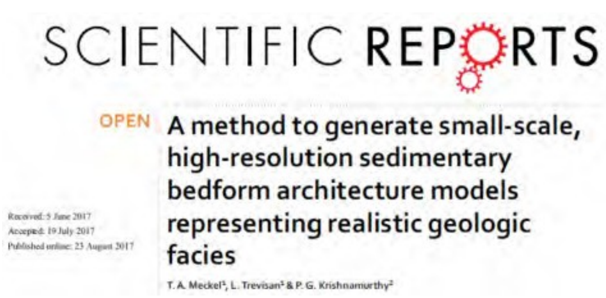
Shi et al. 2011

Flow Visualization and Saturation Prediction at Intermediate scales (sub meter)



Can we use sedimentological descriptors to predict saturations?

High Resolution Realistic Geological Models


SCIENTIFIC REPORTS

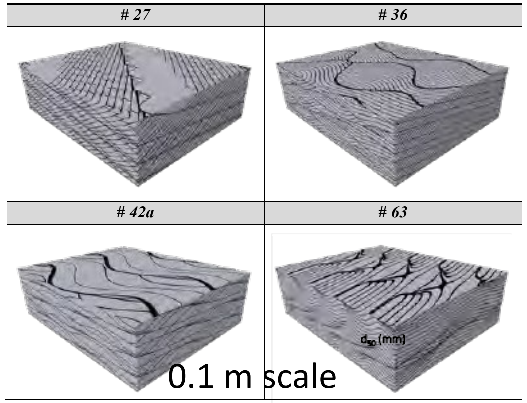
OPEN A method to generate small-scale, high-resolution sedimentary bedform architecture models representing realistic geologic facies

Received: 5 June 2017
Accepted: 19 July 2017
Published online: 23 August 2017

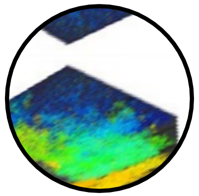
T. A. Meckel, L. Trevisan & P. G. Krishnamurthy

8 fluvial sedimentary models

Based on Rubin & Carter, 2006



0.1 m scale



IP


ELSEVIER

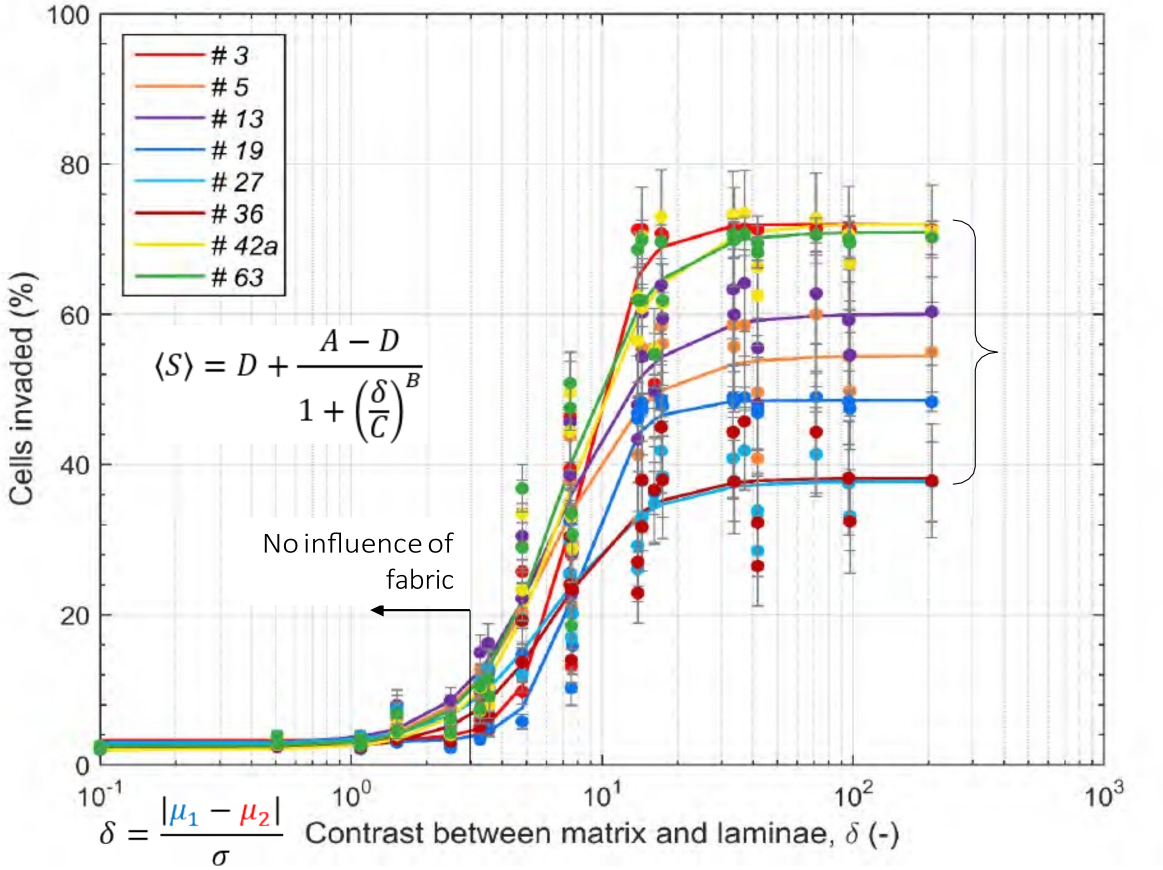
International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Impact of 3D capillary heterogeneity and bedform architecture at the sub-meter scale on CO_2 saturation for buoyant flow in clastic aquifers

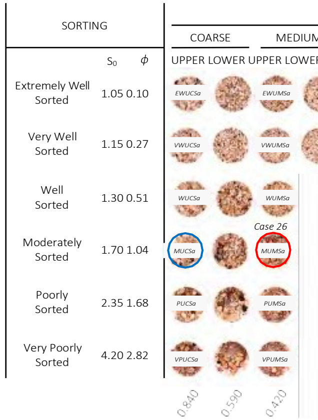
L. Trevisan[a,*], P.G. Krishnamurthy[b], T.A. Meckel[a]

[a] Gulf Coast Carbon Center, Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX, USA
[b] Petroleum and Geosystems Engineering Department, The University of Texas at Austin, Austin, TX, USA



$$\langle S \rangle = D + \frac{A - D}{1 + \left(\frac{\delta}{C}\right)^B}$$

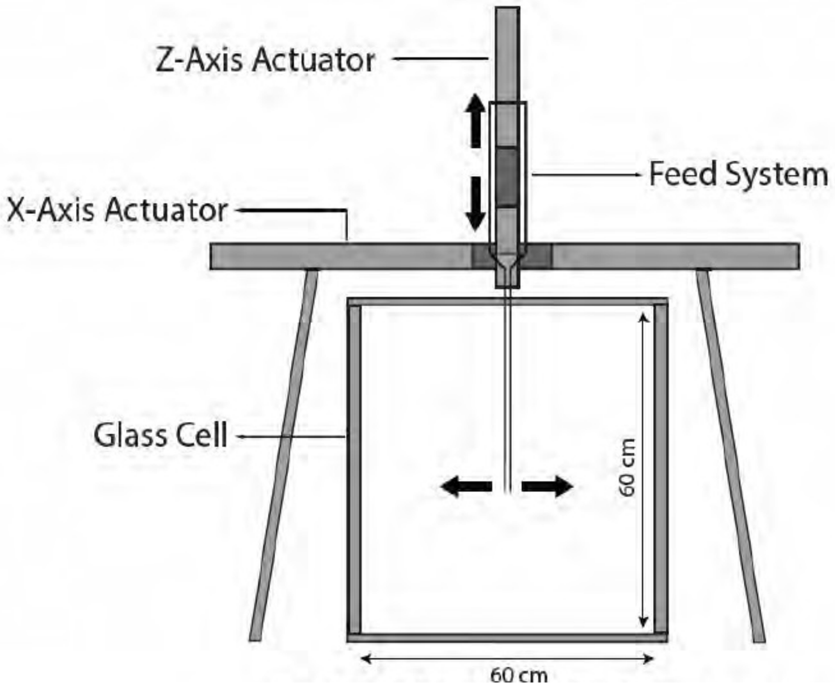
$$\delta = \frac{|\mu_1 - \mu_2|}{\sigma}$$



CAN WE TRUST THESE PREDICTIONS?

