Understanding Buoyancy-driven CO_2 Migration in Heterogeneous Media for Storage Capacity Estimation

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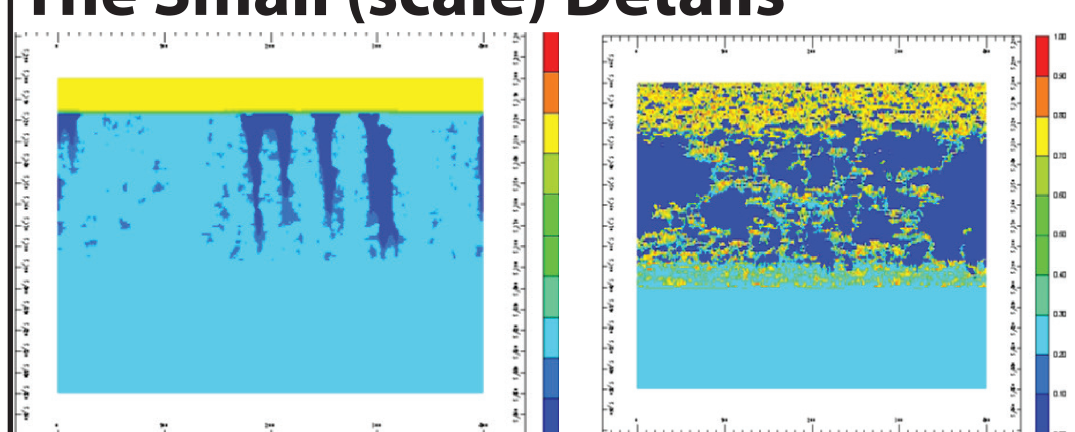
Introduction

The need to quantify the pore saturation of CO_2 injected in geological formations for long term storage has driven research to better understand the flow dynamics of CO2 plumes in the subsurface. Recent observations from field scale geological carbon storage programs like Sleipner have brought to light crucial points that challenge our approach toward modelling such flows. The principal takeaway from these results highlights two aspects that require attention:

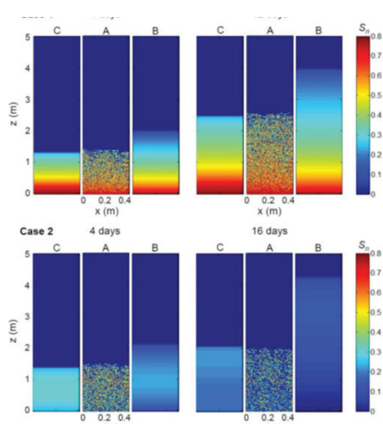
A) Understanding the dominant forces in action that affect the flow physics during migration and storage:- buoyancy and capillarity. B) Accounting for small scale heterogeneities and geologic fabric that affect the flow path in the capillary dominated regime.

In this work we demonstrate and characterize buoyancy driven-capillary dominated migration of CO2 in highly resolved (milllimeter scale) 3-D process based models with realistic sedimentary features, with the goal of developing a predictive method for volumetric storage capacity.

