

## Abstract

Our overall objective is development of a technique for predicting reservoir behavior from the pore structure of low-permeability rock. Our approach is based on acquiring micro and nanometer-scale images of the pore structure of natural rocks using synchrotron X-ray computed microtomography (CT) at the Advanced Light Source and Focused Ion Beam (FIB) milling at the Molecular Foundry at Lawrence Berkeley National Laboratory. These techniques provide three dimensional images of the rich diversity of pore structures present in so called “unconventional resources.” Using these images as input data, Maximal Inscribed Spheres simulations are used to evaluate the two-phase flow properties of the rock.

## Motivation

Gas shale and tight sands are examples of low-permeability formations containing enormous quantities of natural gas. As the availability of energy resources in conventional reservoirs is declining, the importance of these unconventional reservoirs is increasing.

Unconventional production is the largest source of U.S. natural gas supply // U.S. EIA Annual Energy Outlook 2009 with Projections to 2030

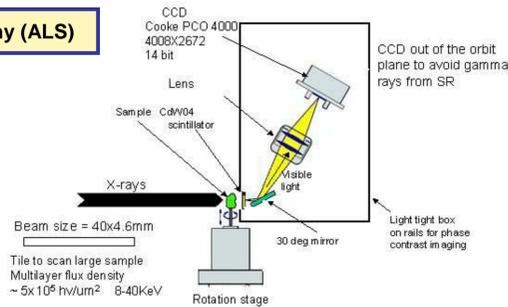
U.S. estimated shale, tight sand, and CBM gas resources: over 8,000 Tcf // Holditch S.A.: SPE 103356

U.S. gas consumption: 22 Tcf / year // U.S. EIA

## Methods

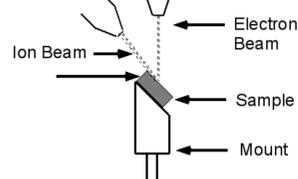
### X-ray microtomography (ALS)

- Micron-scale voxel size
- Large imaging area
- High contrast



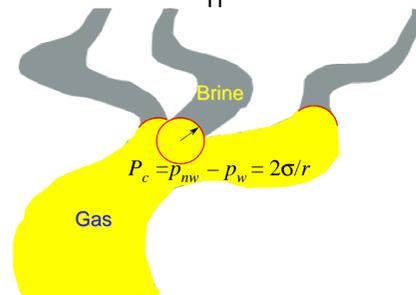
### Focused ion beam (FIB)

- Nanometer-scale voxel size
- Sequential milling and imaging

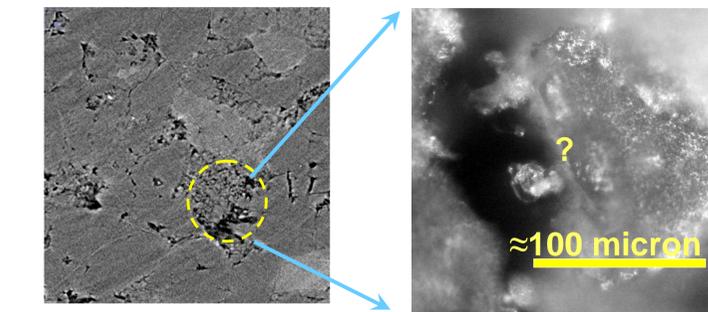
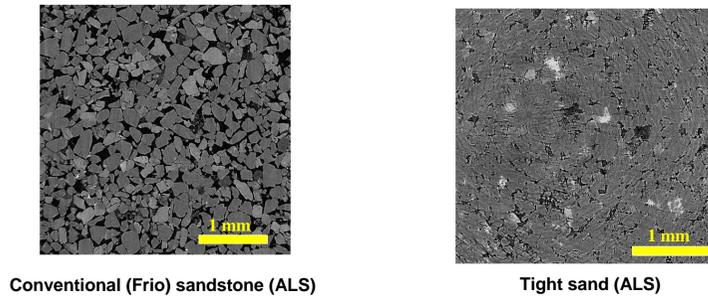


