Multiscale Imaging of Carbonate Rocks and 3D Stochastic Reconstruction for Digital Rock Physics

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Jonghyun Harry Lee & Peter K. Kitanidis (Stanford University)
Hongkyu Yoon & Thomas Dewers (Sandia National Laboratories)

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Sandia National Laboratories

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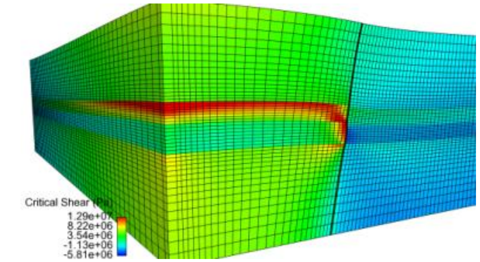
Outline

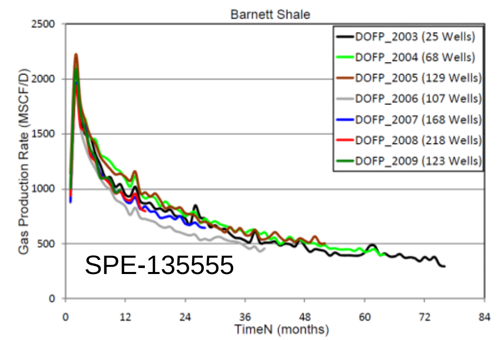
- Motivations/Backgrounds
- Multiscale Characterization of Carbonate Rock - FIB-SEM approach
- CT high pressure CO_2 core flood testing and modeling
- Summary

Research to Advance Our Understanding of Geomaterials

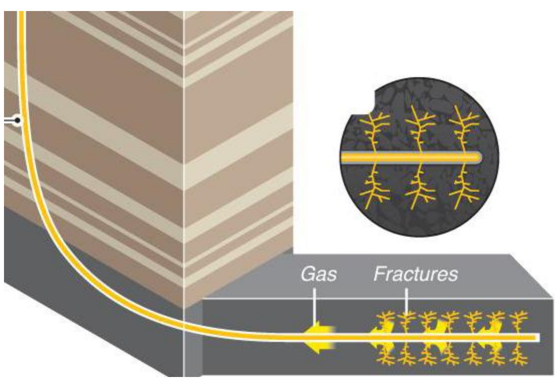
- Develop methodology to connect pore-scale structure to macro-scale behavior to advance constitutive models for poro-hydro-mechanics of fractured and porous rock that directly impact our ability to predict:
  - aquifer response to injected fluids
  - hydrocarbon production decline,
  - efficiency of subsurface carbon storage,
  - Induced seismicity



Injection-pressure-induced deformation and shear failure (Martinez et al., IJGGC 2015)

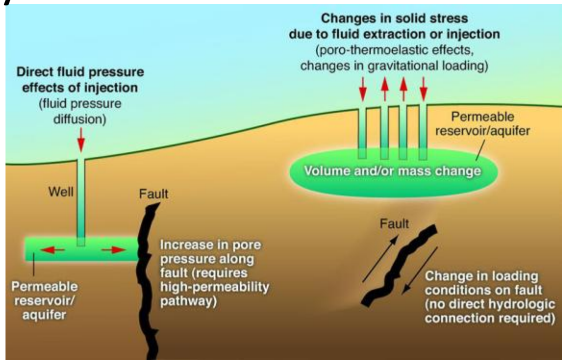


Production decline



Hydraulic Fracturing

Source: Reuters (National Geographic, Chesapeake Energy, EIA, USGS)



Induced seismicity

USGS: http://earthquake.usgs.gov/ Research/induced/modeling.php

Significance of Nano-Porous Geomaterials

- **Plenty of pores at sub-micron scale**

  - Nano-pores in shale and carbonate rocks have become increasingly important for emerging problems such as unconventional as and oil resources, enhanced oil recovery, and geologic storage of CO_2

