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Multiscale Imaging of Carbonate Rocks and Efficient 3-D Stochastic Rock Reconstruction Through Dimension Reduction

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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

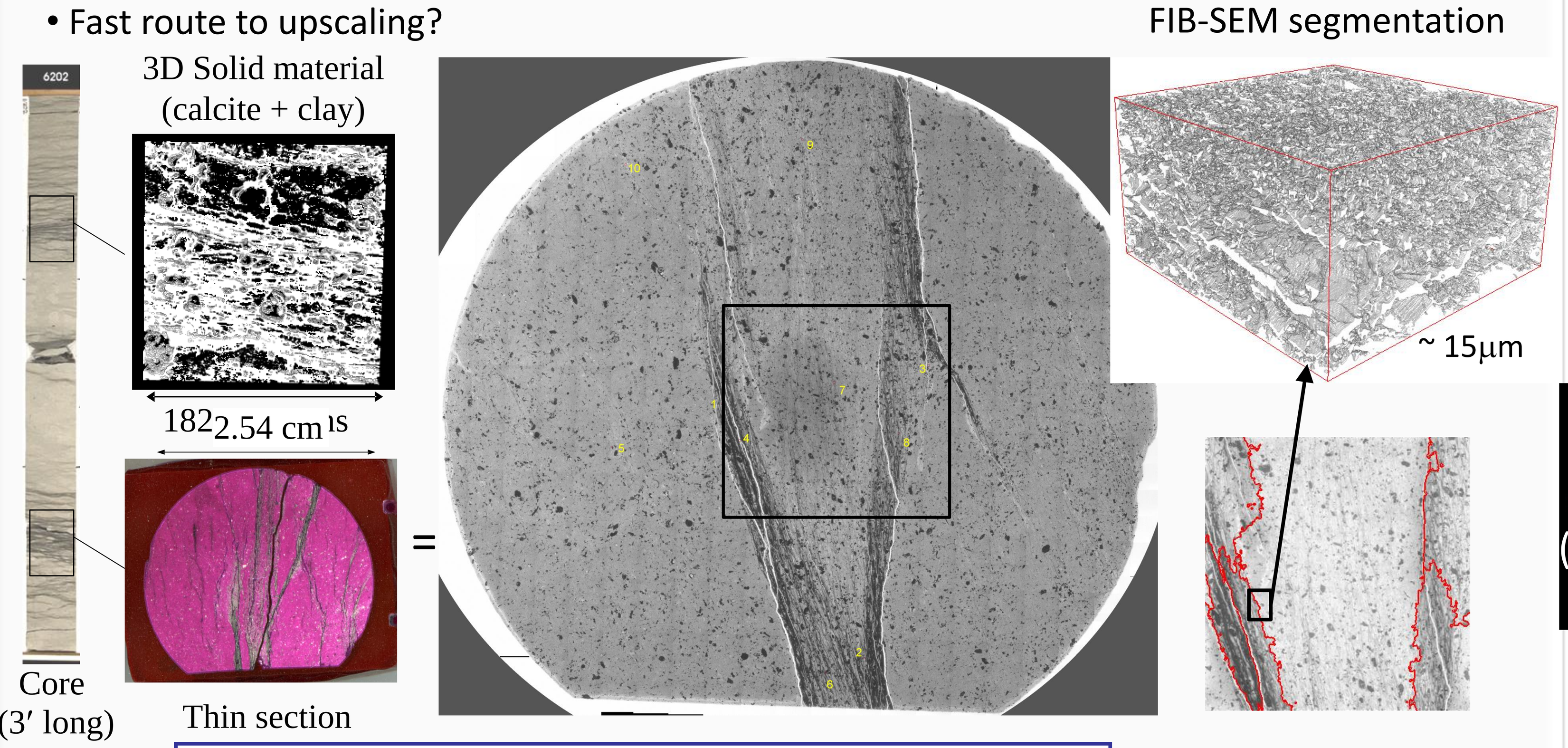
- Reconstruct 3-D stochastic pore structures based on multiscale images and reduce the number of ensemble members through dimension reduction methods
- Develop a workflow for digital rock physics to upscale petrophysical and elastic properties for multiphase flow and reactive transport