Fabric
control, D

Engineering Heterogeneity: Geologic fabrics



Glass Cell and Automated Sand filler System

Engineering Heterogeneity : Geologic fabrics

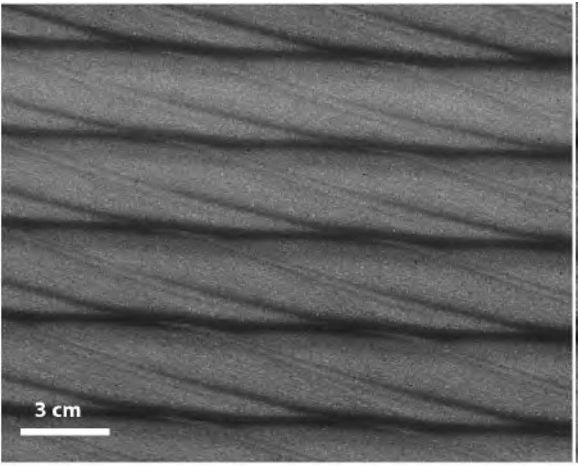
Water Resources Research

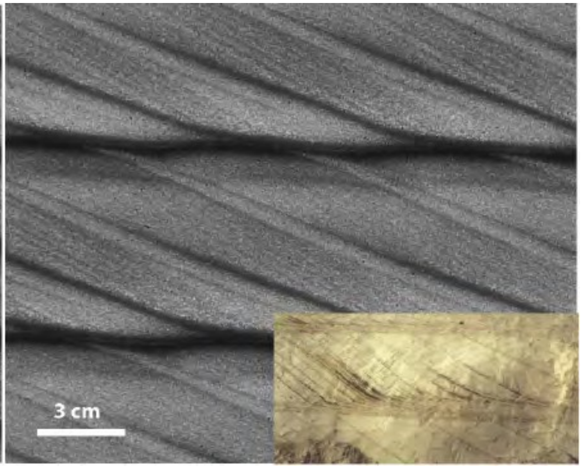
RESEARCH ARTICLE
10.1029/2019WR025664

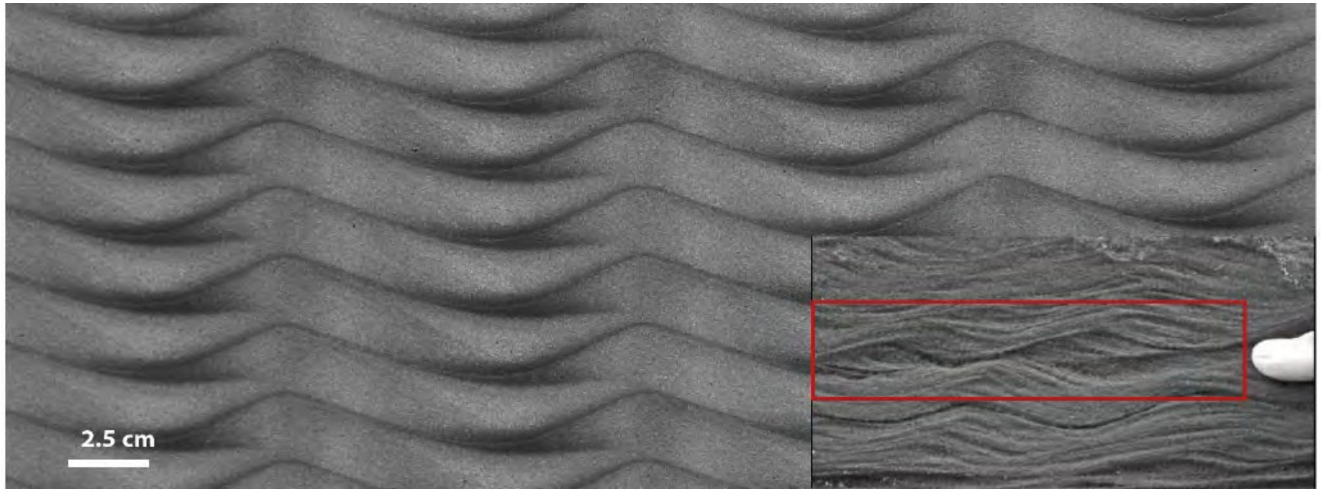
Key Points:
- We present a methodology to reproducibly generate beadpacks

Mimicking Geologic Depositional Fabrics for Multiphase Flow Experiments

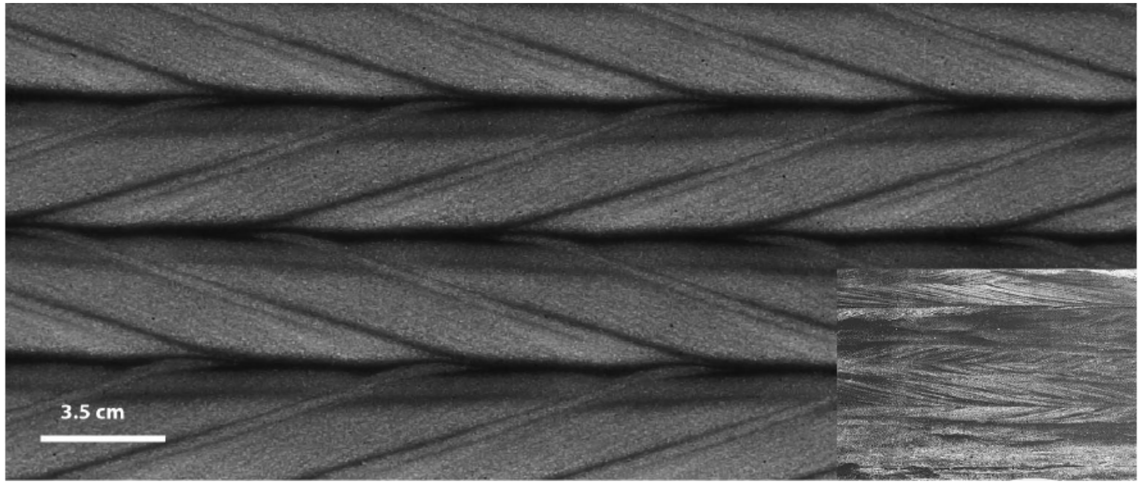
Prasanna G. Krishnamurthy[1], Tip A. Meckel[2], and David DiCarlo[1]