- **Advances in analytical capabilities**

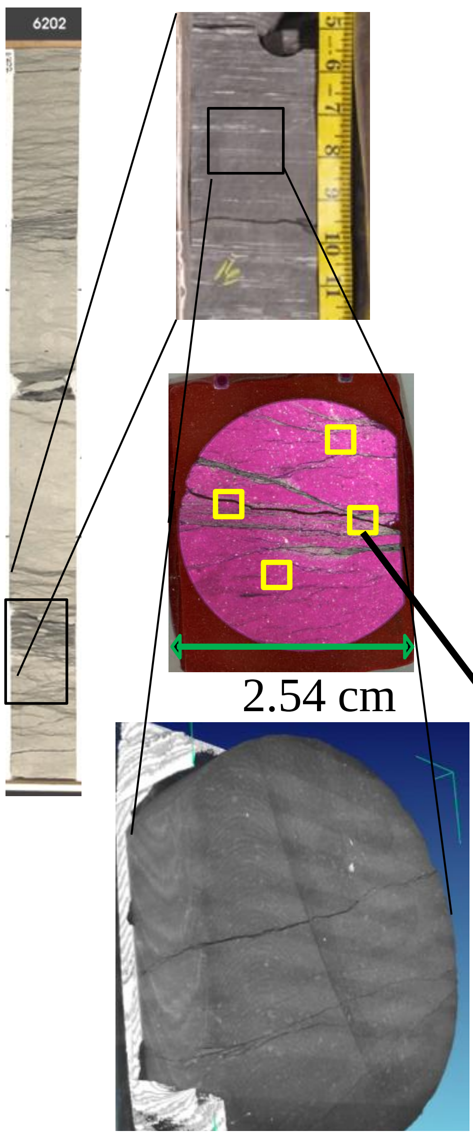
  - X-ray, electron, and ion beams offer practical tools for characterizing pore structures, mineralogy, and reactions across scales from nano- to centi-meter

- **Multiscale digital rock physics**

  - Data integration from multiscale imaging is a key to bridge a gap of different information across scales so that we can link nanometer scale information to larger scales for accurate prediction of coupled geophysical, mechanical, and chemical processes

Multiscale Characterization of Carbonate Rock
FIB-SEM approach

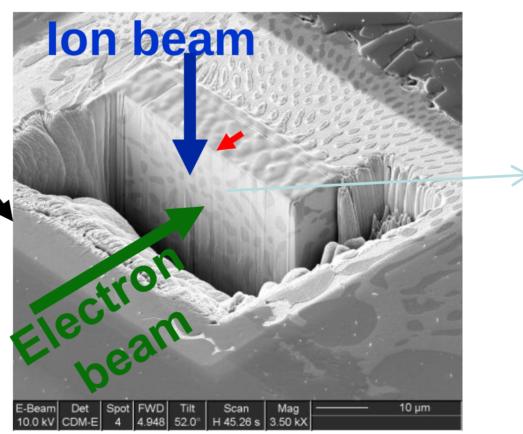
Core (~1m)



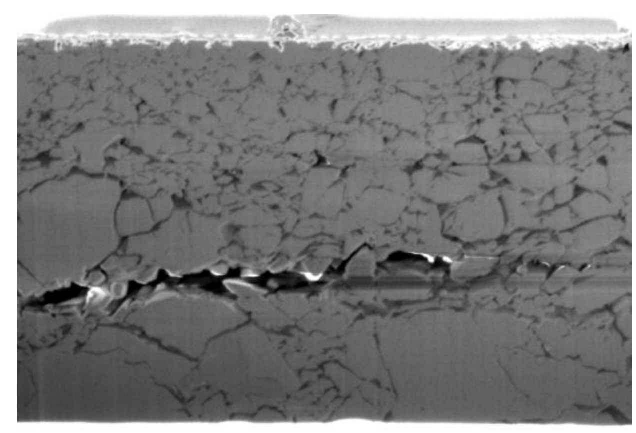
MicroCT (@10μm)

► Carbonate rock formations as hydrocarbon reservoirs, secondary caprock, etc

► Digital rock based on multiscale imaging can help us characterize and understand the role of heterogeneity and multiscale aspects of porous media



Focused Ion Beam-Scanning Electron Microscopy (FIB-SEM)