Multiscale Imaging and Analysis

•Characterization of pore structures, compositional distribution, and surface properties using multiscale imaging techniques (optical and confocal microscopy, x-ray microprobe, QEMSCAN, microCT, FIB-SEM, BIB-SEM, TEM, EDS)

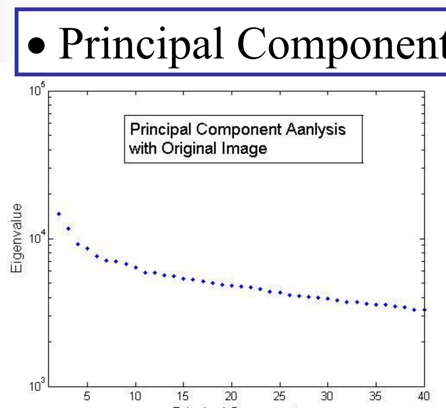
• Fluorescence mapping and feature classification

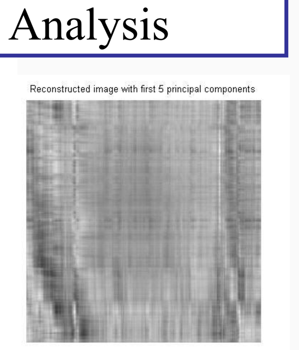
- Fluorescence detection of fluorochromes impregnated in pores
- Spectral segmentation algorithm [e.g., Kim et al. 2013]
- Used as a basis for FIB/SEM sampling
- Fast route to upscaling?



