Organic and Nonorganic Characterization of the Bakken, Marcellus, Pierre, and Woodford

Circe Verba[1*], Dustin Crandall[1], Johnathan Moore[2]

[1]U. S. Department of Energy, Research and Innovation Center, National Energy Technology Laboratory, Albany, OR; USA
[2]AECOM, National Energy Technology Laboratory, Morgantown, WV; USA

The development of effective strategies for hydrocarbon extraction through unconventional shales requires a comprehensive understanding of shale petrophysical properties – specifically the variability of fabric, composition, matrix, porosity, permeability, and thermal maturity/organic content [1-5]. Unconventional resource extraction from shale can involve the injection of carbon dioxide (CO_2) to dissolve within crude oil lowering viscosity and improving recovery. In addition to their hydrocarbon resource value, depleted shale gas reservoirs are being considered for geologic carbon storage (GCS) [1,2,6]. Shale reservoirs are heterogeneous across multiple scales which can make it difficult to predict flow pathways for hydrocarbon migration. The aim of this study was to characterize shale from the Bakken, Marcellus, Pierre, and Woodford formations using different imaging techniques. High resolution computed tomography (CT) was performed to provide multiscale heterogeneity and structure. Correlative focused ion beam-scanning electron microscopy (FIB-SEM) was used to create high resolution images of total porosity, pore distribution, organic volume, and organic hosted porosity. The application of these imaging technologies will help to improve scientific understanding of shale petrophysical properties.

A ZEISS Xradia MicroXCT-400 scanner was used to image ~3 mm diameter sub-cores of the Bakken, Marcellus, and Woodford samples; the Pierre sample could not be obtained due to the mechanical weakness. CT scanned volumes – roughly 9.5 mm^3 in size with a voxel resolution of 0.812 μm^3 – were obtained. The XCT does not reveal composition of the shale: rather, it differentiates microfractures along bedding planes, macropores, and organic matter. To resolve the pore network and related petrophysical properties, a FEI Inspect F field emission SEM with an Oxford energy-dispersive spectrometer (EDS) was used congruently with a Helios FIB-SEM to image the shales in 3 dimensions using a 10 nm/voxel slice size milled at 30 kV (i-beam) and accelerating voltage of 1-3 kV (e-beam). FIB-SEM image slices were processed using Avizo 9® Digital Rock Physics modules. Additional image post-processing was used to interrogate porosity (interparticle, intraparticle, and organic hosted), organic and inorganic constituents, pore diameter, and volume distribution.

The CT scanning revealed that the heterogeneity observed in the micro-fabric via FIB-SEM was not scale dependent. Bedding, partings and/or fractures (>1 µm) throughout the matrix existed in all samples analyzed. The Marcellus sample had the greatest amount of heterogeneity as shown by the presence of a mineral rich organic band in the scan. The Bakken and Woodford shale samples were more uniform, but demonstrated anisotropy based on fractures, mineral zonation, and variable fabric.

FIB-SEM analysis enabled direct evaluation of the porosity. The Bakken sample had the highest total porosity of 27%, whereas the sample with the lowest porosity was 0.8% in the Woodford. Respectively, the greatest percentage of mesopores (0.002-0.05 µm) was within the Bakken (53.4%), followed by the Woodford (31.3%); the remainder of pores sizes fell within the macropore range. The Marcellus samples and the Pierre sample pore sizes are predominantly macropores (>0.05 µm). Because smaller pores have more surface area than larger pores of the same overall volume, there are more surface sorption sites for CO_2 in shales with smaller pore diameters. Both pore size and overall porosity have important implications for GCS, and a shale such as the Bakken with high overall porosity and a high proportion of mesopores should be evaluated as a potentially significant resource for GCS.

CT and FIB-SEM characterization revealed considerable differences between the organic and nonorganic matter between the four shales. The results of this study subsidize publically available data of shale microstructures and provide a basis for a statistically significant sampling. These petrophysical properties provide physical controls these properties within and across shale plays that is critical for reducing uncertainty in recovery and developing GCS strategies.

References:
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[7] The authors acknowledge Oregon State University Electron Microscopy Facility for FIB-SEM data collection and reconstructions.

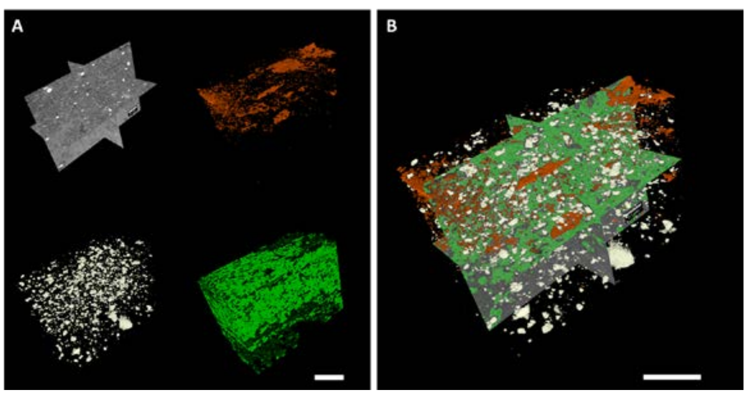

Figure 1. CT image of the Marcellus. (A) Orthographic slices through the greyscale CT volume, fractures (orange), heavy minerals (white), and organic matter (green). Scale bar ~0.25 mm. (B) Combined isolated features.

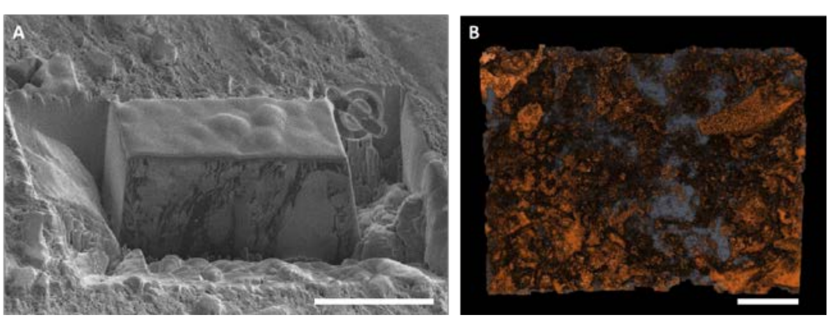

Figure 2. FIB-SEM of Bakken shale (A) Backscatter electron image. Scale bar is 20 µm. (B) Segmented porosity image. Scale bar is 10 µm.