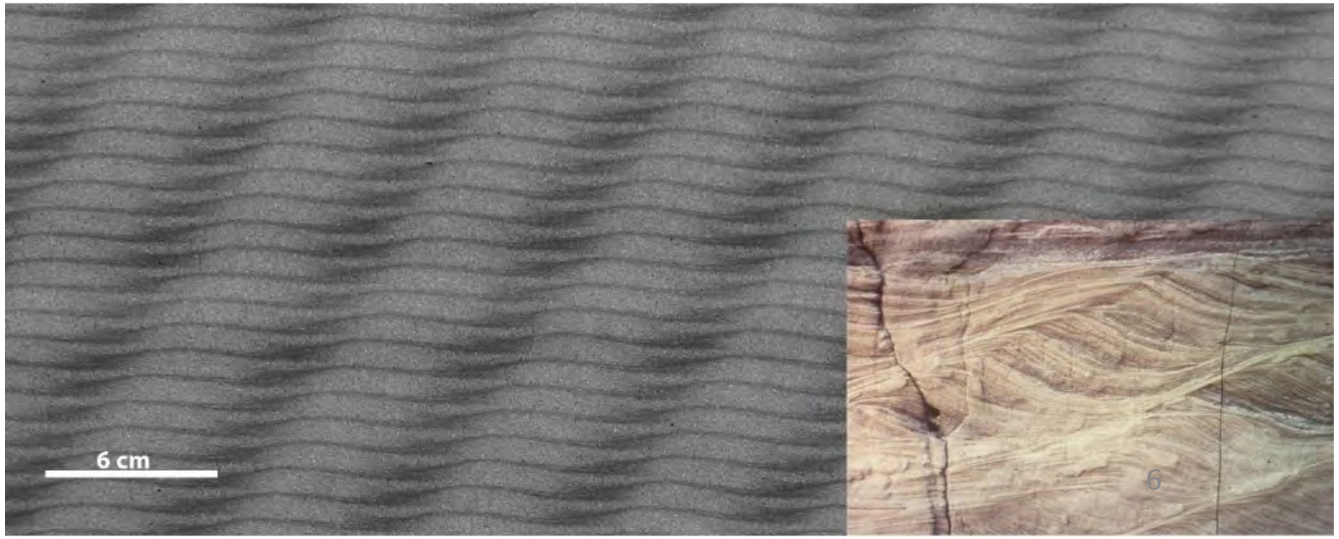




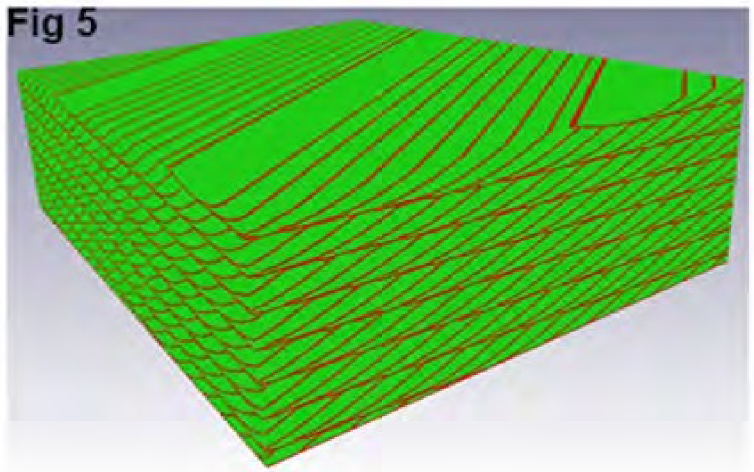


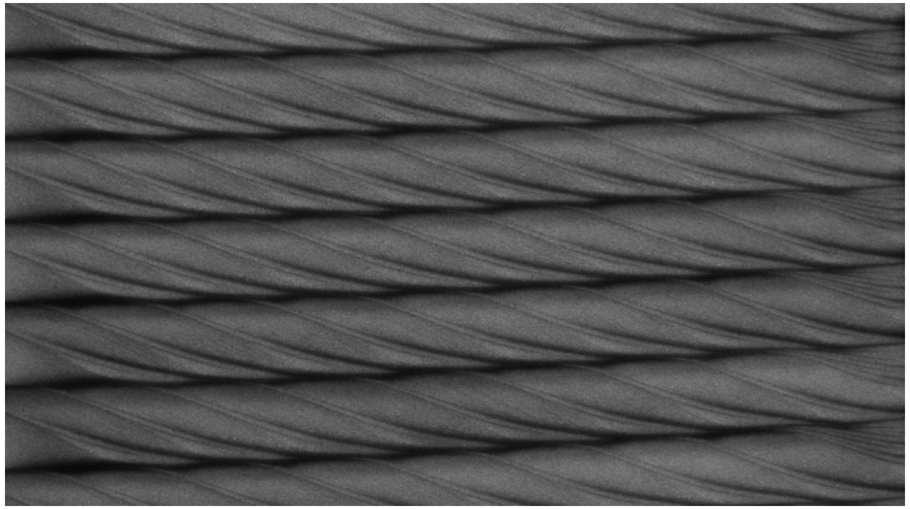
Insets show images of actual outcrops for comparison

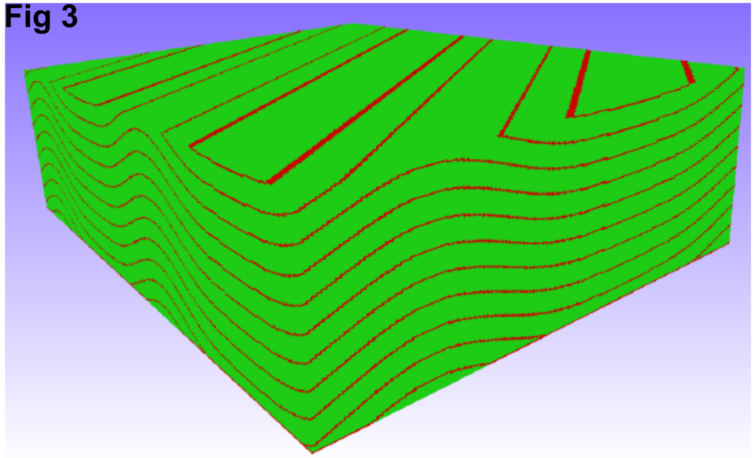


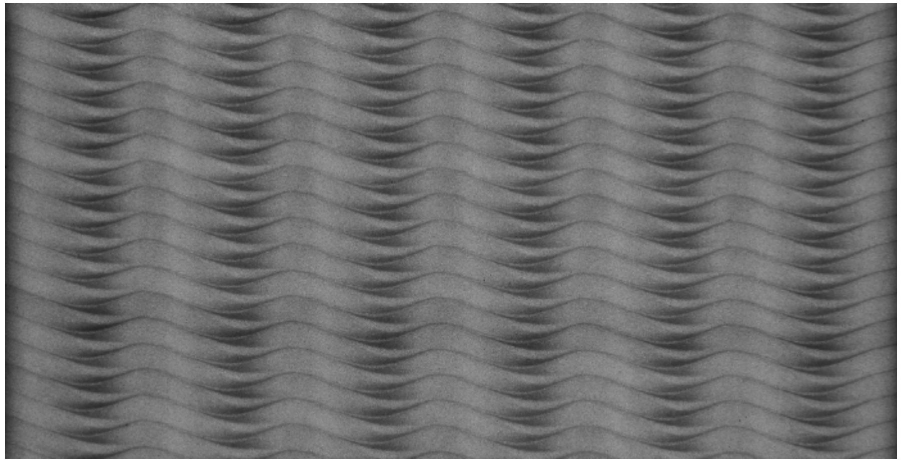


Engineering Heterogeneity





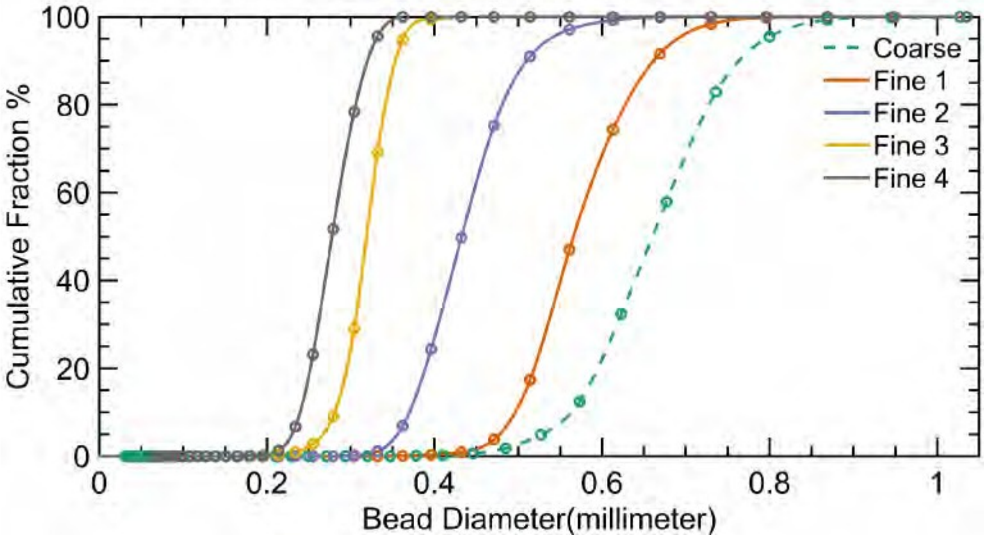


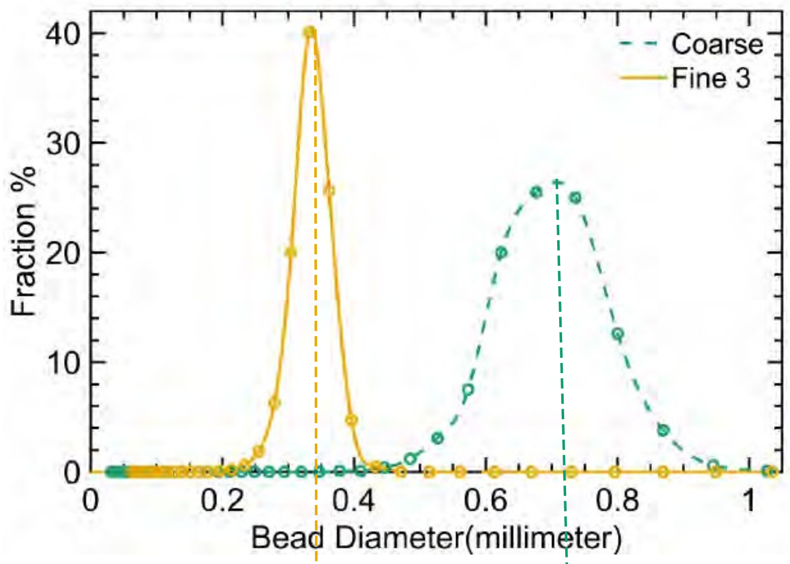


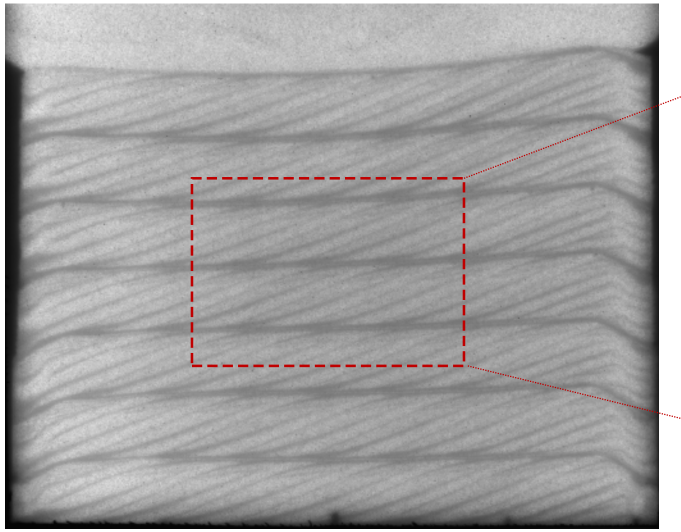
The automated filling system allows us to conduct experiments analogous to our simulations

