PS Visualization and Quantification of 3D Pore Networks in Tight Reservoir Rocks Using Confocal Laser Scanning Microscopy*

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Abstract

Imaging micropores from core samples and cuttings is a key building block for accurately evaluating the volumetric pore space of a rock sample. Standard petrographic techniques have limited value for micropore quantification due to the interference of multiple crystallographic layers and limited optical resolution. High-resolution imaging techniques, such as SEM and micro-CT scanning have played a pivotal role in the characterization of micropores. However, these latter imaging techniques are destructive, and/or they cannot easily obtain a wide field of view, thus provide a limited understanding of the variable pore types in a sample. This study discusses the technical and practical aspects of Confocal Laser Scanning Microscopy (CLSM) with application to imaging and quantifying complex micropore networks in tight hydrocarbon reservoirs. In the life sciences, CLSM is an established multidimensional light microscopy technique for imaging fluorescently-labeled specimens. In the geosciences, CLSM recently has been applied as a promising method for generating high-resolution 3D datasets of pore networks in conventional and unconventional reservoirs that can help to bridge the resolution gap between standard petrographic microscopy and higher-resolution techniques. The ability to produce optical sections – a non-destructive imaging approach which uses light rather than a physical method to section the sample – allows the imaging of pore networks in delicate samples and the reproduction of results, thus helping to build confidence in the analysis. In this study, optical sections were captured down to a resolution of ~300 nm in the vertical direction and ~ 200 nm in the horizontal direction to image and quantify the 3D pore volume and 3D pore network of tight reservoir rock samples from a variety of North American basins. The dominant pore size distribution was determined by applying spatial statistics and ranges from <1µm to ~25µm in the analyzed samples. Pore volumes were calculated using image analysis techniques and are confirmed by independent porosity and permeability measurements. Most importantly, the reservoir rocks analyzed as part of this study reveal a complex anisotropic pore network at a scale that is below the resolution limit of standard optical microscopy but exceeding the boundaries of higher resolution techniques. The results from this study aim to serve as the input parameters for advanced flow models and flow simulations.

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This study discusses the technical and practical aspects of Confocal Laser Scanning Microscopy (CLSM) with application to imaging and quantifying complex micropore networks in tight hydrocarbon reservoirs. In the life sciences, CLSM is an established multidimensional light microscopy technique for imaging fluorescently-labeled specimens. In the geosciences, CLSM recently has been applied as a promising method for generating high-resolution 3D datasets of pore networks in conventional and unconventional reservoirs that can help to bridge the resolution gap between standard petrographic microscopy and higher-resolution techniques. The ability to produce optical sections – a non-destructive imaging approach which uses light rather than a physical method to section the sample – allows the imaging of pore networks in delicate samples and the reproduction of results, thus helping to build confidence in the analysis.

In this study, optical sections were captured down to a resolution of ~300 nm in the vertical direction and ~ 200 nm in the horizontal direction to image and quantify the 3D pore volume and 3D pore network of tight reservoir rock samples from a variety of North American basins. The dominant pore size distribution was determined by applying spatial statistics and ranges from <1µm to ~25µm in the analyzed samples. Pore volumes were calculated using image analysis techniques and are confirmed by independent porosity and permeability measurements. Most importantly, the reservoir rocks analyzed as part of this study reveal a complex anisotropic pore network at a scale that is below the resolution limit of standard optical microscopy, but exceeding the boundaries of higher resolution techniques. The results from this study aim to serve as the input parameters for advanced flow models and flow simulations.