The Small (scale) Details



Sadatpoor 2011

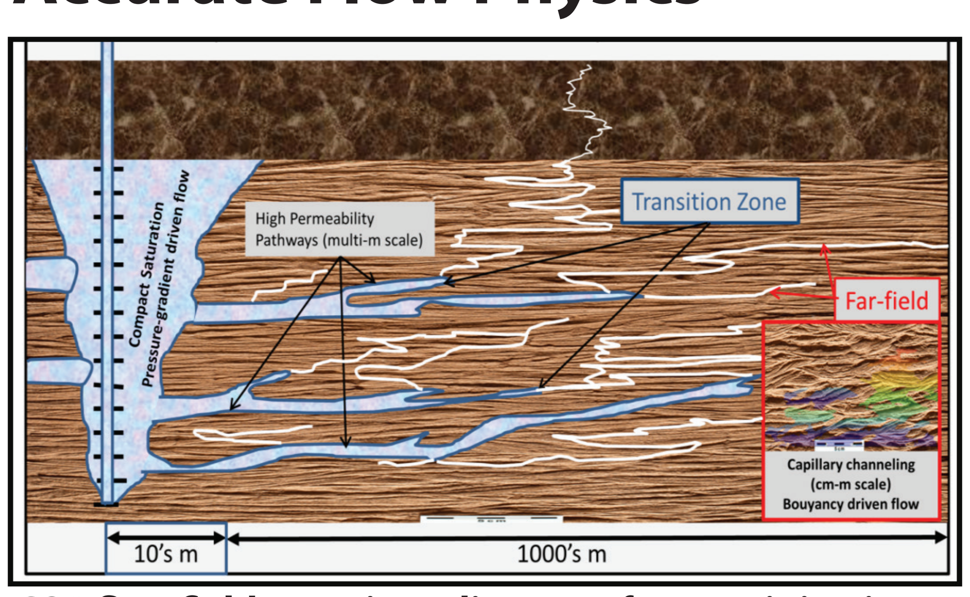


Li and Benson 2015

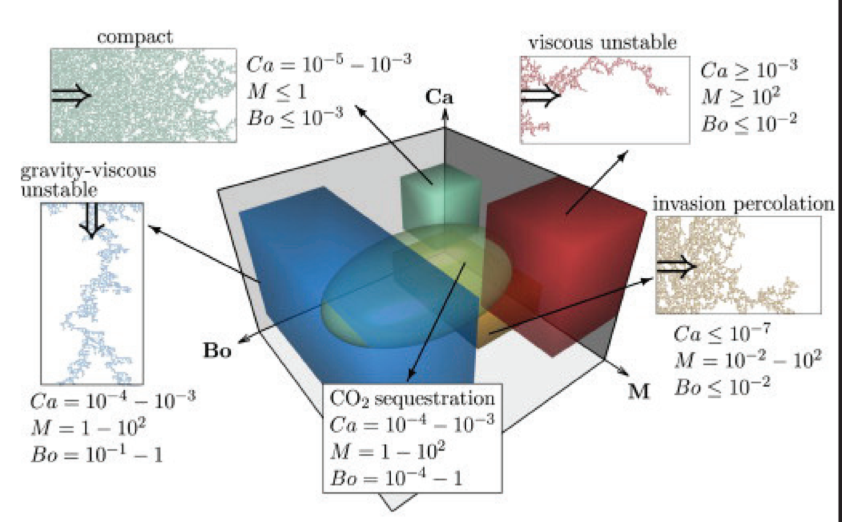
Homogeneous vs Heterogeneous Capillary field accounting for small scale features

The influence of rock heterogeneities due to depositional processes significantly affects dynamics of migration of CO_2. Due to the principally different forces in action during such migratory flows in comparison to hydrocarbon production, the scale of heterogeneity that needs to be considered is significantly smaller. Capturing such fine details is challenging in numerical reservoirs considering the computational cost and time.