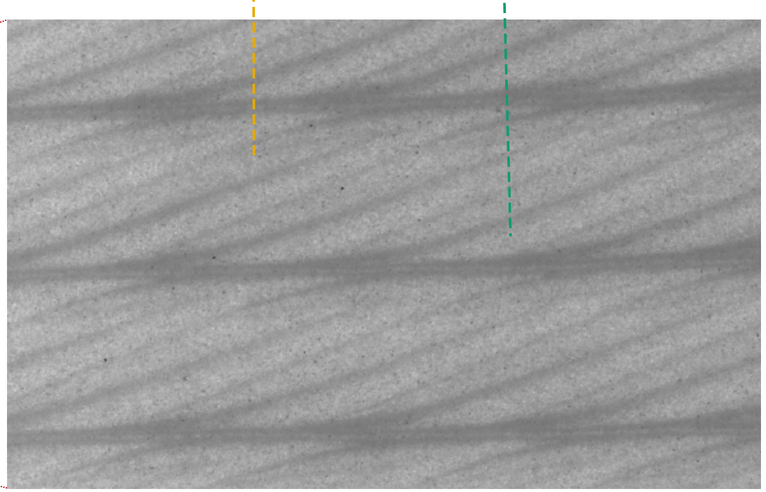
Engineering Heterogeneity: Grain Sizes

Coarse fraction size remains constant while the fine varies

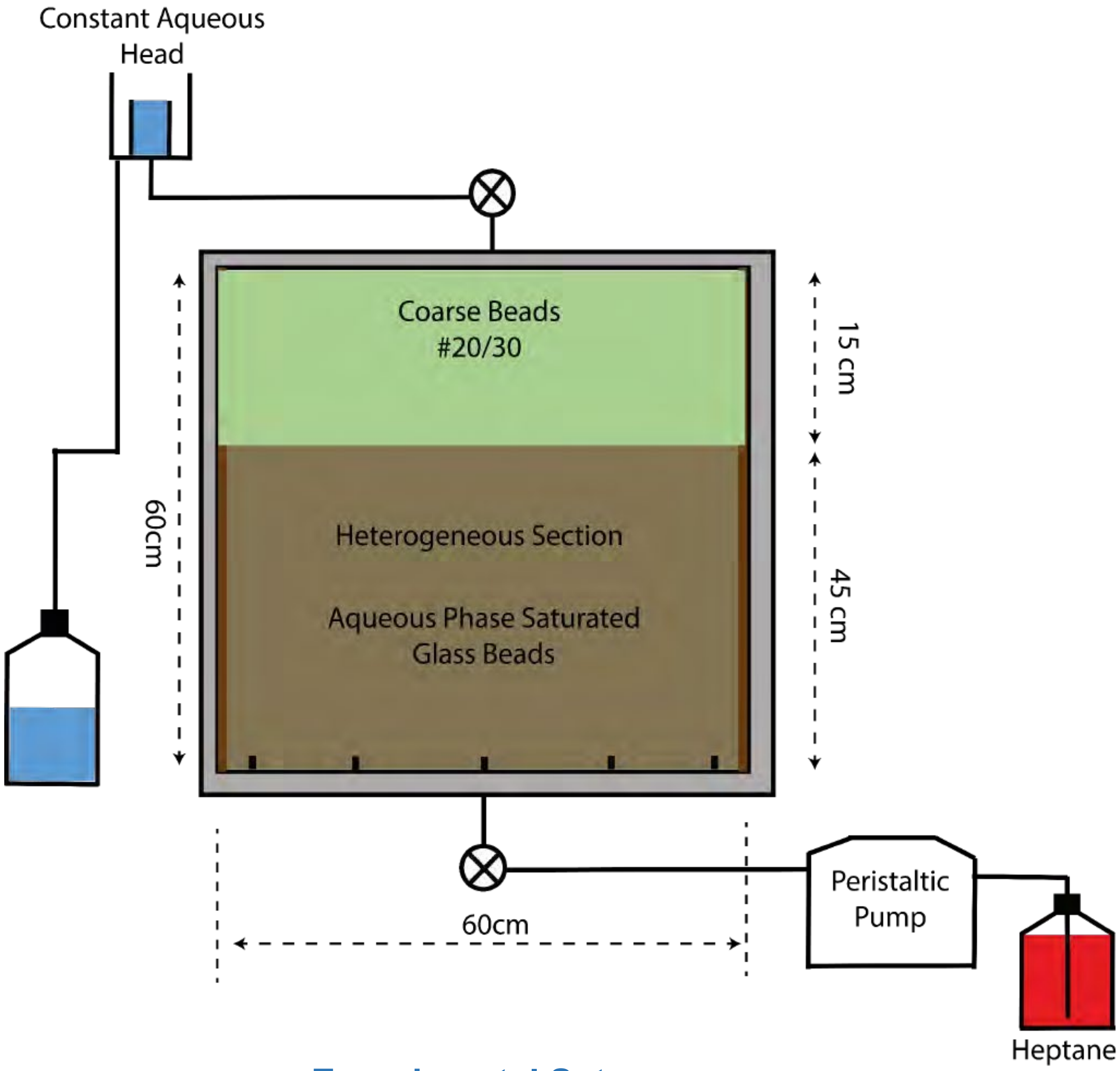








Multiphase Flow Experiments



Experimental Setup

Fluid Properties

	Viscosity (cP)	Density (kg/m3)
Heptane (Non wetting)	0.41	684
Glycerol+ Ultrapure Water (Wetting) (50:50 w/w)	6.25	1115
Viscosity Ratio M (μl/μd)		0.065
Δrho kg/m3		431
IFT mN/m		36

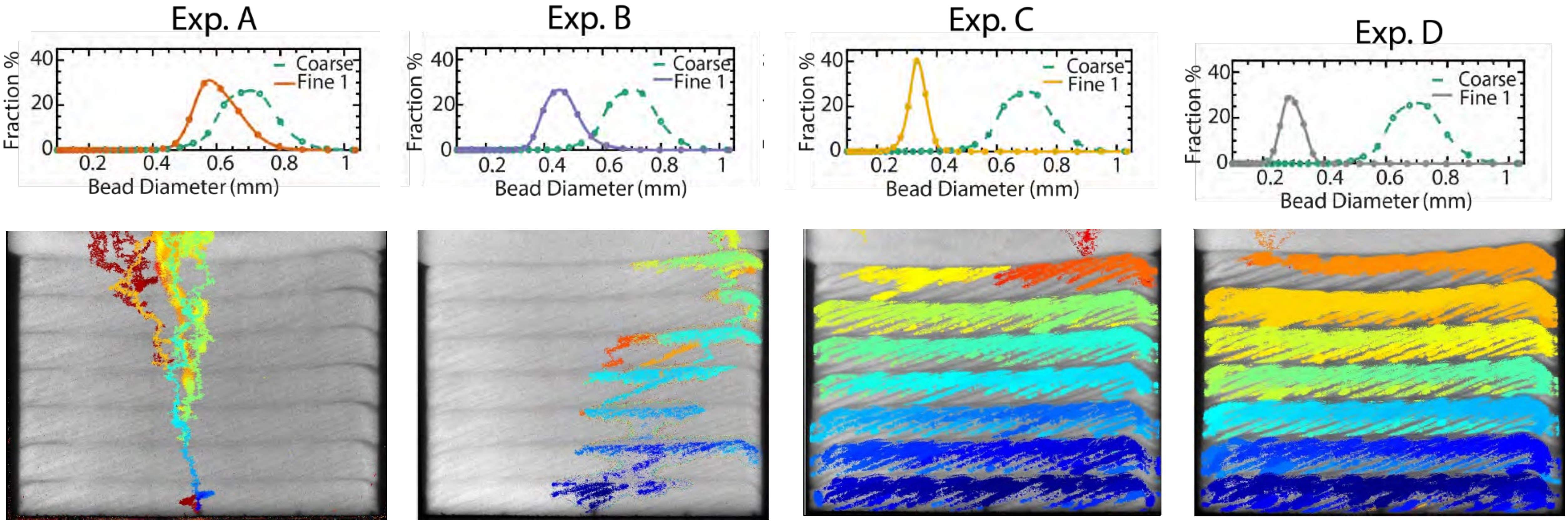
Reservoir Conditions

	Cold shallow	Cold deep	Warm shallow	Warm deep
Temperature (°C)	35	85	65	155
Pressure (MPa)	10.5	31.5	10.5	31.5
Density of CO_2 (kg/m^3)	714	733	266	479
Density of brine (kg/m^3)	1121	1099	1104	1045
Viscosity of CO_2 (mPa.s)	0.0577	0.0611	0.0395	0.0395
Viscosity of brine (mPa.s)	1.19	0.511	0.687	0.254
Density difference (kg/m^3)	407	366	838	566
Viscosity ratio	0.0485	0.1196	0.0575	0.1555