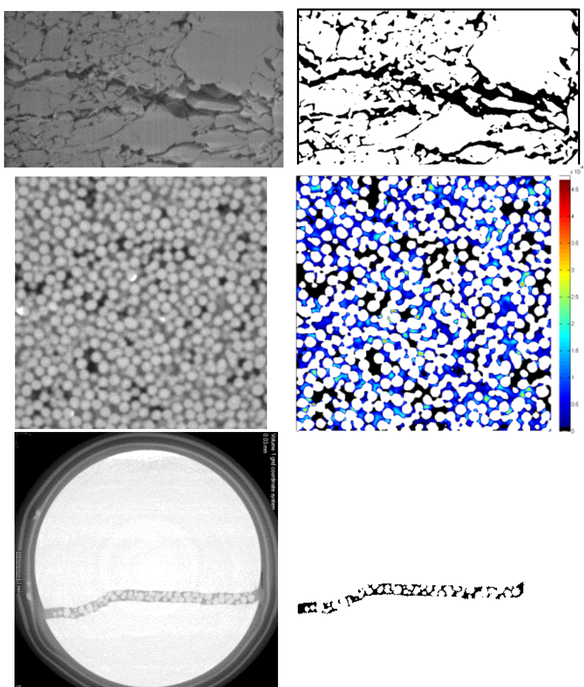


~16 μm @10nm

Image Process and Quantitative Analysis

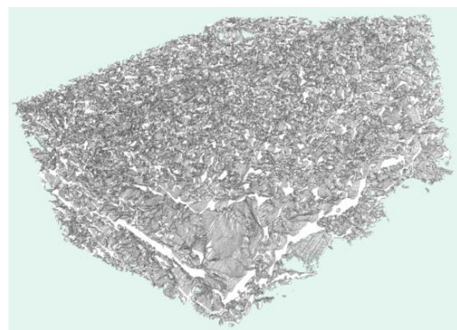
Segmentation Process

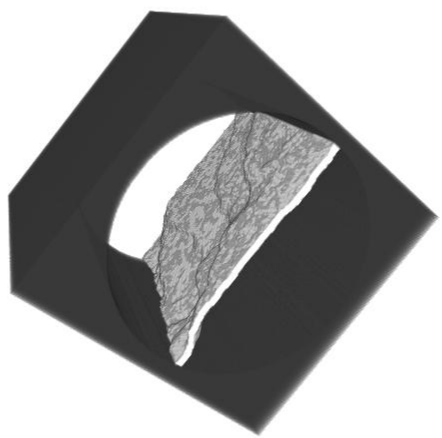
Alignment
Enhance contrasting
Multiple Filtering
Thresholding
Post processing (e.g, dilation, erosion)



