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Multiscale Imaging of Carbonate Rocks and Upscaling for Digital Rock Physics

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Motivations

- **Plenty of pores at sub-micron scale** (nano-pores) in shales and carbonate rocks have become increasingly important for emerging problems such as unconventional gas and oil resources, geologic storage of CO_2 and nuclear waste disposal
- **Advances in analytical capabilities** with laser, X-ray, electron, and ion beams offer emerging tools for characterizing pore structures, mineralogy, and reactions at the sub-micron scale
- **Multiscale imaging capabilities –** integration of experimental and numerical tools to probe the structure and properties of materials across scales (e.g., core to nanometer scale) are rapidly advanced
- **Digital rock physics** – data interrogation about how to take nanometer scale information and apply it to the thin-section or larger scale for accurate prediction of coupled geophysical, mechanical, and chemical processes

Objectives

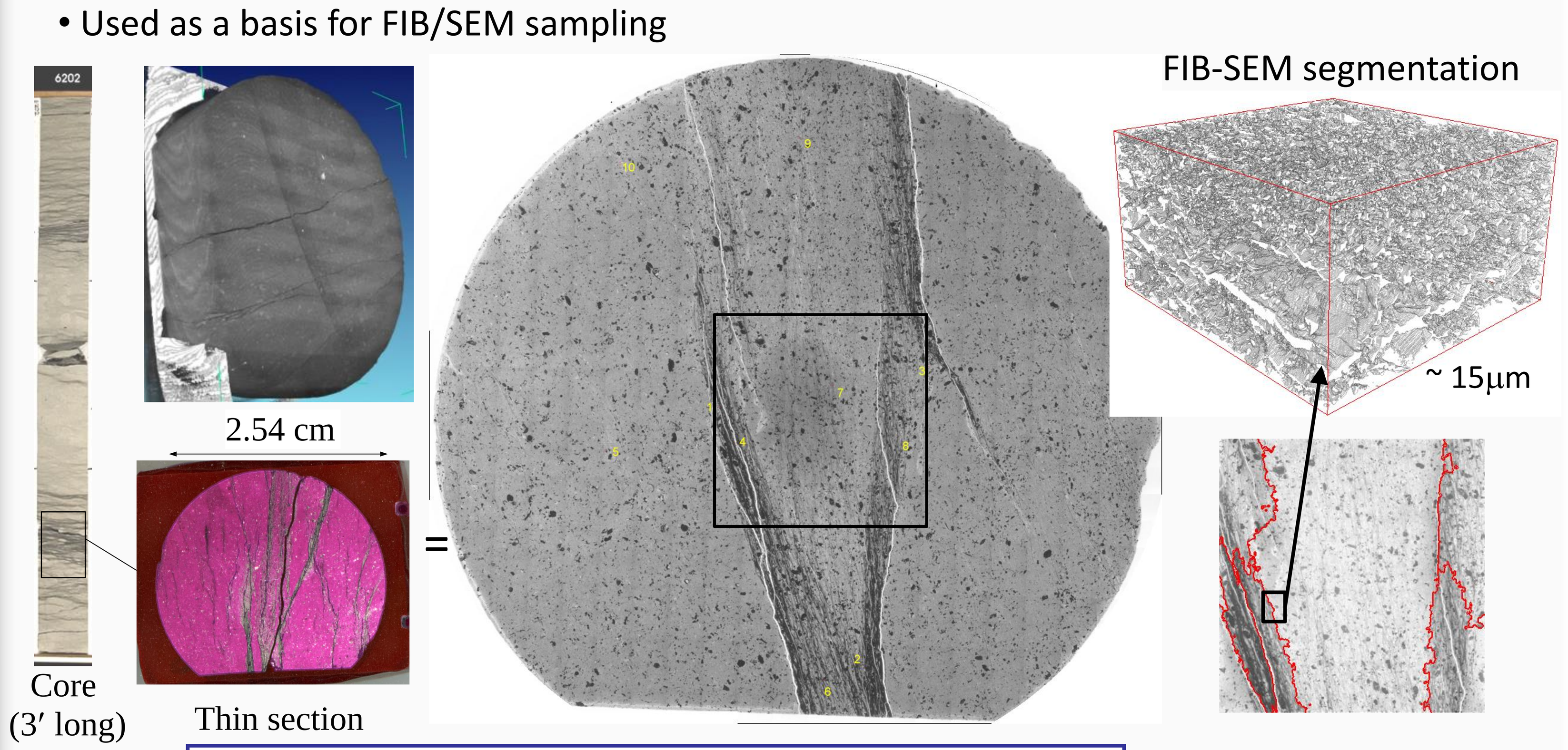
- Reconstruct 3-D stochastic pore structures based on multiscale images and reduce the number of ensemble members through dimension reduction methods
- Develop a workflow for digital rock physics to upscale petrophysical and elastic properties for multiphase flow and reactive transport