Nordbotten et.al 2005

Buoyant Flow Dynamics

Heterogeneity effects on invasion patterns

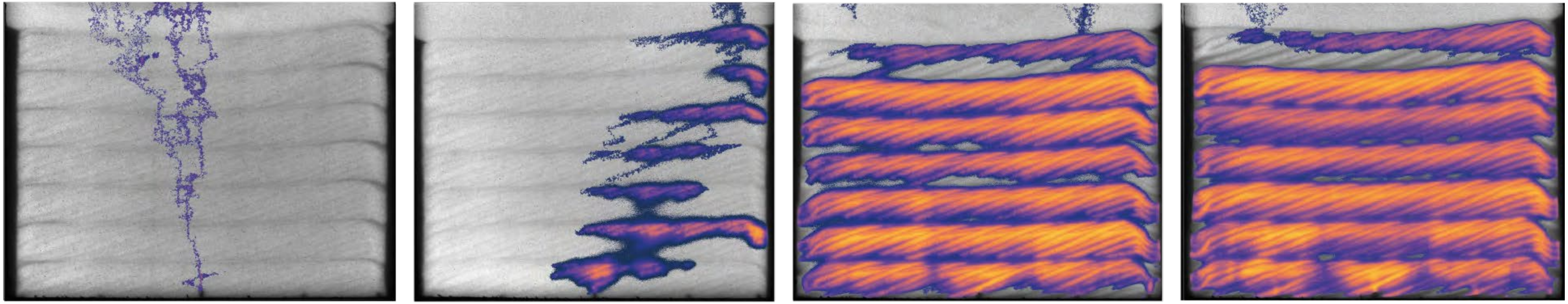


6.5 min | 273 min ~4.5 hrs | 2665 min ~ 44 hrs | 3336 min~55 hrs

Capillary entry pressure contrast varies from 50 to 350 Pa

Orientation of the laminae dictates vertical flow direction

How much of the CO_2 eventually escapes?



S_{NWP}= 0.2%%

S_{NWP}= 2.84%

S_{NWP}= 28.5%

S_{NWP}= 26.8%

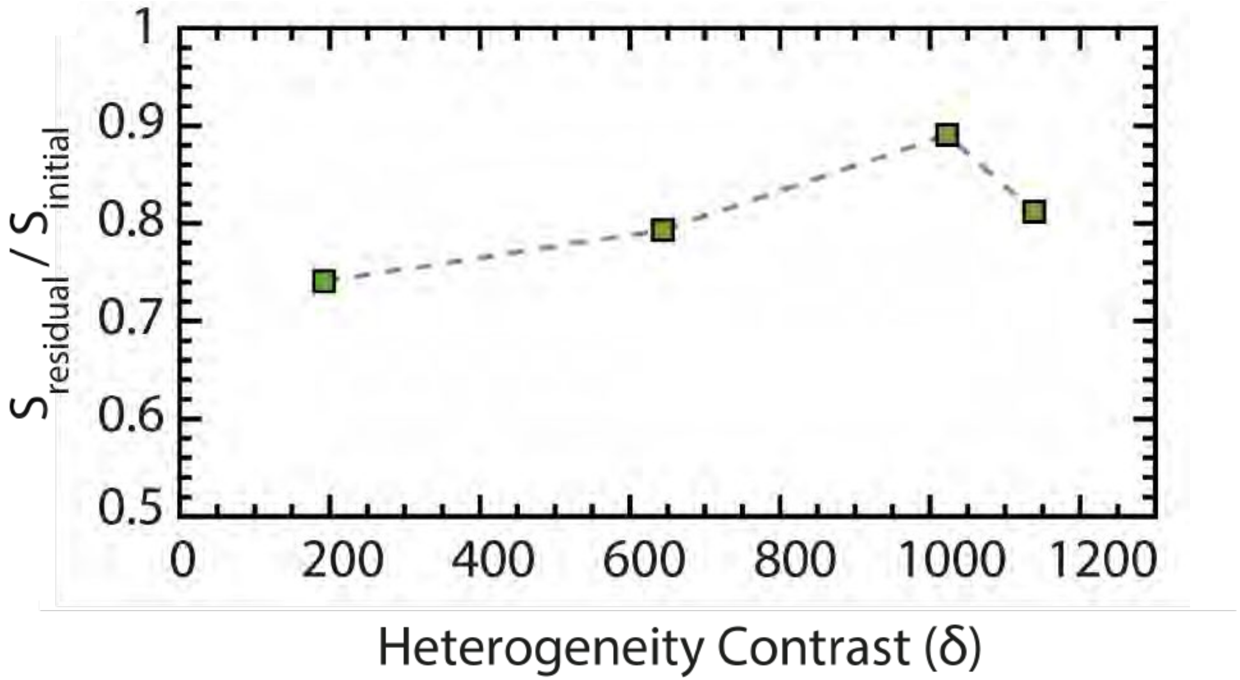
NWP displaced during gravity driven redistribution (Imbibition)

End of Drainage

With increasing heterogeneity contrast and initial saturation, more CO_2 leaves the system

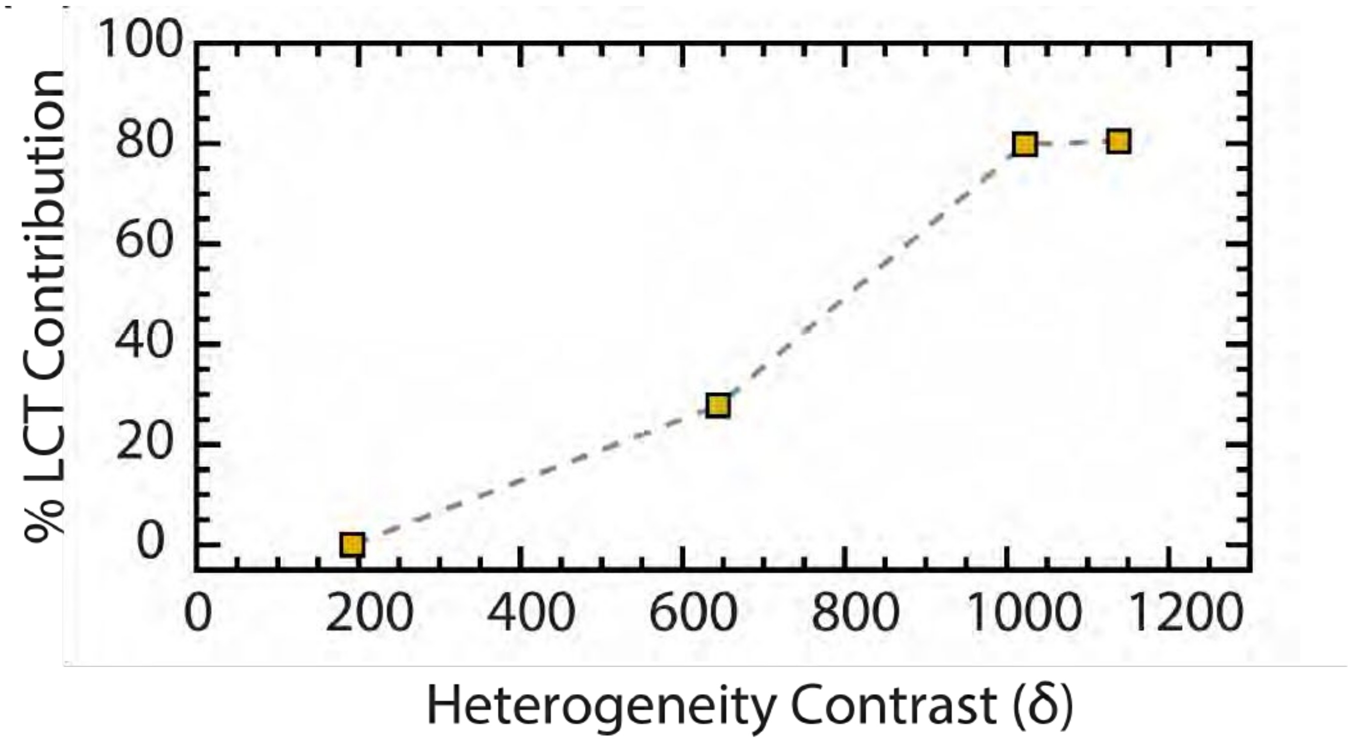
But what is the fraction that is left behind?