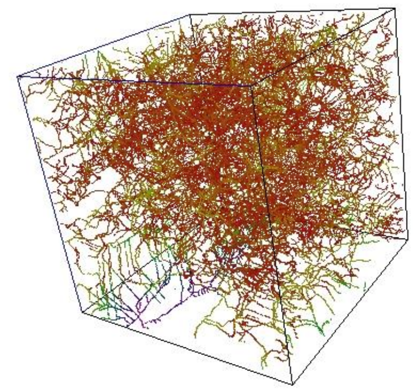
3D Digital Rock Construction

- Binary or ternary pore and fluid distribution construction



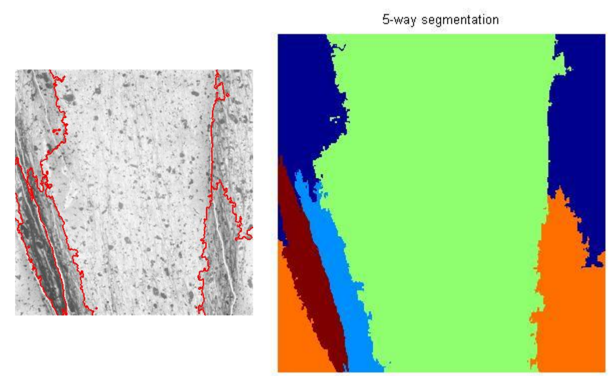


Quantitative Analysis



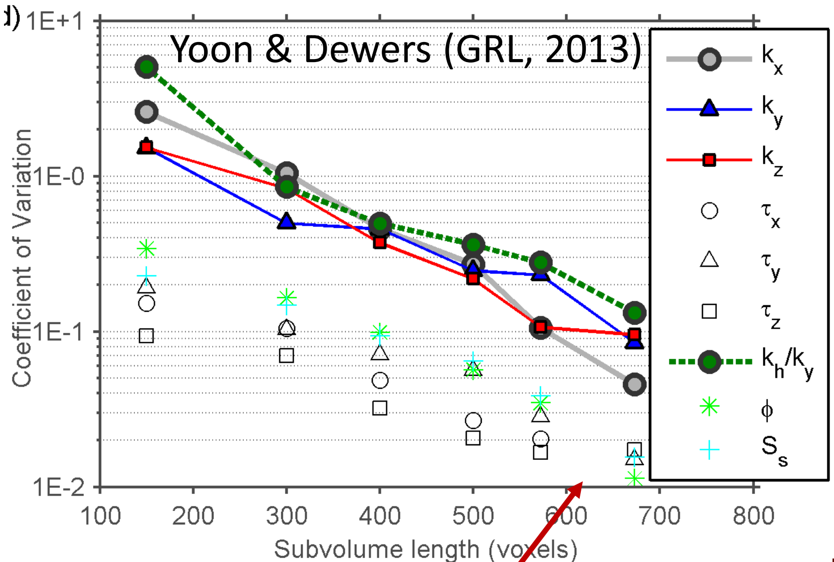
Medial Axis Analysis

Topological Analysis



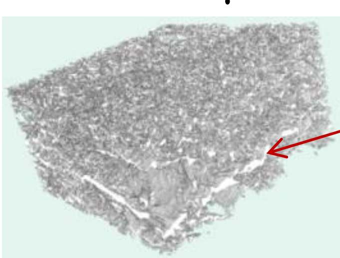
Representative Scale for Reconstruction

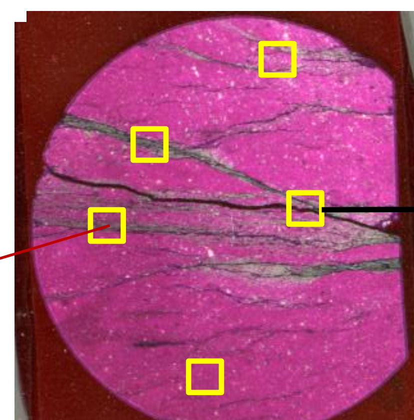
- Reconstruct 3-D pore structures and multi-scale pore networks using a statistical methodology for pore-scale modeling



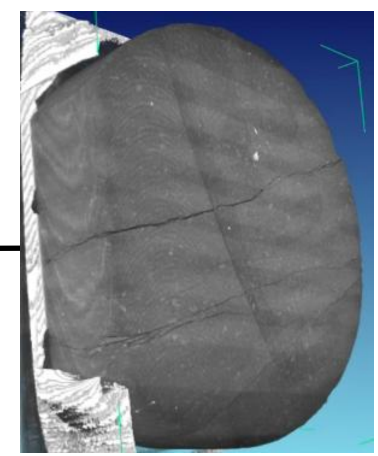
- MicroCT 3D image at ~2-5 cm scale
- This sections for detailed 2D features
- FIB-SEM samples at ~10-50 μm scale
- 4-6 regions can be selected based on principal component analysis of thin section image