### Maximal Inscribed Spheres (MIS)

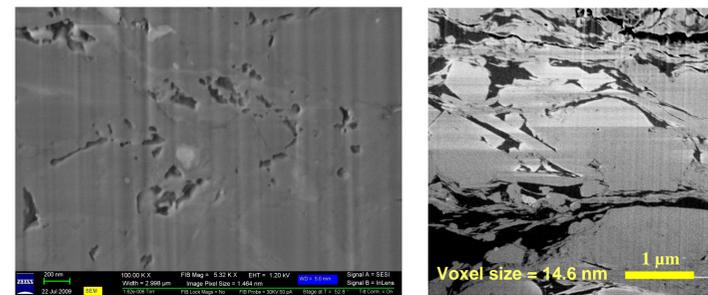
- Capillary equilibrium
- Fluid distribution
- Capillary pressure curve
- Porosimetry



## Pore space geometry

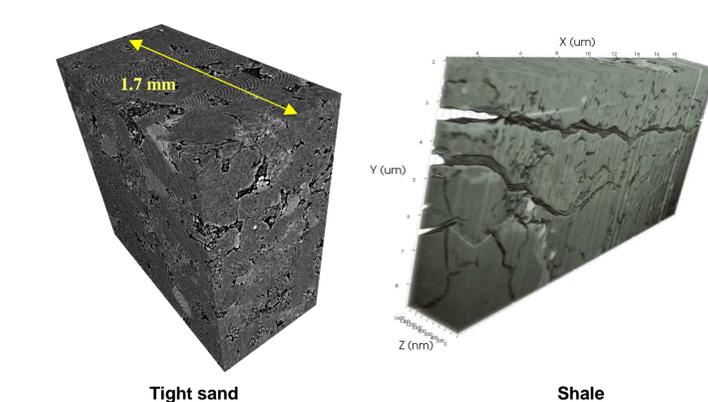


Tight sand: zooming into the pores

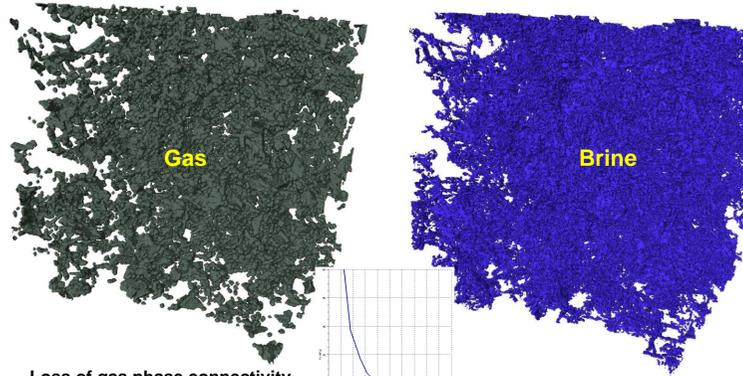


Nanometer-scale porosity (FIB/SEM) Gas shale (FIB/SEM)