Trapping Efficiency



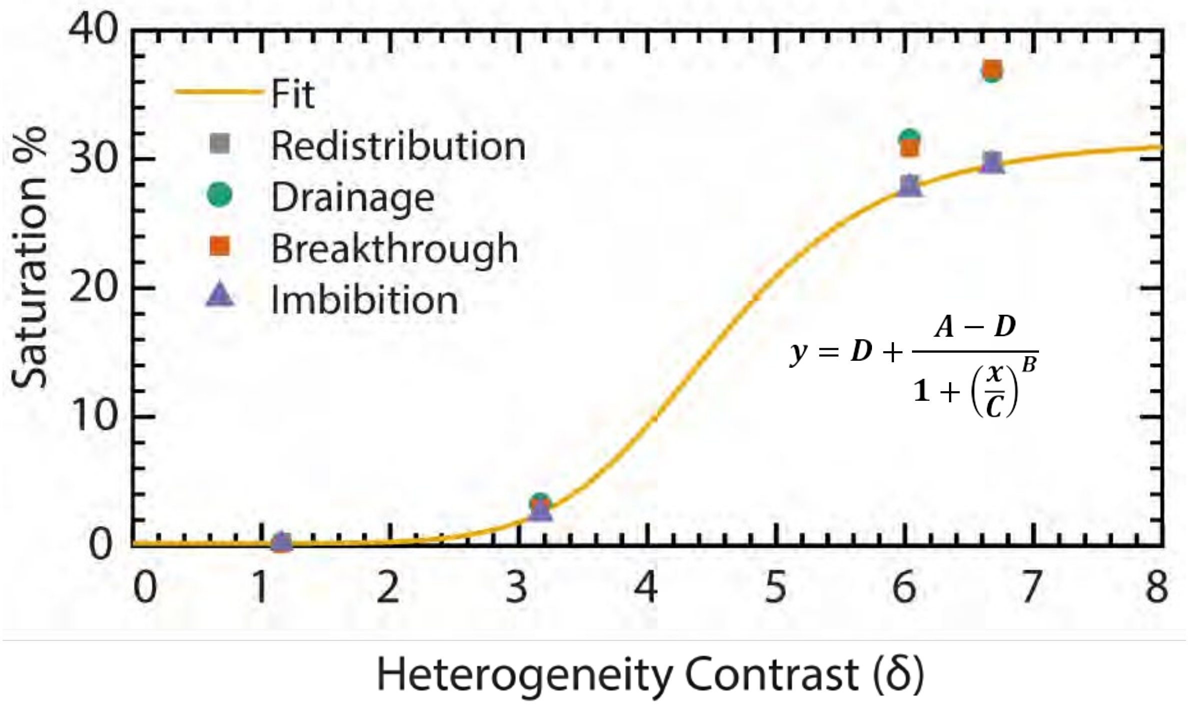
The efficiency of trapping (final: initial saturation) increases with increasing grain size contrast

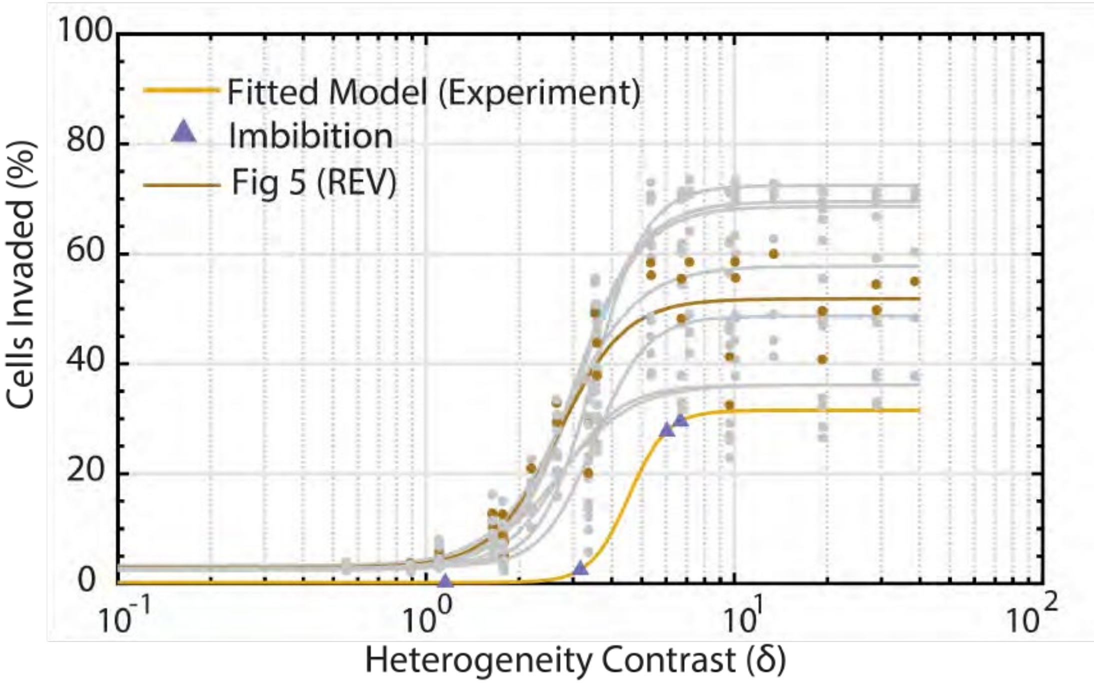
Local Capillary Trapping



Majority of the trapping potential is derived from capillary heterogeneities rather than residual trapping

Correlating Heterogeneity with Trapped Saturation





The non-linear behavior persists in the experimental results.

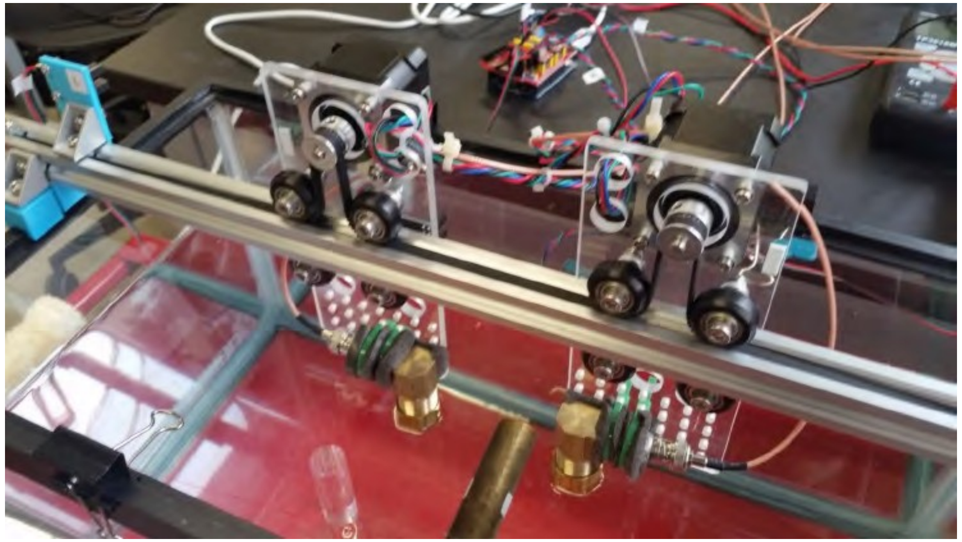
But not enough data to verify decoupling

Takeaways

- First ever visualization and quantification of flow through meter-scale complex heterogeneous porous media
- Heterogeneity (grain size contrast) has a strong influence on migration pathways and trapping behavior
- Small perturbations in the capillary heterogeneity contrast (<1kPa) lead to drastic (non-linear) effects
- Capillary heterogeneities major contributor to overall trapped capacities
- Predictive model from simulations (partially) verified using experiments