Multiscale Imaging and Analysis

- Characterization of pore structures, compositional distribution, and surface properties using multiscale imaging techniques (optical and confocal microscopy, QEMSCAN, micro-CT, FIB-SEM, BIB-SEM, TEM, EDS)

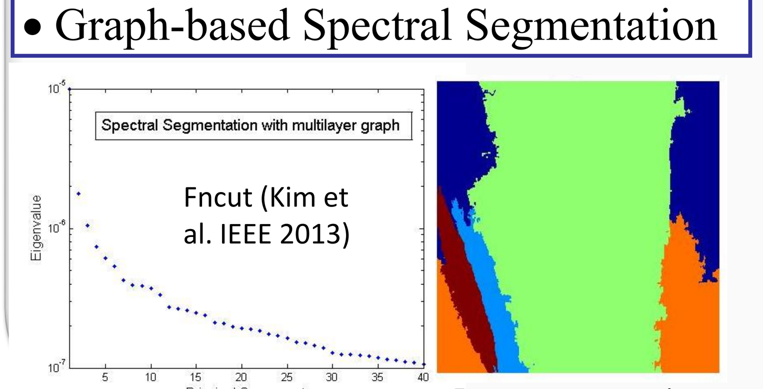
• Fluorescence mapping and feature classification

- Thin section analysis and micro-CT imaging
- Identify distinctive features (e.g., micro-fractures, clay seam, matrix) from 2D thin section using feature selection algorithm (e.g., spectral segmentation (Kim et al. 2013))
- Used as a basis for FIB/SEM sampling