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

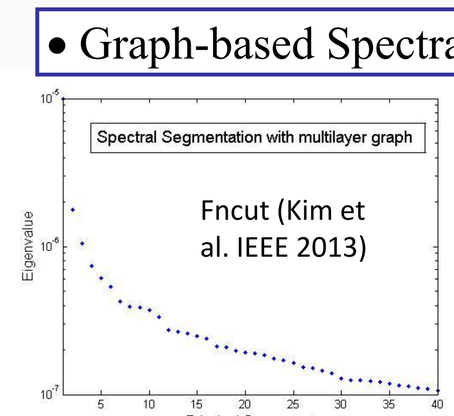
• Principal Component Analysis

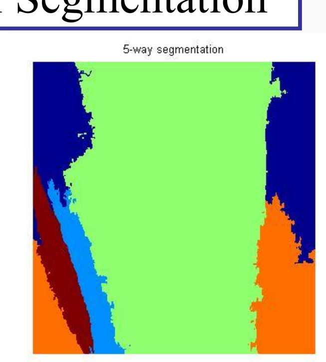




5 principal components

• Graph-based Spectral Segmentation

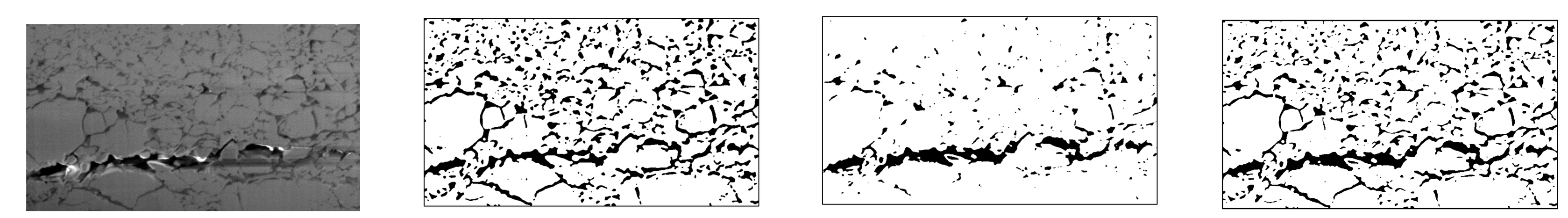




5-way segmentation

Image Analysis and Multiscale Sampling

• Image segmentation



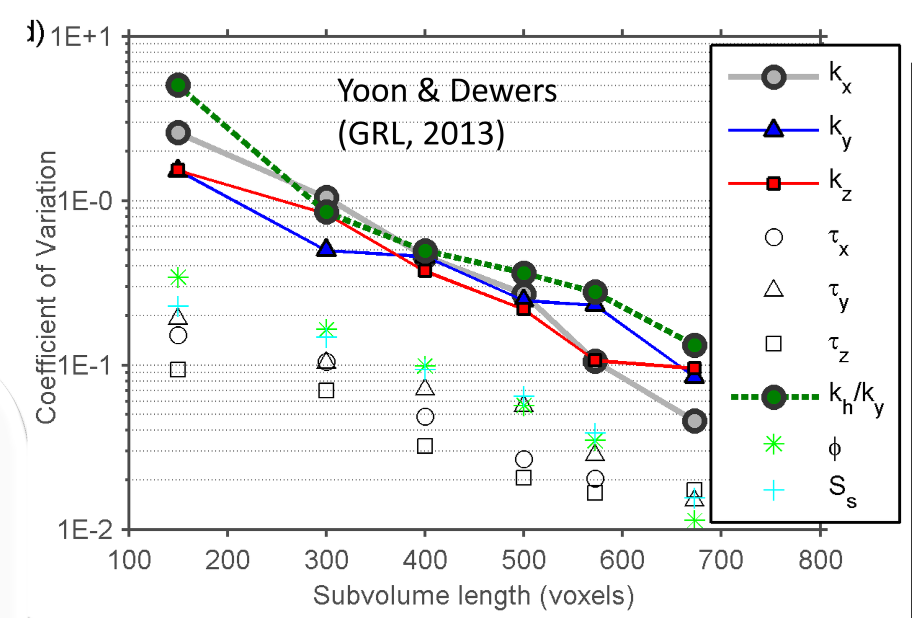
Raw image:
- Uneven background
- Uneven illumination & horizontal scan lines
- Charging effect (bright white spots)

Small pores captured
- Background correction
- FFT bandpass filter
- Median filter
- Thresholding

Large fractures captured
- Background correction
- Median filter
- Higher threshold value

Connectivity recovered
- Combine two binary images
- Dilate & Erode (twice)