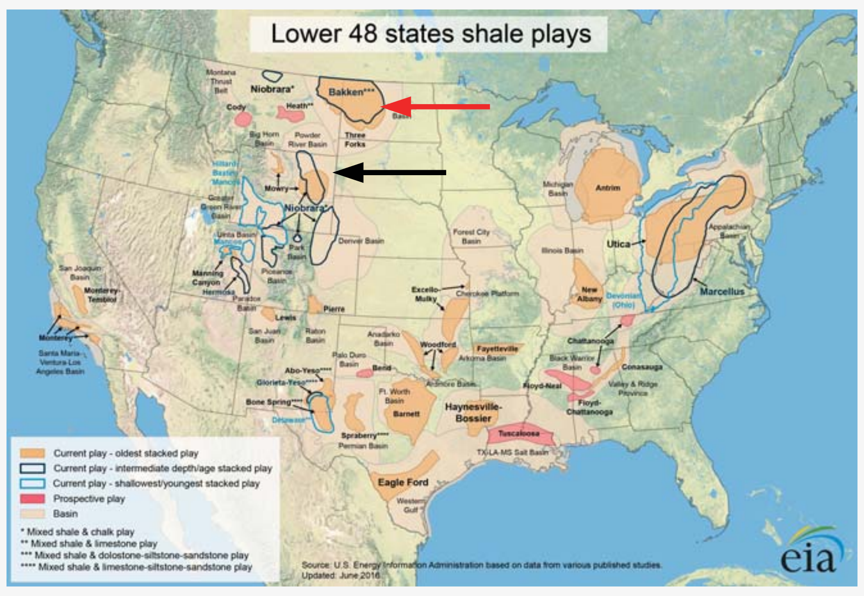
Objectives and Key Findings:

- Quantify pore networks using the confocal 3D visualization technique
- Quantify effective porosity, pore sizes, and pore network relationships
- Understand porosity controls on permeability

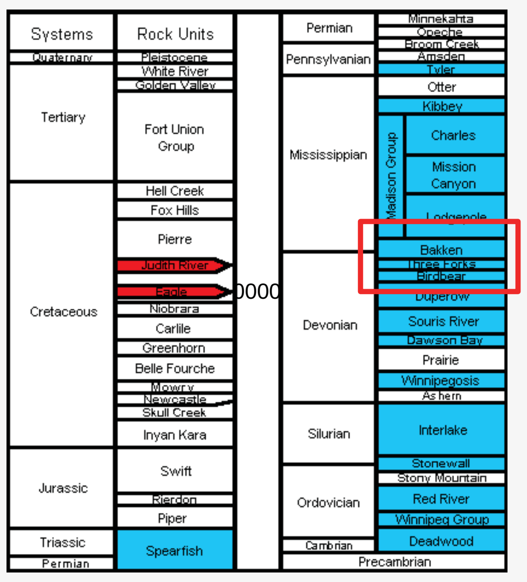
  - Pore distribution in all samples is highly heterolithic, in horizontal and vertical directions
  - The Williston Basin Bakken sample has dominant pore sizes from 6-25 µm with lower total porosity and a less heterogeneous porosity distribution
  - The Powder River Basin Parkman Sandstone sample has dominant pore sizes from 5 to 20 µm with greater total porosity and a highly heterogeneous porosity distribution

Study Areas and Stratigraphy

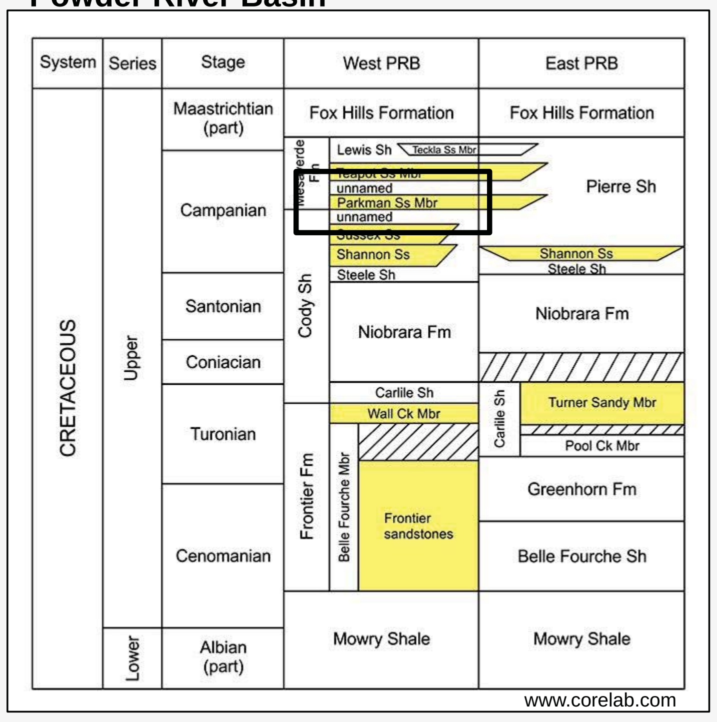
The samples included in this study are from the prolific tight oil Bakken play in the Williston Basin in North Dakota, USA (red arrow) and the Parkman Sandstone in the Powder River Basin in Wyoming, USA (black arrow).