Rhodamine-B scan of thin section & FIB-SEM Locations

• Graph-based Spectral Segmentation



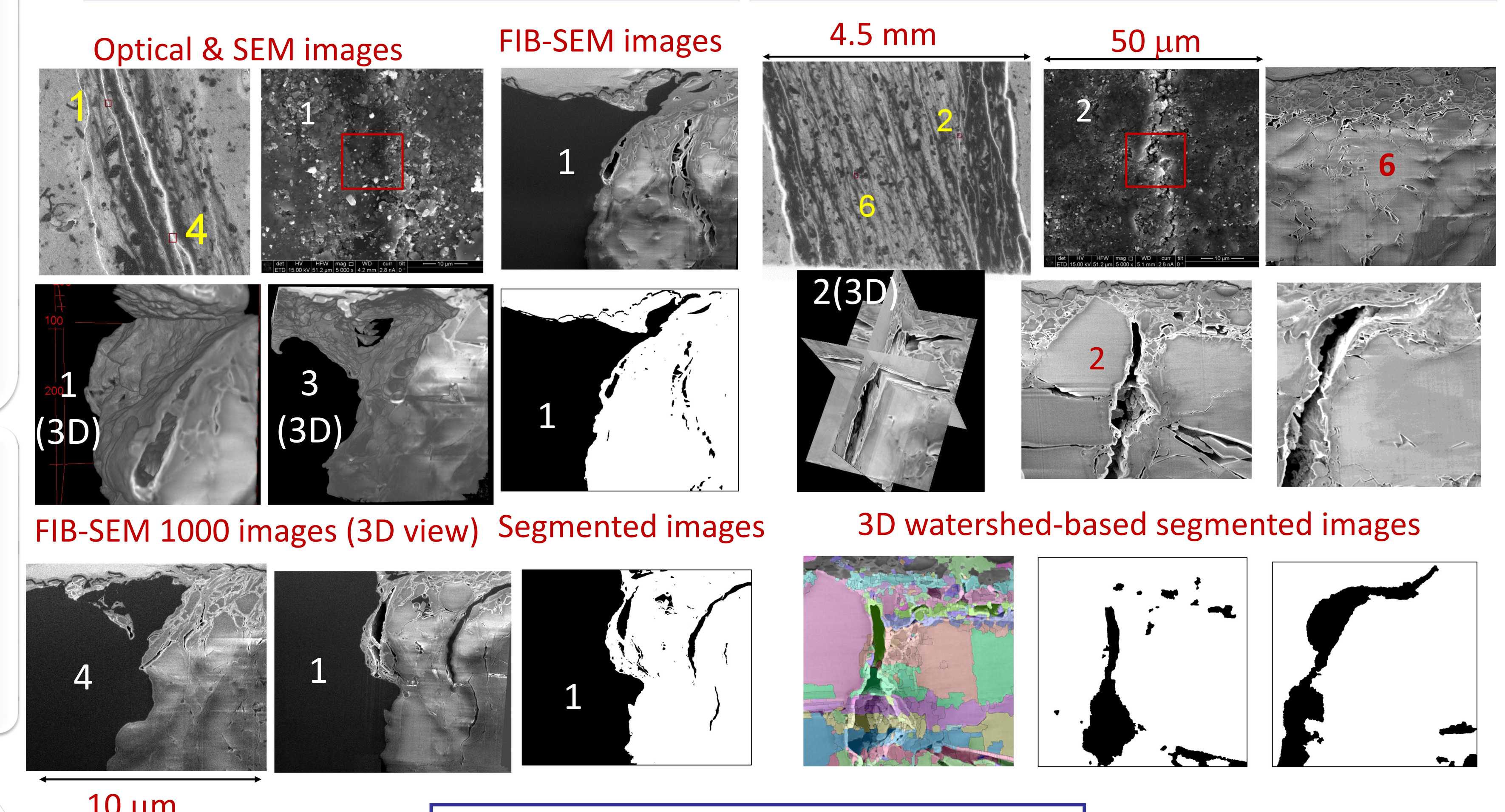
We proposed a "two-scale" approach:

1) Multiple FIB-SEM analysis to characterize nano-porous structures
2) Perform pore scale simulations using reconstructed 3D digital rock ensemble members
3) Assign effective permeability or response function for flow and transport modeling at Darcy-scale images (e.g, thin section/micro-CT)