• Reconstruct 3-D pore structures and multi-scale pore networks

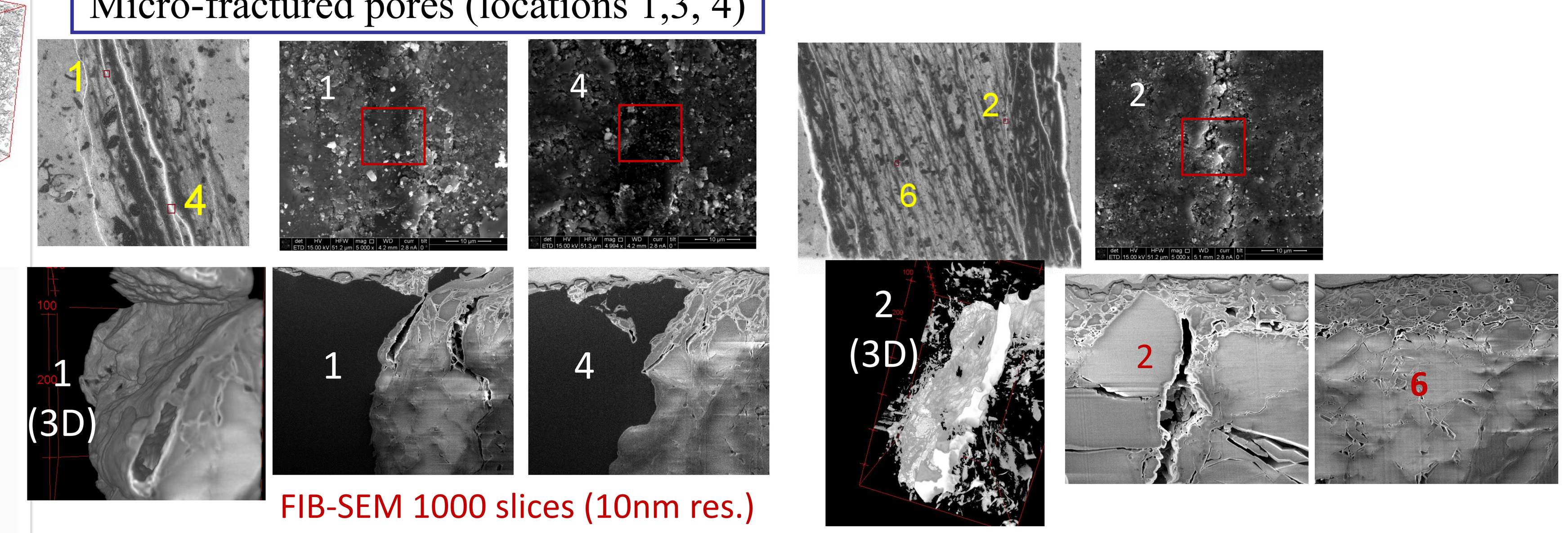


- FIB-SEM sample volume has a size of statistical elementary volume at ~ 10 μm
- Based on this analysis, 4-7 spots can be selected to account for nanopore structures which can not be resolved at thin section

- The thin section image can be segmented into primary clustering representing main features
- Microfracture can be treated as an inclusion of local heterogeneity in addition to main clusters
- Primary spots can be selected to represent one microfracture network and one around the microfracture, one from central region, and the last one from secondary microfracture networks
- Support vector machine (SVM) will be used for texture classification in the following analysis

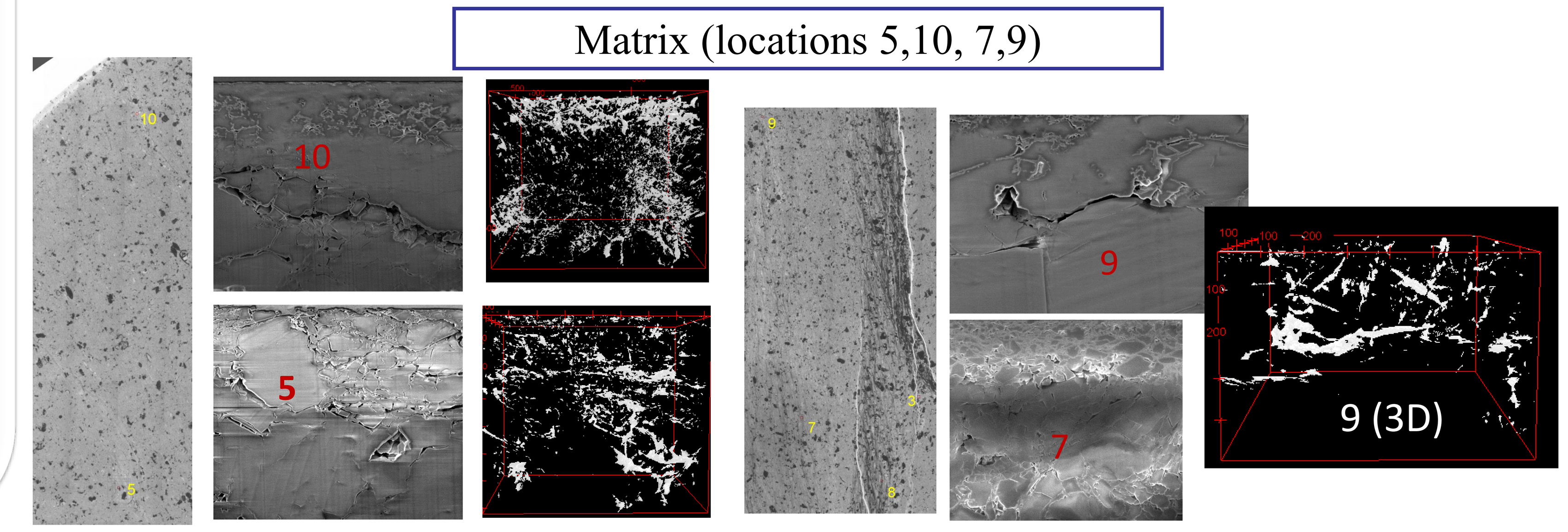
• Representative microfacies based on FIB-SEM analysis