Future Directions

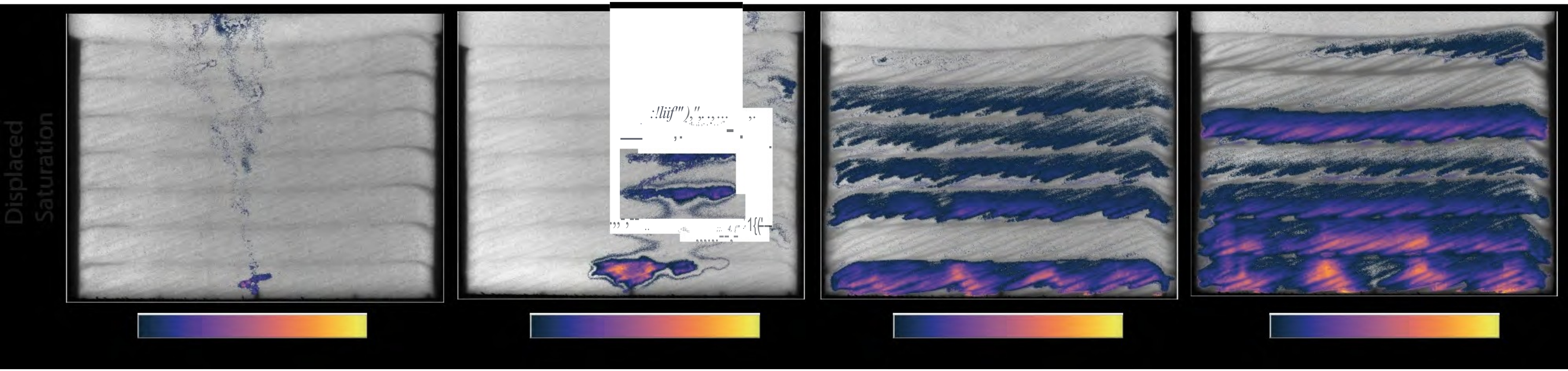
- Acoustic Sensing In Tank Experiments



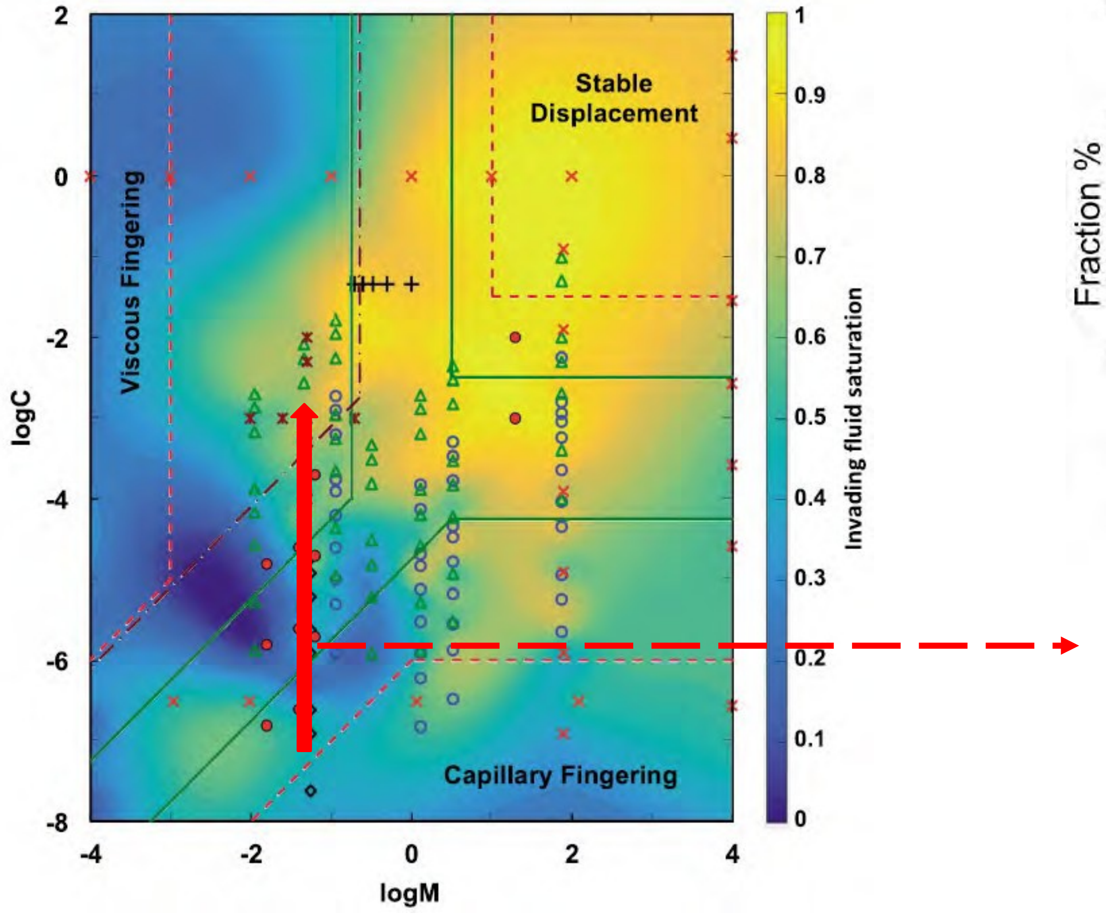
Courtesy: Dr. Nicola Tisato & PhD student Ricardo de Bragança

- Nanoparticles to alter sweep efficiencies
- Simulating fault leakage
- CO_2 Dissolution in heterogeneous porous media

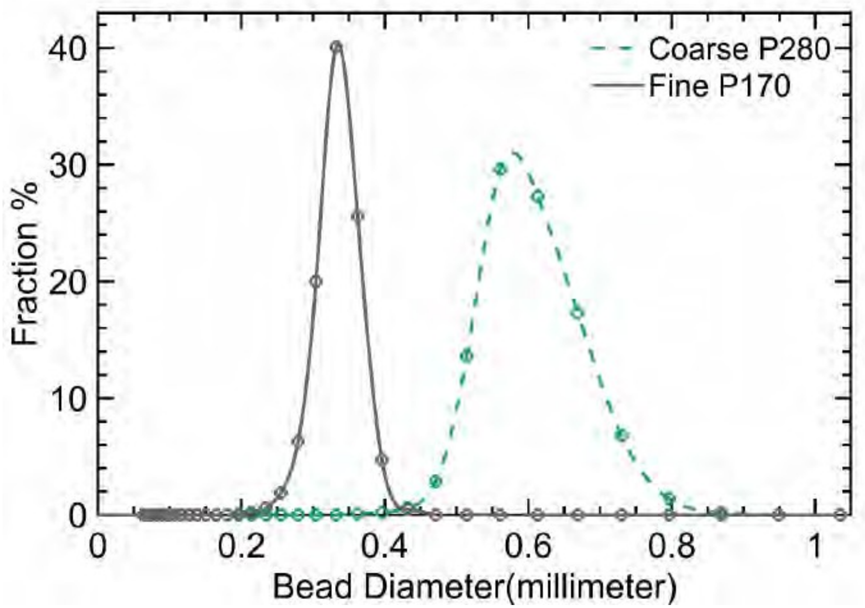
Questions?


Displaced Saturation

Q2: How much does trapping depend on Ca



Zheng et al. 2017

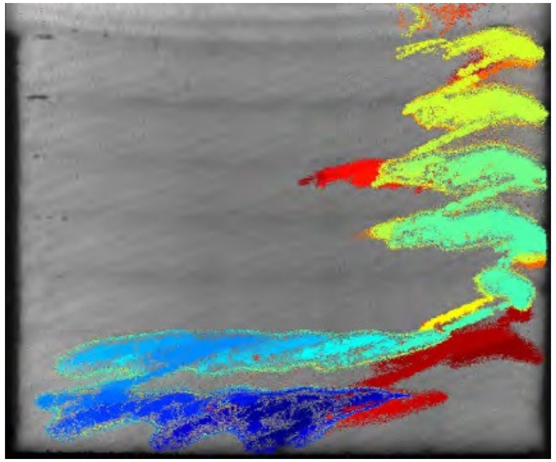


Keeping the underlying heterogeneity and viscosity ratio constant, we vary the flow rate/ velocity