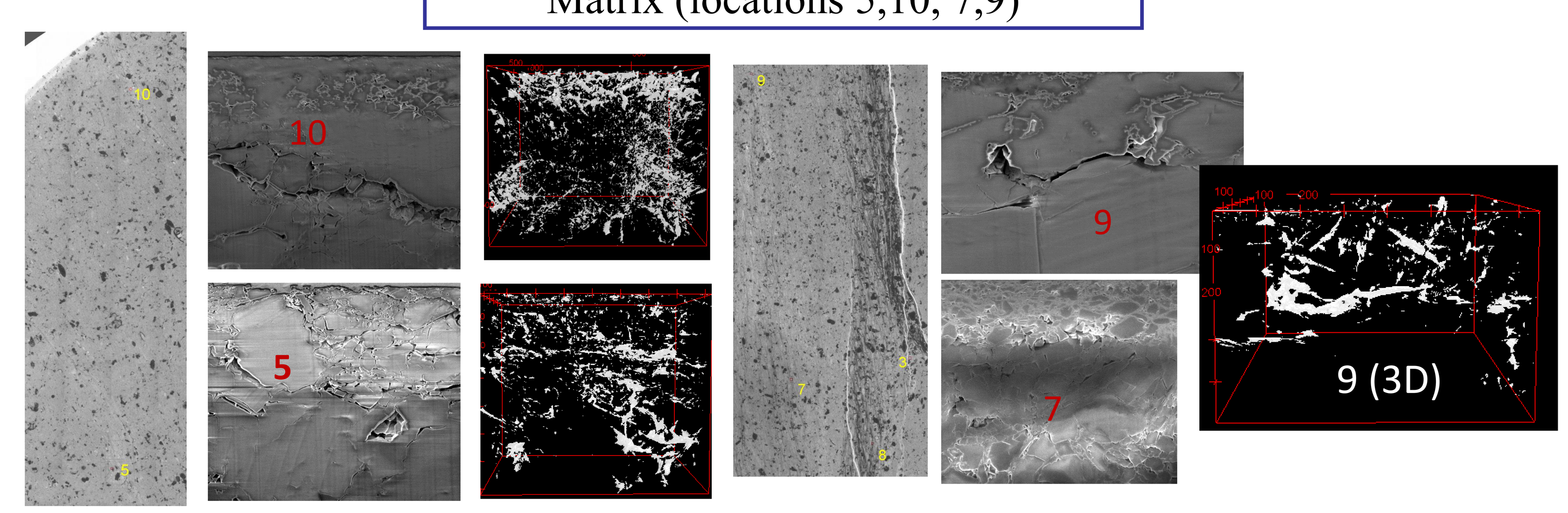
Multiple Focus Ion Beam - SEM Analysis

- Representative microfacies based on FIB-SEM images (10 nm resolution in 3D)

Micro-fractured pores (locations 1,3, 4) | Clay, stylolitic microseams (locations 2, 6, 8)



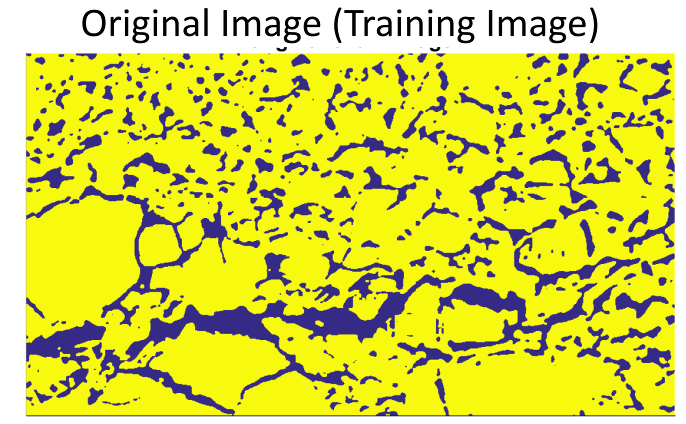
Matrix (locations 5,10, 7,9)

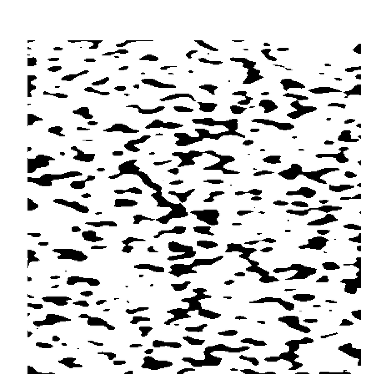


Workflow for Digital Rock Physics

Rock Sample → Multiscale Imaging & Analysis → Multiscale Digital Rock Reconstruction → Flow and Transport Properties → Static Effective Elastic Properties → Wave Propagation

Original Image (Training Image)