Accurate Flow Physics



CO2 flow field at various distances from an injection



Cinar and Riaz 2014

Flow regimes during CO2 storage

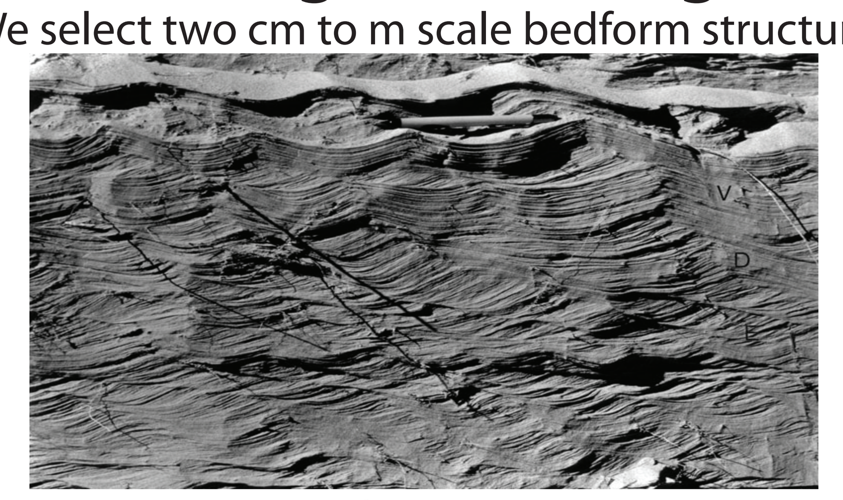
Pressure gradients fall to hydrostatic levels within a few hundred meters of a well and most of the flow occurs in the absence of viscous forces where buoyancy and capillary forces dominate.

Walking the Talk: Invasion Percolation

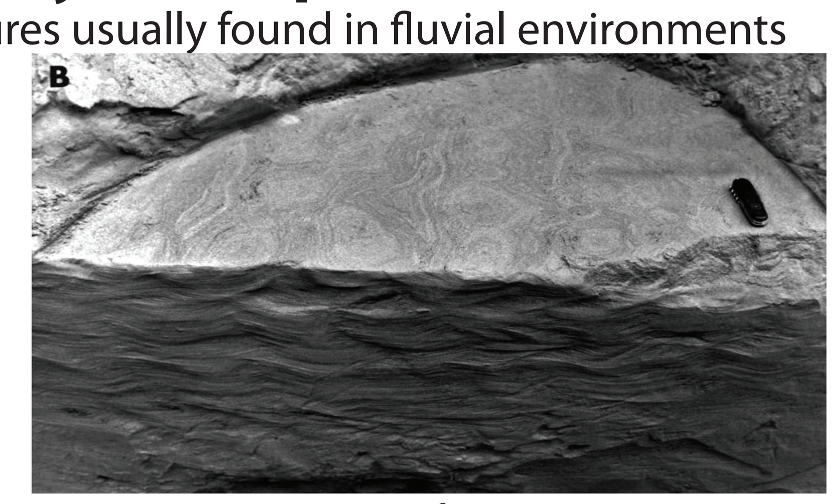
Invasion percolation theory provides a numerically efficient framework for describing fine rock properties on entry-pressure dominated fluid flow. Permedia from Halliburton uses a modified form of invasion percolation theory by considering the pressures necessary to create a connected stringer of petroleum that spans a network of pores and pore throats across a volume of rock. We simulate capillary channel flow of CO_2 in highly resolved nature mimicking models in the REV scale using Permedia's Invasion Percolation protocol

Accounting for Heterogeneity: A) Depositional Features

We select two cm to m scale bedform structures usually found in fluvial environments