Micro-fractured pores (locations 1,3, 4)

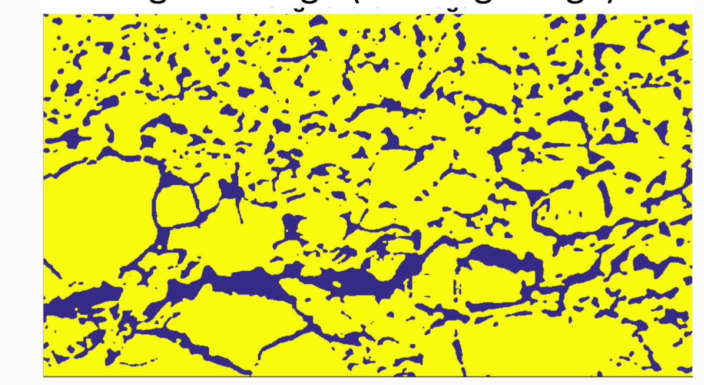


FIB-SEM 1000 slices (10nm res.)

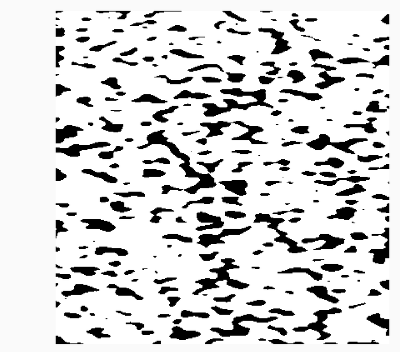
Matrix (locations 5,10, 7,9)



Workflow for Digital Rock Physics



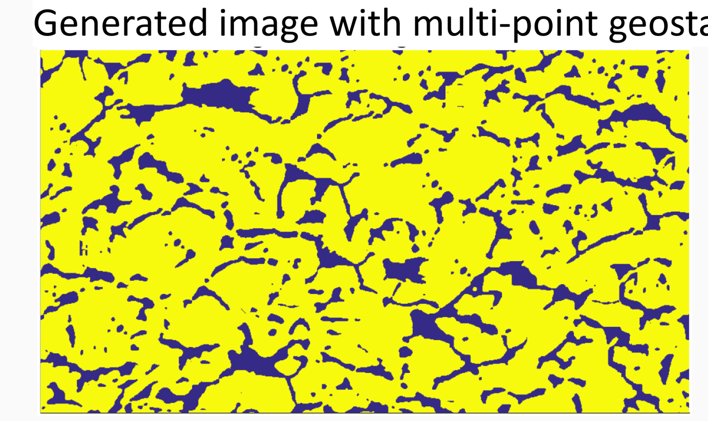
Original Image (Training Image)