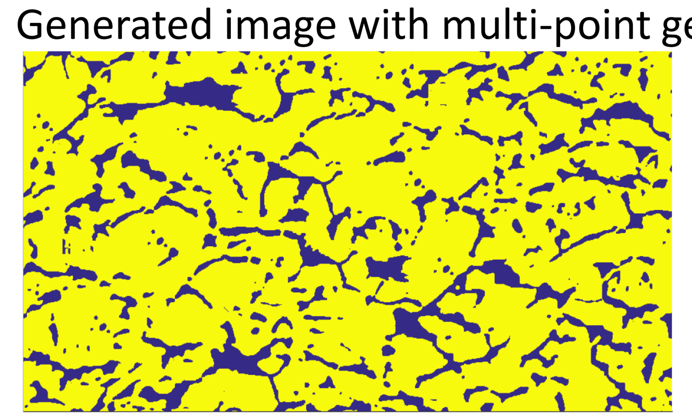




Reconstructed image using Gaussian model (two point statistics)

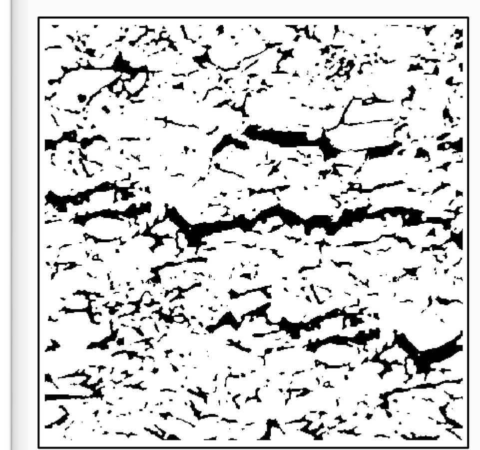
Traditional two-point statistics is not enough to characterize the long-range connectivity
A prior geological interpretation is required and it is NOT multi-Gaussian

Generated image with multi-point geostatistics (MPS)

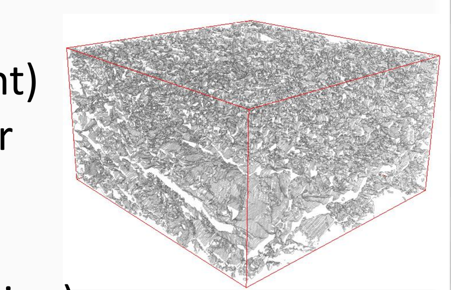


- Image Quilting (IQ, Mahmud et al., 2014) as an example of multiple-point statistical techniques was used to regenerate a carbonate rock image
- IQ reproduces the long range connectivity well
- Preserving porosity and identifying suitable training images need further study

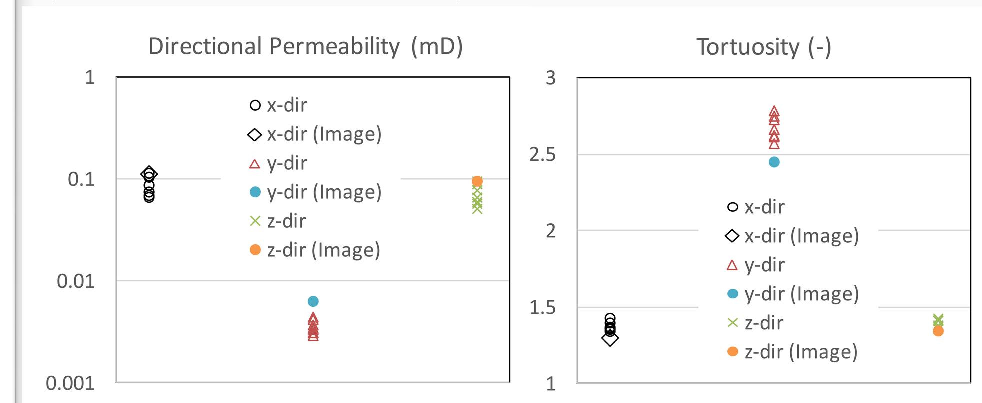
Multipoint Statistics for Digital Rock Reconstruction