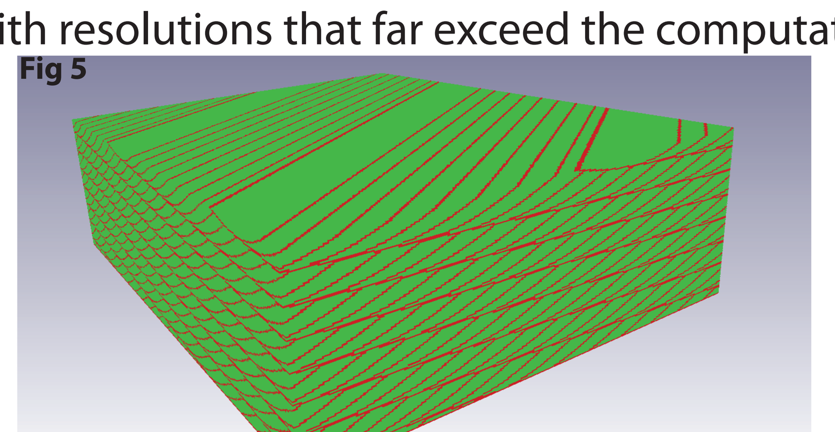
~0.5m



~1 m

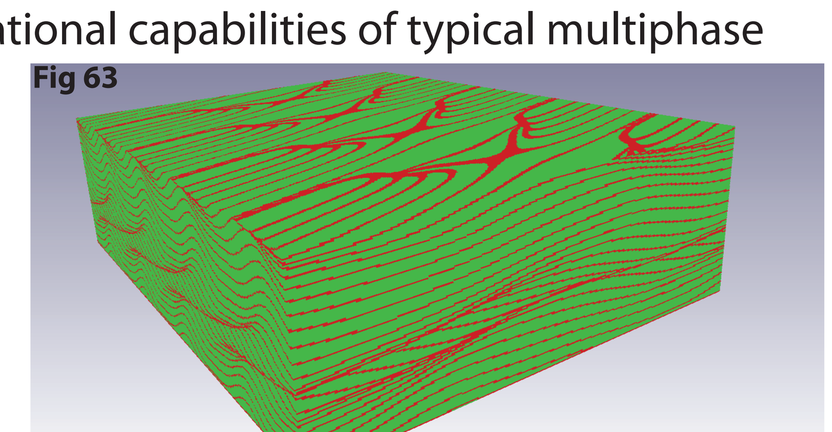
Building upon a previously known (Rubin and Carter, 2006) process-based numerical scheme, we generate 3-D bedform models using MATLAB. The 3-D model is then converted to a high resolution gridded volume (2mm x 2mm x 2mm voxels) with a binary (Lamina-Matrix) scheme. The model dimensions are at a scale that captures the REV, yet with resolutions that far exceed the computational capabilities of typical multiphase

Fig 5



495x142x400 cells

Fig 63



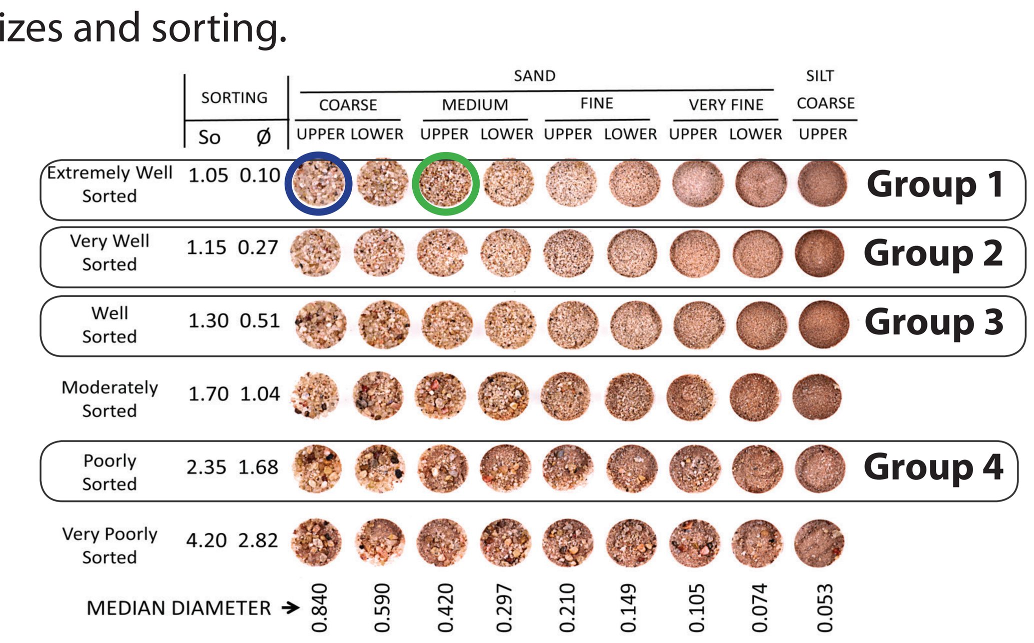
495x142x400 cells

Gridded 3-D models of Fig 5 and Fig 63 from the USGS report by *Rubin and Carter 2006*