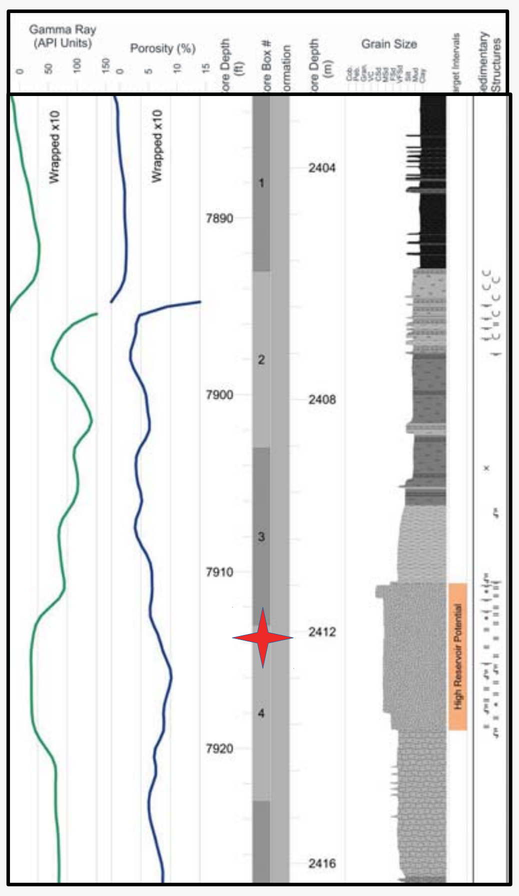


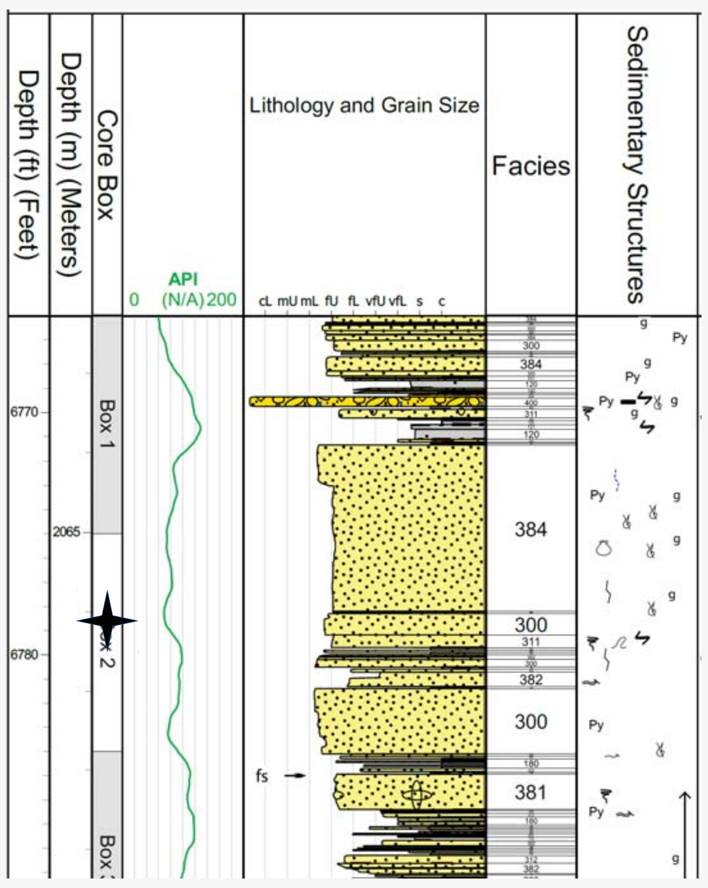
Williston Basin



Powder River Basin





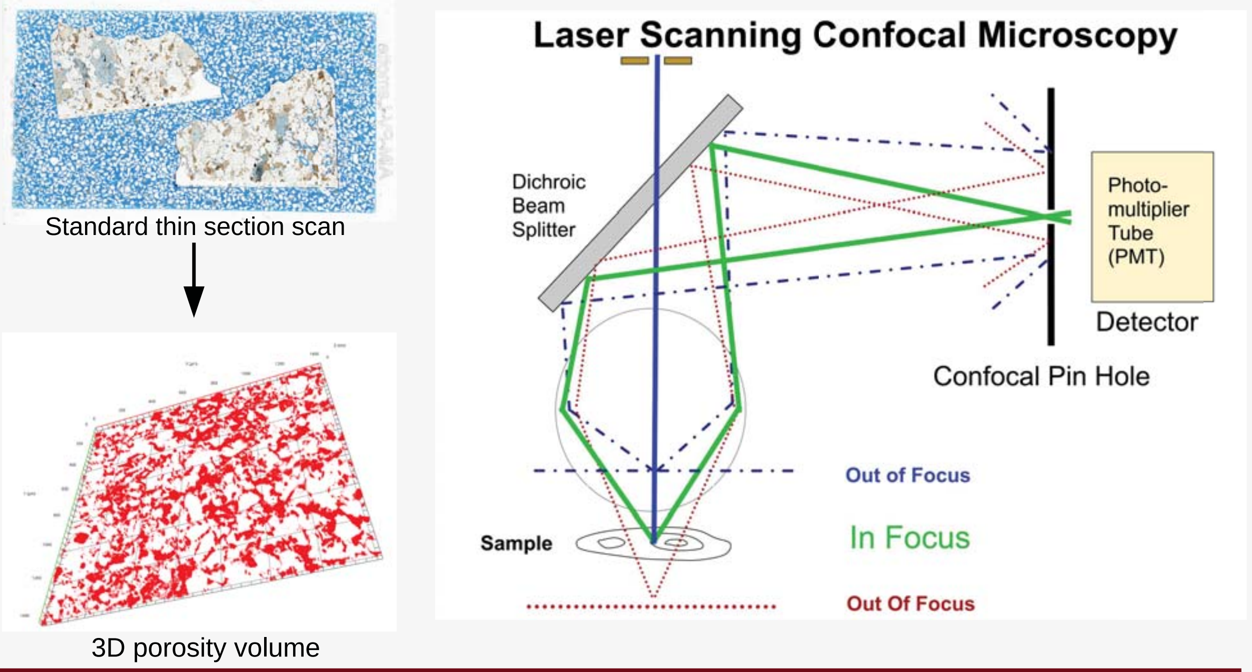


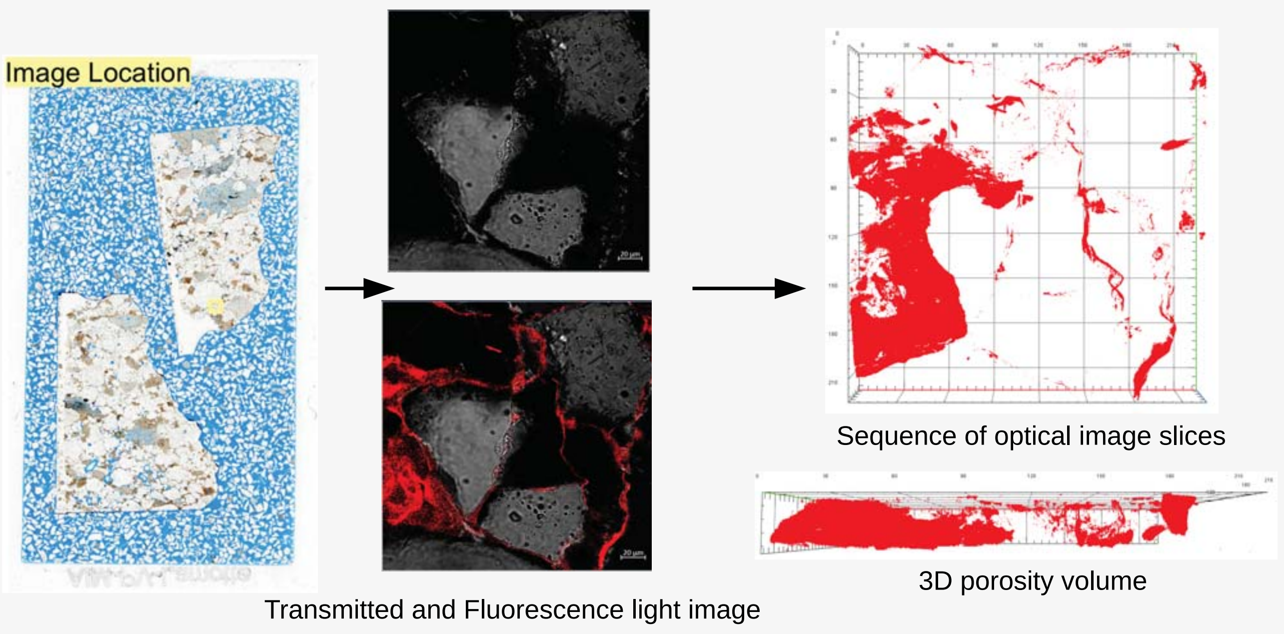
The Williston Basin sample is from the Middle Bakken Formation. The dolomitic quartz arenite is the coarsest grained reservoir unit in the core. Grain size is commonly silt size to vf sand size. Dolomite is common as a cement and replacement mineral, occluding most of the primary porosity visible using standard optical microscopy.