FIB-SEM sample volume has a size of statistical elementary volume at ~ 10 μm



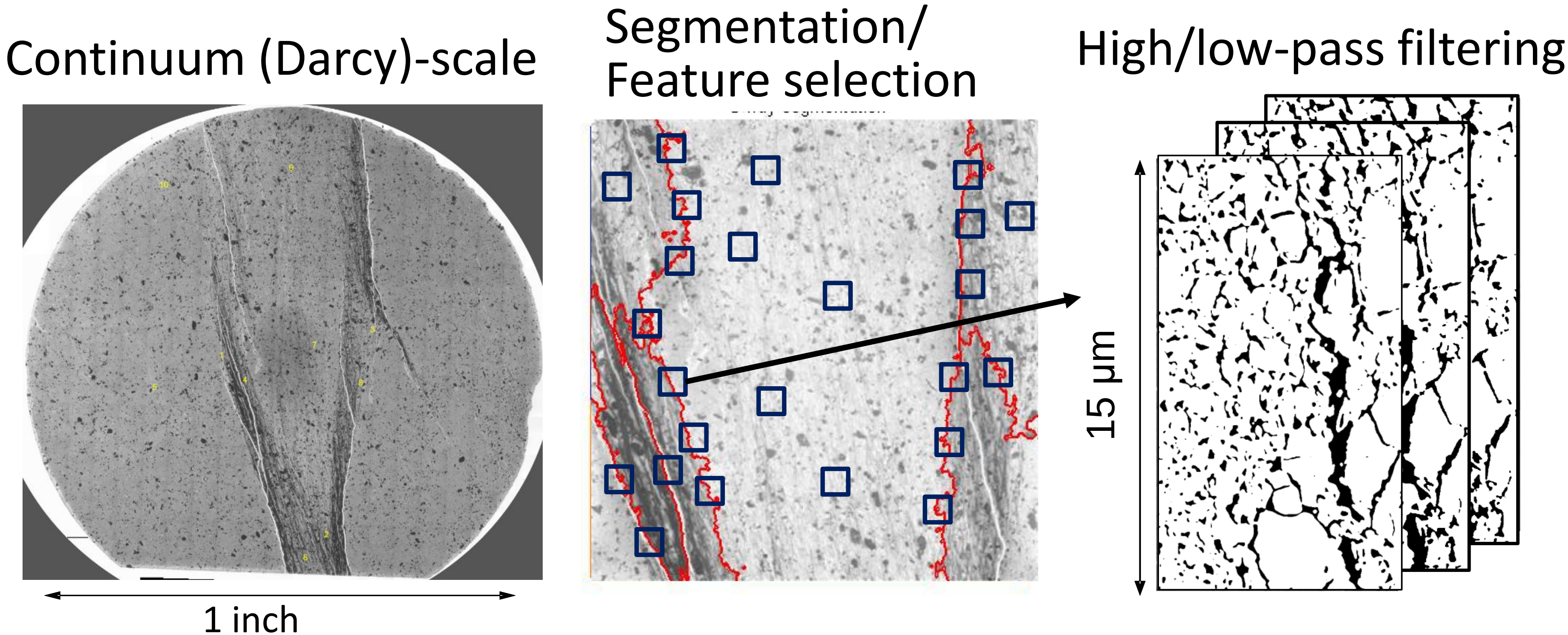


2D Thin Section



3D microCT image

3D Digital Rock Reconstruction

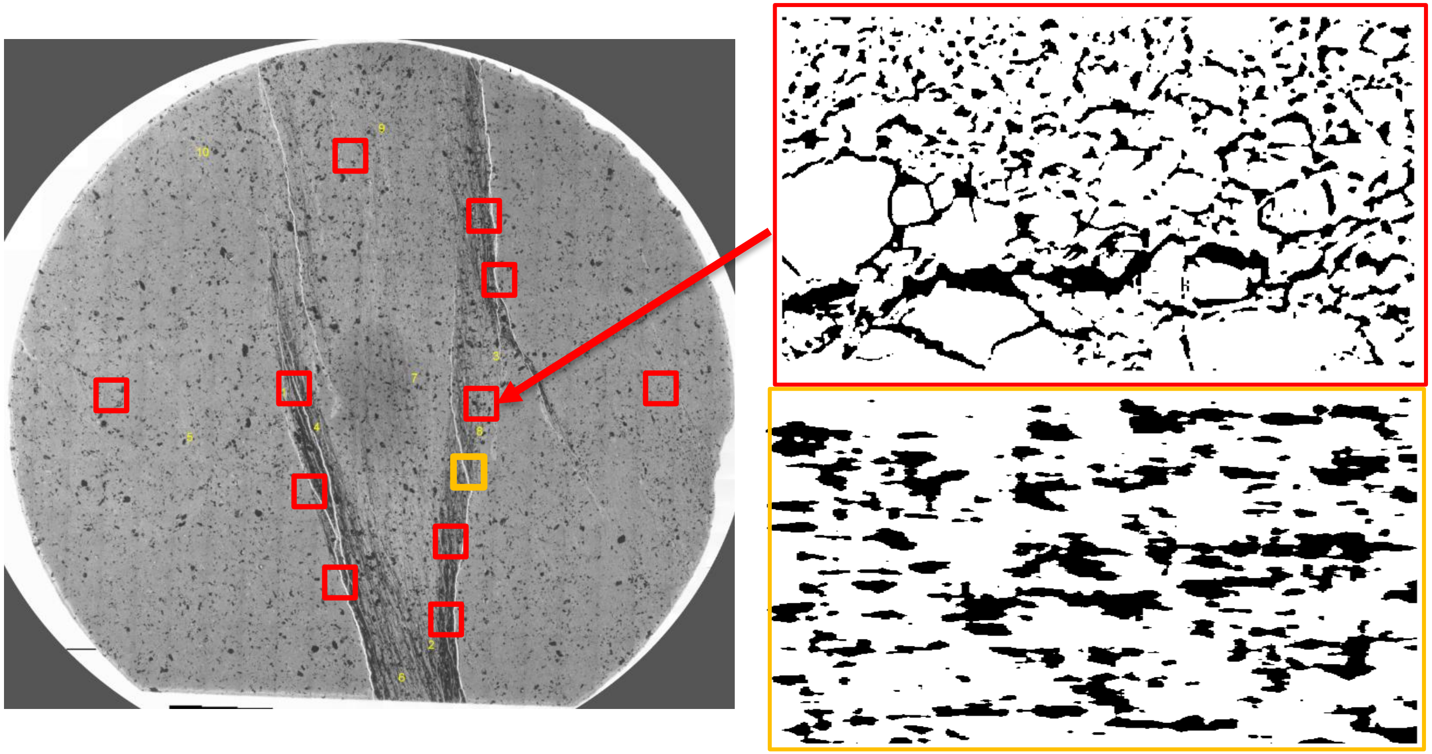


We proposed a “two-scale” approach:

1) Find distinctive features (e.g., micro-fracture, clay seams, matrix) from 2D thin section darcy-scale image for flow and transport modeling

2) Assign effective permeability or response function computed from pore-scale simulations using nano-scale chalk images

Stochastic Approach for Digital Rock Reconstruction

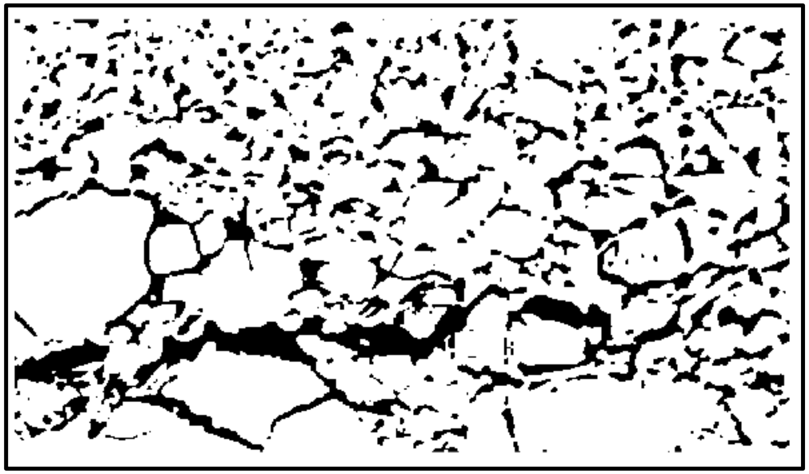


Original chalk image

Reconstructed image using Gaussian model

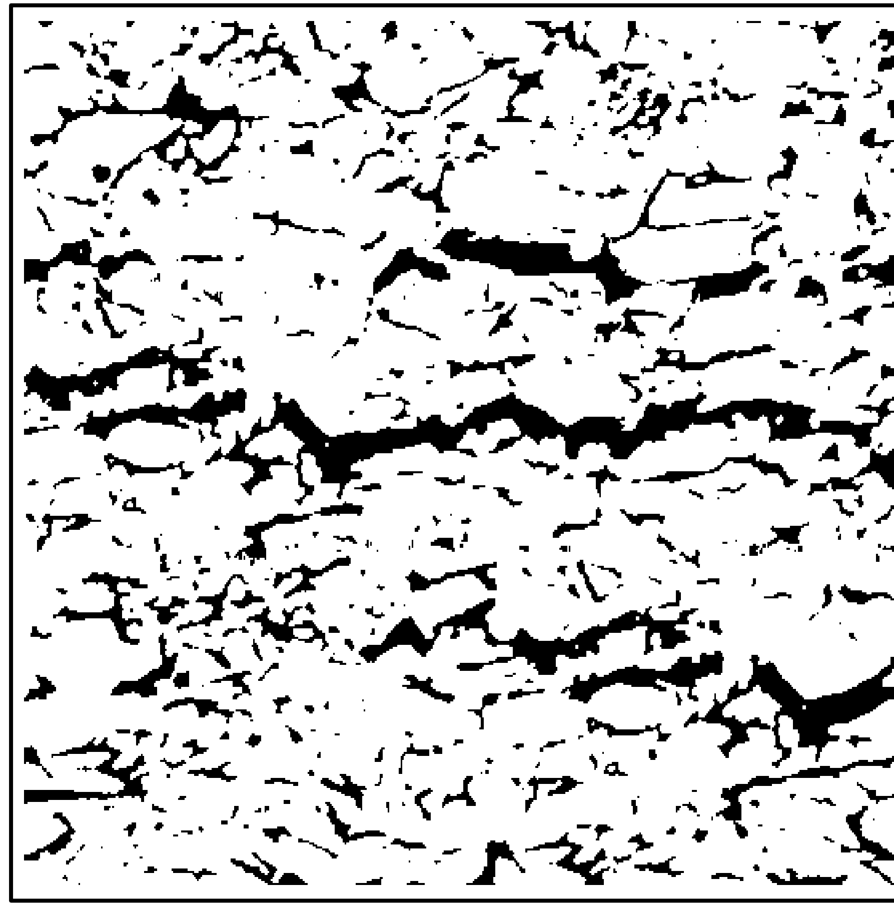
- Traditional two-point statistics – fail to reproduce multi-scale features and long-range connectivity
- We use **multiple-point statistics (MPS)** method to carbonate rock reconstruction

MPS – Feature-based Conditional Image Quilting



Original chalk image stack (920 x 500 x 1000)