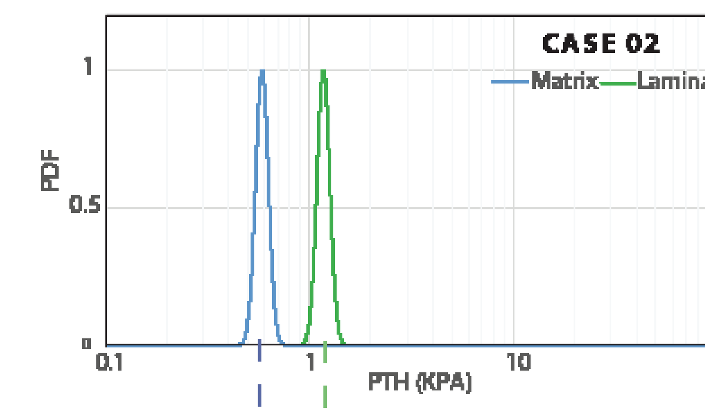
http://walrus.wr.usgs.gov/seds/bedforms/index.html

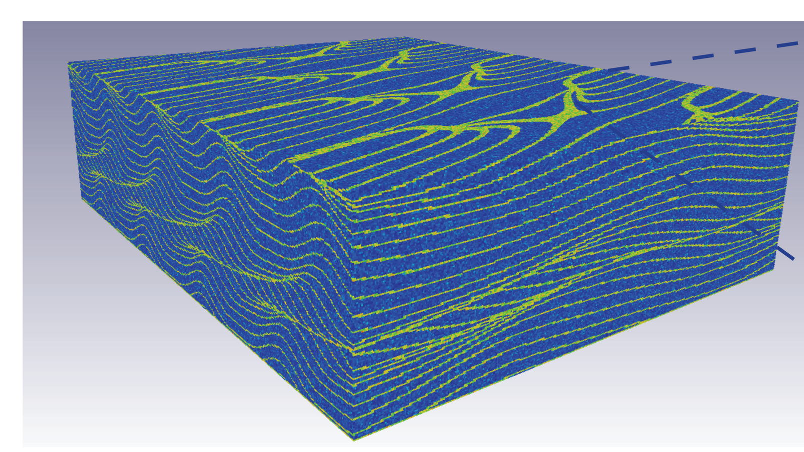
Accounting for Heterogeneity: B) Facies contrast

We populate the binary 3-D model with Pth (capillary entry pressures) values from a matrix of 54 different log-normally distributed threshold pressure values that are associated with varying mean grain sizes and sorting.