2D slice of 3D realization (1000x1000x1000 voxels)



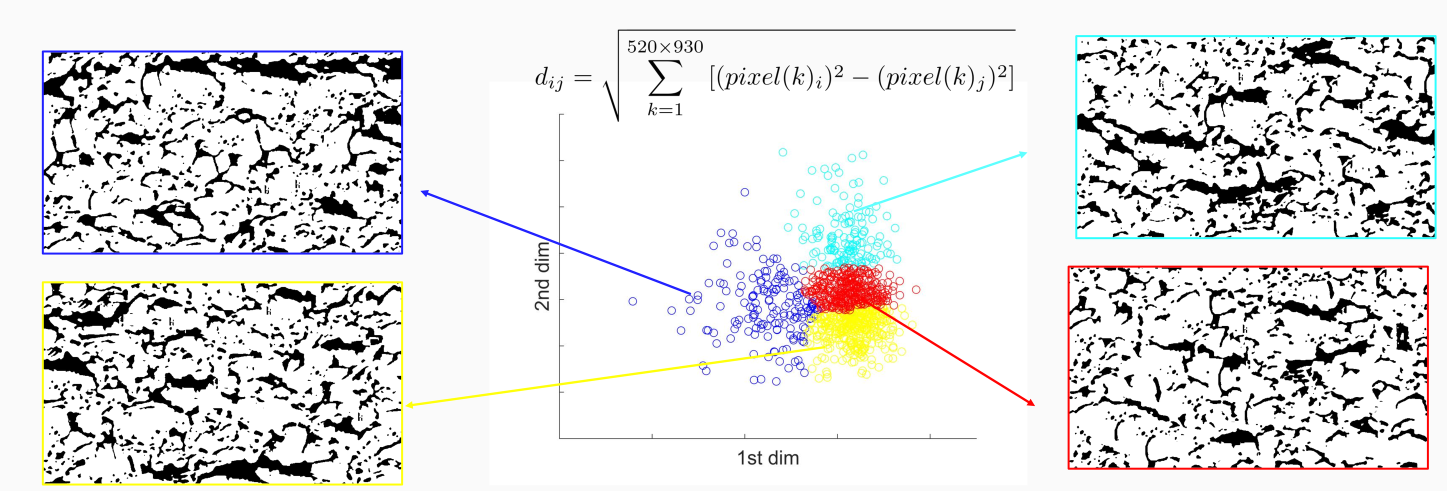
- Feature-based Conditional IQ from segmented FIB-SEM image stack (right)
- Porosity, correlation length, and Euler characteristics are consistent
- 10 realizations of 3D pore structure (1000 x 1000 x 1000 at 15 nm resolution)
- Lattice Boltzmann simulation of single phase flow (e.g., Yoon et al., 2013)
- Directional permeability and tortuosity are compared
- IQ based realizations have slightly less connected



- MPS based realizations are strongly influenced by training images
- 2D thin-section and 3D microCT data can provide training images to describe features, connectivity, and hard data

Dimension Reduction

- A large number of realizations are prohibitively expensive
- Dimension reduction can be applied to reduce the number of ensemble members to represent flow and elastic properties of chalk
- Multi-dimensional scaling based on the Euclidean distance measure is applied to demonstrate the linear dimension reduction approach



Future Works

- Nonlinear dimension reduction will be applied to reduce the number of ensemble members to represent flow and elastic properties of geomaterials
- Pore scale single- and multi-phase flow modeling and reactive transport modeling will be performed to assess the accuracy and efficiency of MPS methods
- Effective properties based on pore scale analysis (e.g., permeability or response function for reactive transport parameters) will be mapped over thin-section (2D) and micro-CT images (3D) for upscaling from pore- to Darcy-scales

References

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Acknowledgments

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