The Powder River Basin samples is from the Parkman Formation. The feldspathic litharenite is a typical example of the main reservoir facies. Grain size is commonly vf to f sand size. Where present, patchy calcite cement destroyed most of the primary pores visible by standard optical microscopy.

Methodology

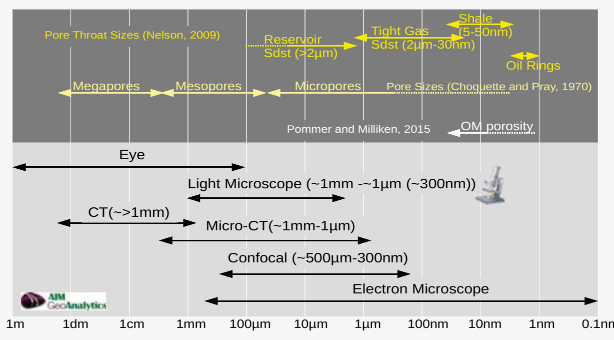
1. Samples are vacuum-impregnated with a fluorescing dye
2. A known excitation wavelength causes the dye to fluoresce
3. The known emission wavelength travels to the detector
4. The pinhole eliminates out-of-focus light
5. Sample and pinhole can move, allowing for vertical optical sectioning





Transmitted and Fluorescence light image

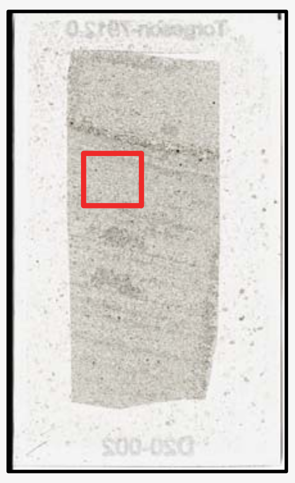
- Standard petrography is resolution-limited by the thin section thickness: ~25 µm
- High-res methods such as micro-CT and FIB-SEM achieve resolutions of 1 µm to nanometers respectively, but at the cost of imaging area
- Confocal imaging achieves a high resolution and larger imaging areas but requires fluorescence and relatively translucent samples