Simulating a reverse capillary-desaturation curve like scenario

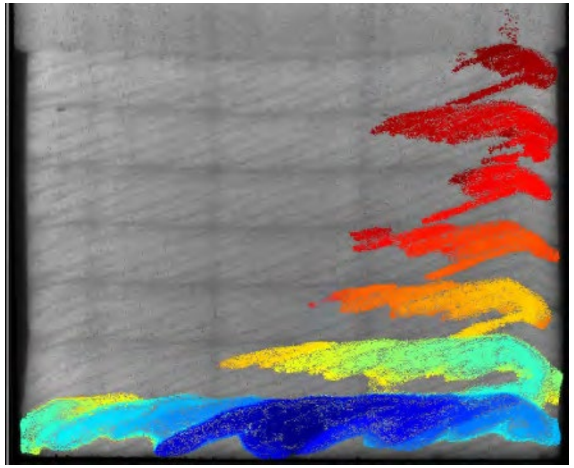
Capillary Number Vs Invasion Pathways

Ca~10^{-7}



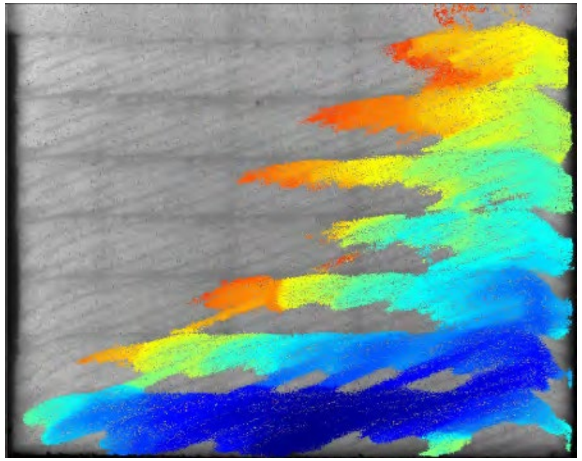
3209 min~ 53 hrs

Ca~10^{-6}



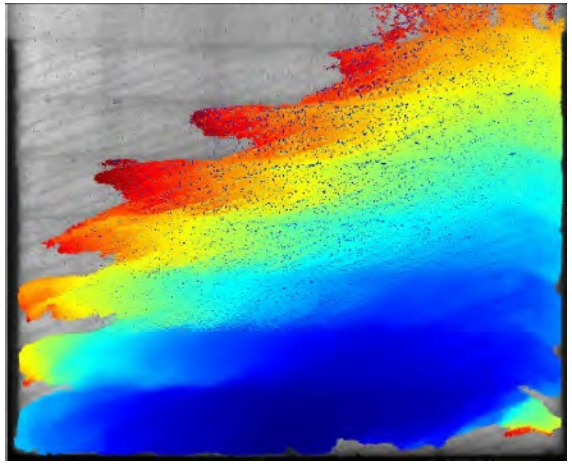
674 min

Ca~10^{-5}



108 min

Ca~10^{-4}



26 min

Increasing flow rate Ca~ 10^{-7} to 10^{-3}

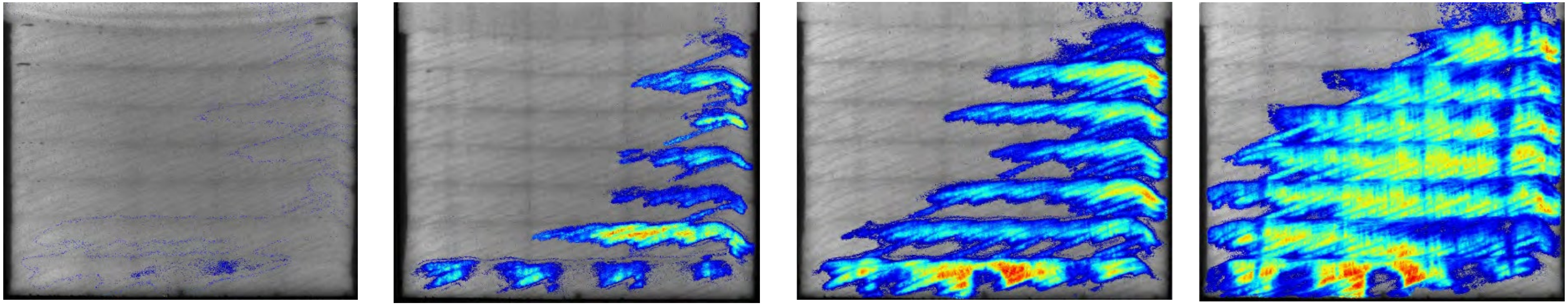
Strong non-linearity in the breakthrough times

Capillary barriers stabilize the front and greatly increase sweep efficiency

Yet again the question of how much of the NWP is immobilized?

Capillary Number Vs Trapping Potential

NWP displaced at the end of natural imbibition

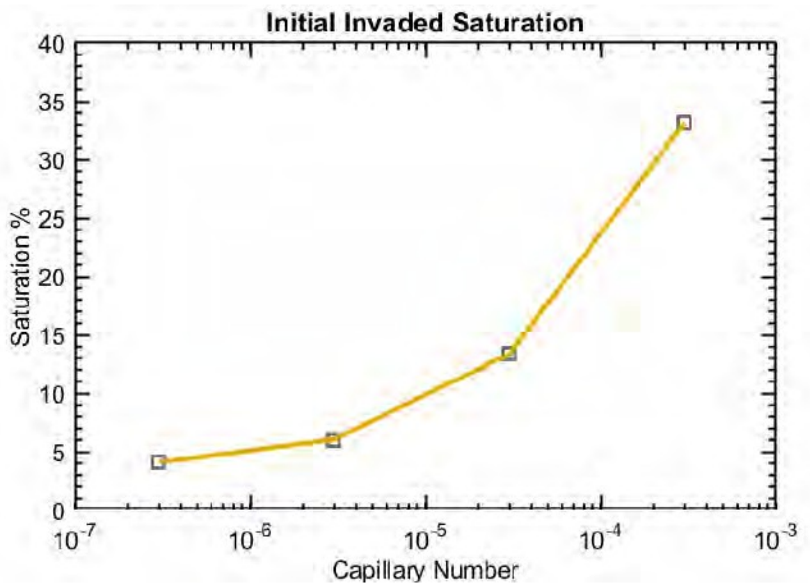


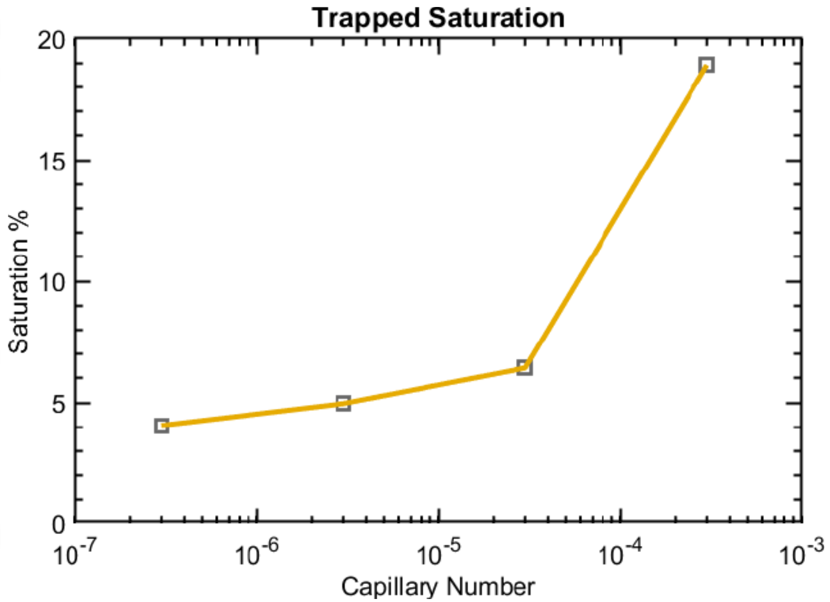
End of Drainage

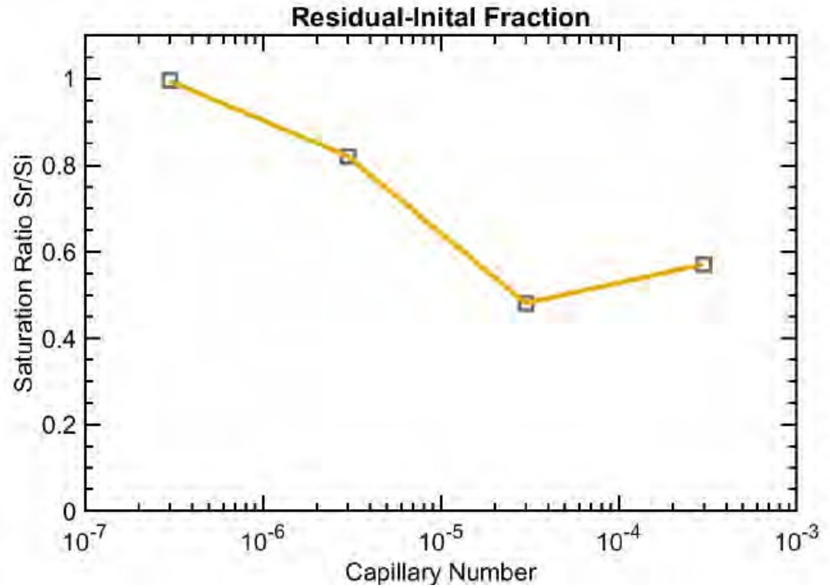
NWP displaced during gravity driven re-distribution (Imbibition)

Increased sweep along with backfilling also leads to more connected pathways

Quantifying the effects







High capillary number flows lead to increased invaded saturation and trapped saturations. However the efficiency of trapping reduces simultaneously