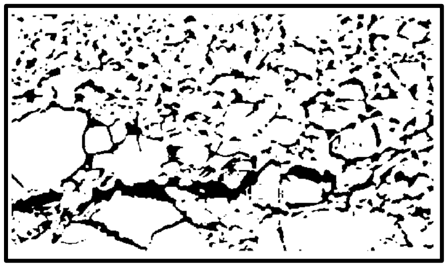
- Porosity, correlation length, Euler characteristics are consistent



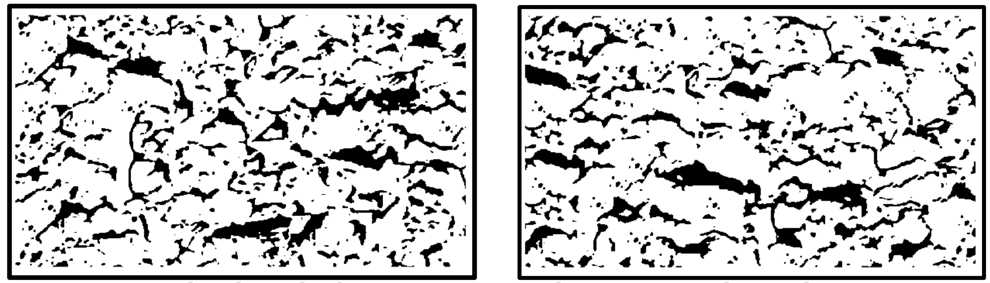
chalk image realization (1000x1000 x 1000)

Ref: Mahmud (WRR, 2014), Simulation of Earth textures by conditional image quilting

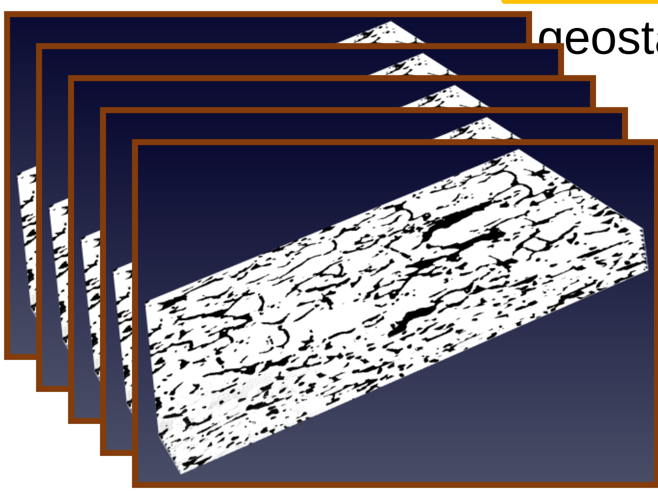
Stochastic Generation of 3D Pore Network