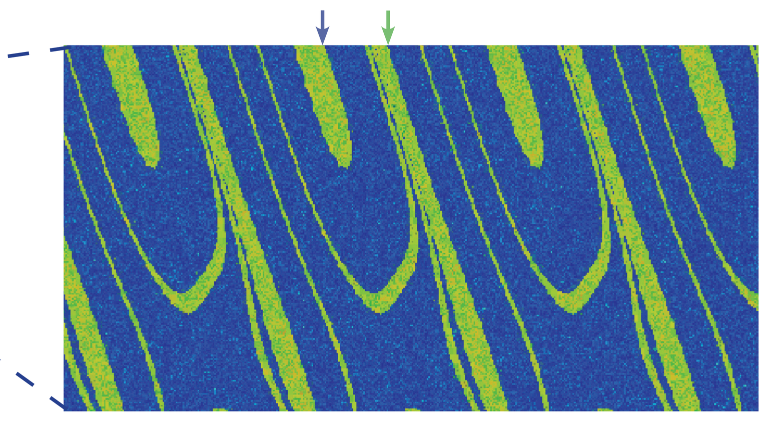


Beard and Weyl 1973





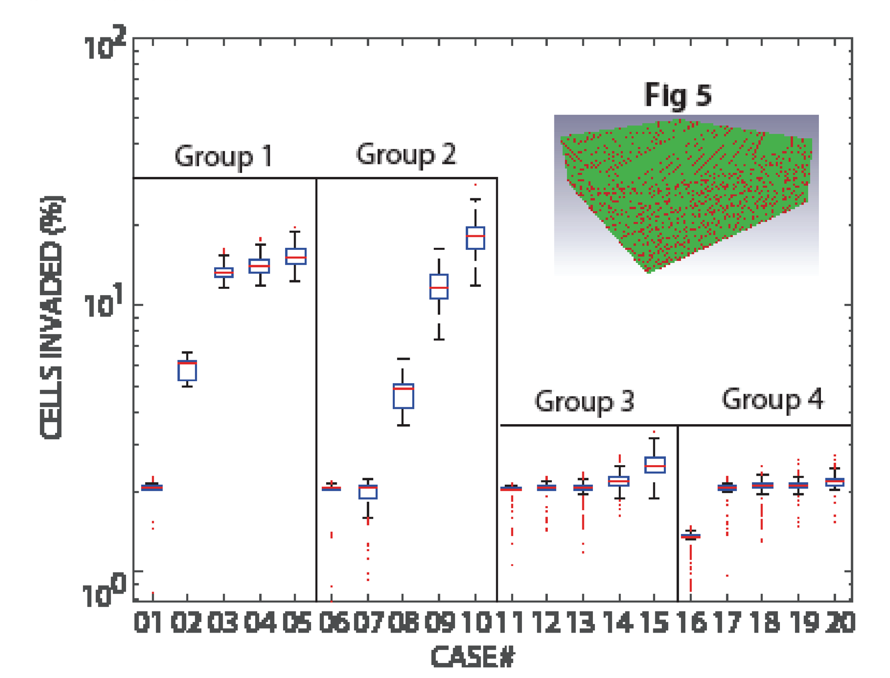
Capillary entry pressure field of a model, visualized in Permedia.

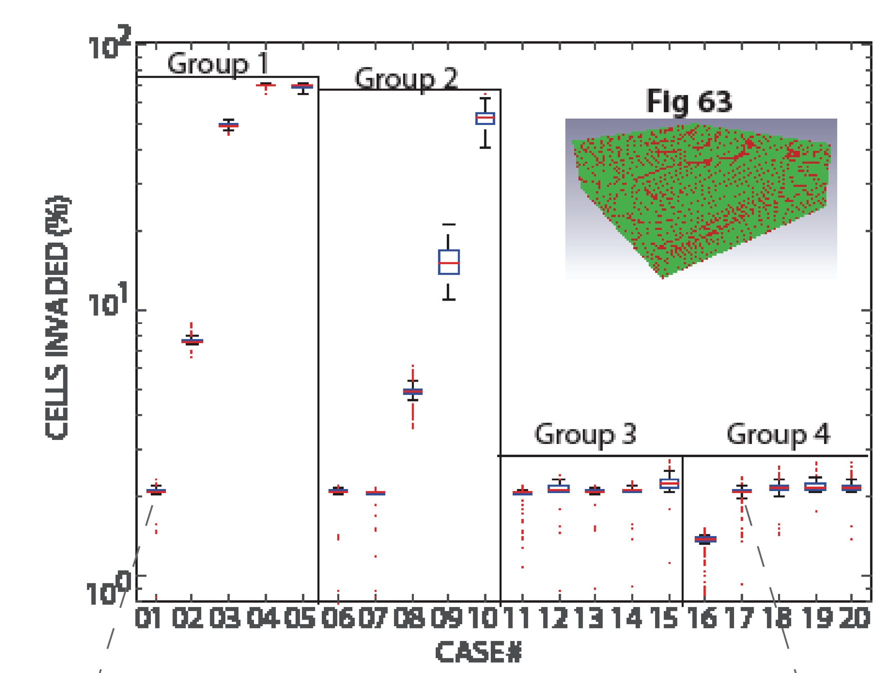


The lamina grain sizes are finer than the matrix, hence the lamina have higher entry pressures thereby acting as barriers to flow.