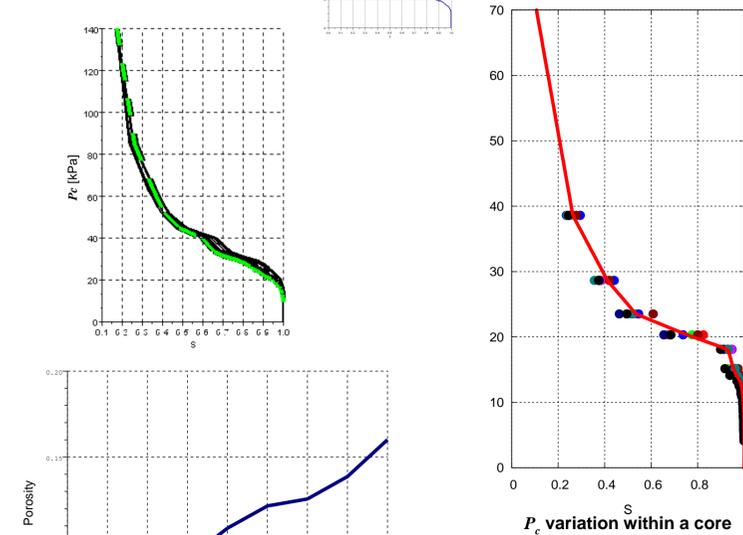
## 3D reconstruction



## Analysis



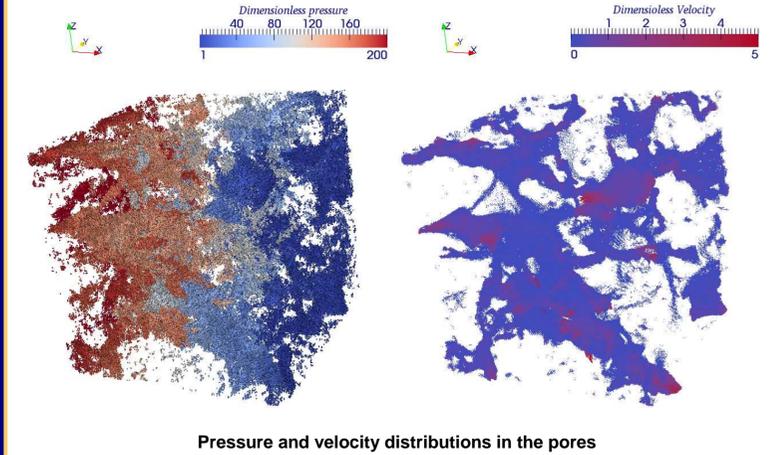
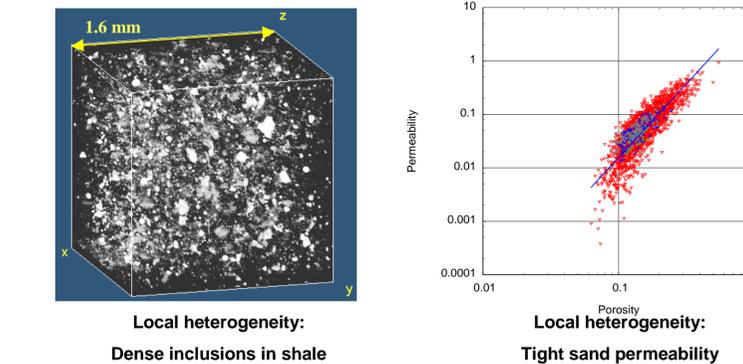
Loss of gas phase connectivity



$$\eta \nabla^2 v = \nabla p$$

$$\nabla \cdot v = 0$$

Slippage:  $v_\tau = G \frac{\partial v_\tau}{\partial n}$



## Conclusions

Unconventional reservoir rocks is an umbrella term covering a rich variety of porous media. Each rock has features making it different from the others. X-ray micro-CT along with nanometer-scale FIB imaging characterize 3D pore space geometry. Flow and fluid distribution simulations on real pore space geometry may offer a viable alternative to core experiments, which are difficult and time-consuming due to the extremely low permeability of the rock.

Uncertainties of the approach: Small sampling volume (scale up); Limited resolution; Binary data segmentation.

MIS computations are efficient, robust with respect to the uncertainties of segmentation. Predictive capabilities are limited by sub-resolution-scale uncertainties. The model assumes capillary equilibrium and is sensitive to binary data noise.

Finite-difference flow simulations can handle a variety of boundary conditions. Problem decoupling and distributed computations can reduce the computer power requirements and improve efficiency.

## References

1. Tomutsa, L., Silin, D., and Radmilovic, V. Nanometer-Scale Imaging and Pore-Scale Fluid Flow Modeling in Chalk, SPE Reservoir Evaluation and Engineering Journal, 2007, June, v. 10, 3, p. 285-293
2. Silin, D. B., and Patzek, T. W. Pore space morphology analysis using maximal inscribed spheres. Physica A, 371:336-360, 2006

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