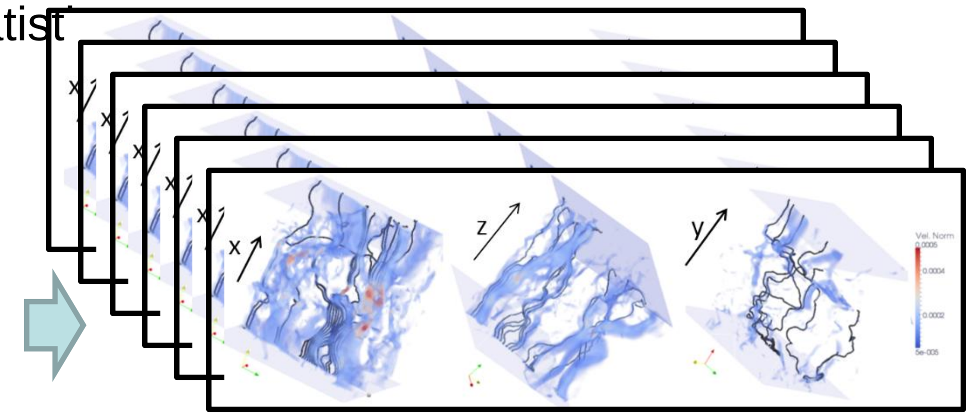
Original chalk image



Generated chalk images using multi-point geostatist



Reconstructed 3D pore network

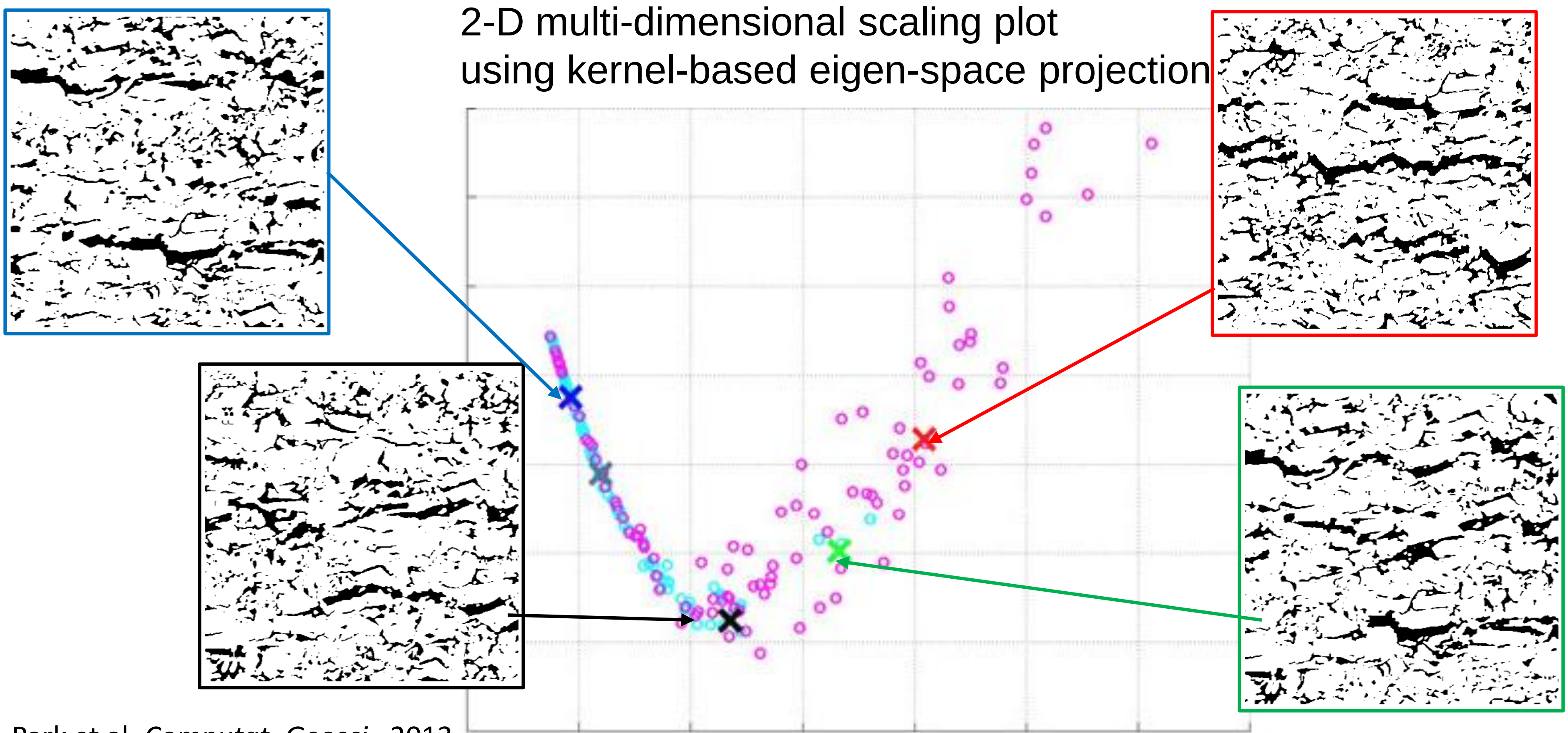


Monte Carlo simulation to find statistically averaged properties

- Effective model parameters (i.e., permeability) computed from pore-scale simulation using a large number of chalk realizations and statistical average values are assigned to the Darcy-scale chalk image -> Expensive!!!

Dimension Reduction for Ensemble Members

- A large number of pore-scale simulations needed for upscaling
- Using low-dimensional distance-based transformed space, a relatively small number of representative chalk realizations can be chosen



Park et al, *Computat. Geosci.*, 2013

Summary

- Recent advances in multiscale imaging capabilities provide rich 3D imaging data (e.g., microCT and FIB-SEM) to reconstruct 3D stochastic members
- For Darcy-scale (i.e., continuum scale) data, 2D thin-sections with 3D microCT images can provide training images for features, connectivity, and hard data
- For pore-scale data, data from FIB-SEM images can provide training images for features, connectivity, and hard data to generate stochastic ensemble members at pore scale
- Nonlinear dimension reduction can be effectively applied to reduce the number of ensemble members to represent flow and elastic properties of chalk
- Pore scale single- and multi-phase flow modeling and reactive transport modeling will be performed to assess the accuracy and efficiency of MPS methods