IP Simulation Results

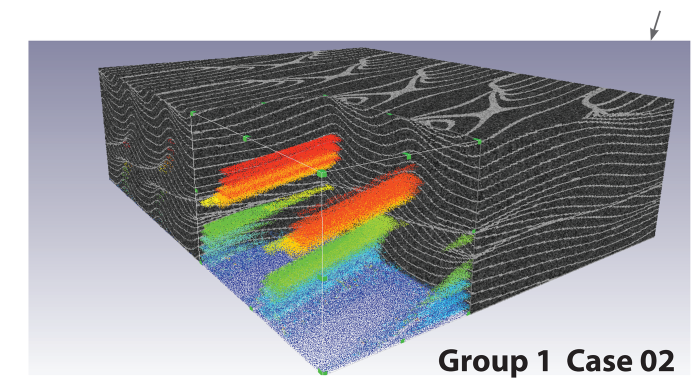
The matrix and laminae cells are populated with Pth values randomly from the respective log-normal distributions. Hence 200 realizations are generated for each case and simulated in Permedia.



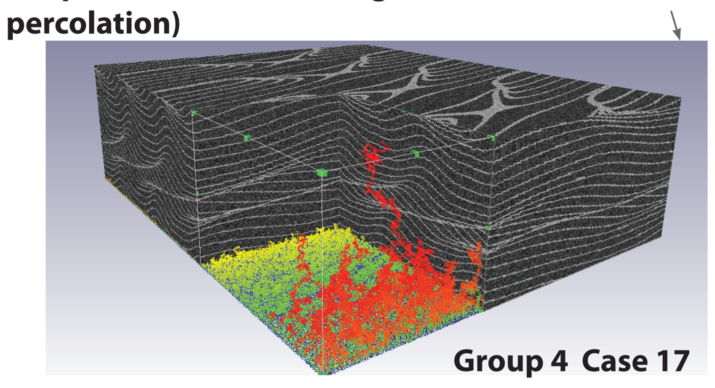


Variance of Pth field increases from Group 1 to Group 4
Within a group, the grain size contrast increases with each case

Sample visualizations of CO_2 flow path post migration with different fabric heterogeneity. Migration stops when the first stringer reaches the top (at percolation)



Group 1 Case 02



Group 4 Case 17

Observations and Perspectives for the Future

Preliminary trends made obvious by the results of simulating CO_2 migration on the two models with heterogeneity are:

- Facies/grain-size contrast takes precedence over fabric complexity (bedform pattern) when it comes to the number of cells invaded (~saturation) [Compare Fig 63 vs. Fig 5].
- Overlap of the two PDFs (Lamina & Matrix) highly influences the retardation of upward flow [Compare Group 1&2 vs. Group 3&4 in both models]

Future directions/ Questions :

- Finding an appropriate metric for characterizing the heterogeneity, that places emphasis on grain size contrast.
- Determining the REV for capillary pressure heterogeneity
- Validation of model with natural geologic specimens and lab scale experiments
- Implications of saturation variability for capacity estimation

References

1. T.A. Meckel, S.L.Bryant and P.R. Ganesh, Int. J. Greenh. Gas Control, 2015, 34, 85-96.
2. D.C. Beard and P.K. Weyl, AAPG Bulletin, 1973,349-369.
3. E Saadatpoor, S.L. Bryant and K. Sepehrnoori, Transport Porous Med, 2010, 82, 3-17.
4. B.Li and S.M. Benson, Adv. Water Resour., 2015, 83, 389-404.
5. D.M. Rubin and C.L. Carter, SEPM Atlas Series No. 2, U.S. Geological Survey, 2006.
6. Y.Cinar and A.Riaz, J. Petrol. Sci. Eng., 124, 367–380.

Acknowledgments

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