Generated image with 2-point correlation

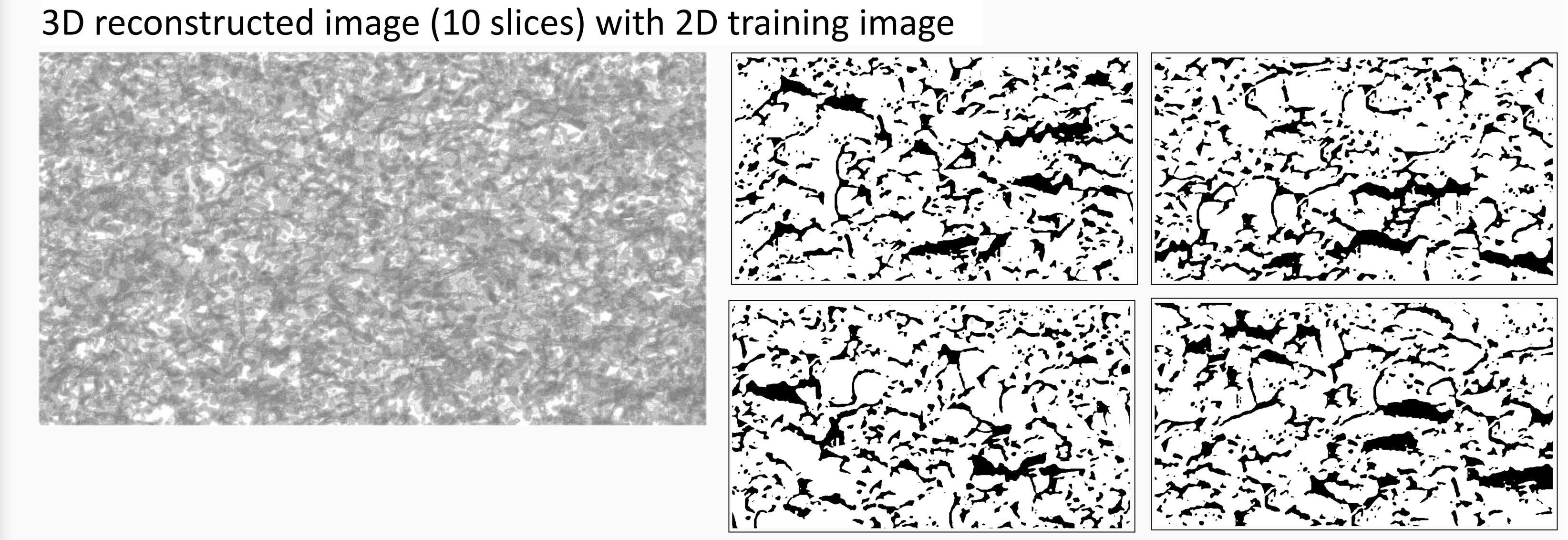
Traditional two-point statistics is not enough to characterize the long-range connectivity
A prior geological interpretation is required and it is NOT multi-Gaussian

Generated image with multi-point geostatistics



- Image Quilting (IQ, Mahmud et al. WRR2014) as an example of multiple-point statistical techniques was used to regenerate carbonate rock image
- IQ reproduces the long range connectivity well
- Preserving porosity and identifying suitable training images need further study

3D reconstructed image (10 slices) with 2D training image



Slices of 3D regenerated data

Research Directions

- Testing of training images
  - For pore-scale data, 2D thin-sections can provide training images for multiple-point statistics to describe features, connectivity, and hard data
  - Recent advances in multiscale imaging capabilities currently provide rich 3D imaging data (e.g., microCT and FIB-SEM) to reconstruct 3D stochastic members
  - At the field scale, outcrops (2D images) can be used as training data sets for petroleum geostatistics
- Nonlinear dimension reduction will be 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

References

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- T.H. Kim, K.M. Lee, and S.U. Lee, "Learning Full Pairwise Affinities for Spectral Segmentation," IEEE Transactions on Pattern Analysis and Machine Intelligence, 2013
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NNSA National Nuclear Security Administration

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