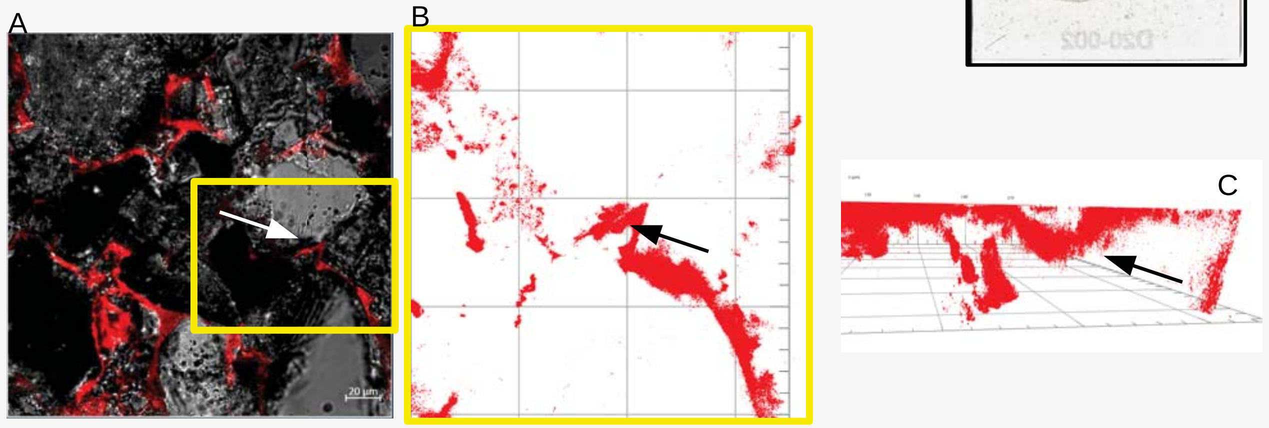


Pore Network Heterogeneity

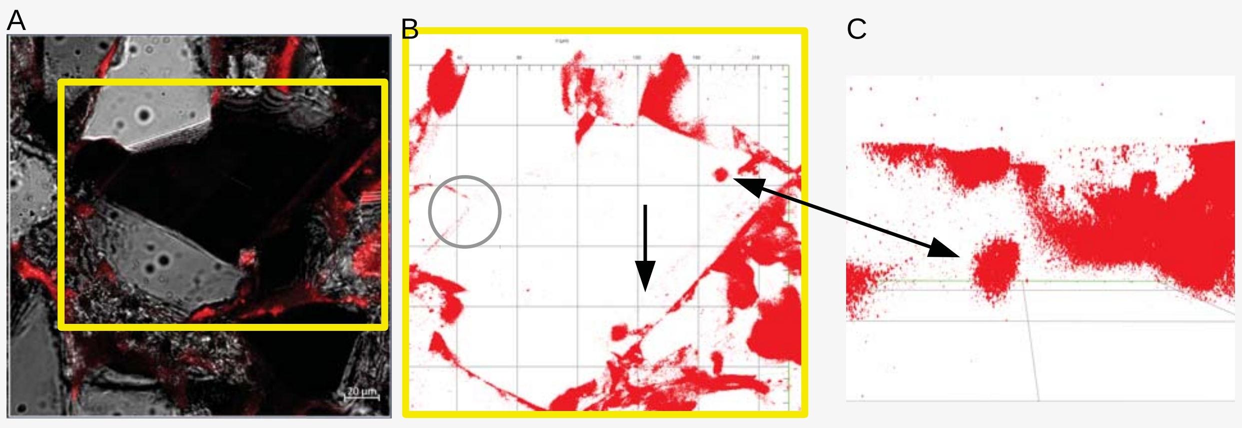
1. Bakken Formation (Williston Basin)

The dolomitic quartz arenite contains large, >25 µm interparticle and intercrystalline pores. However, much primary open porosity is occluded by replacement dolomite and dolomite cement. The large pores are connected by dominantly intercrystalline pores on the scale of 1-10 µm as observed with confocal imaging. Images below acquired within imaging area outlined by red box at right.

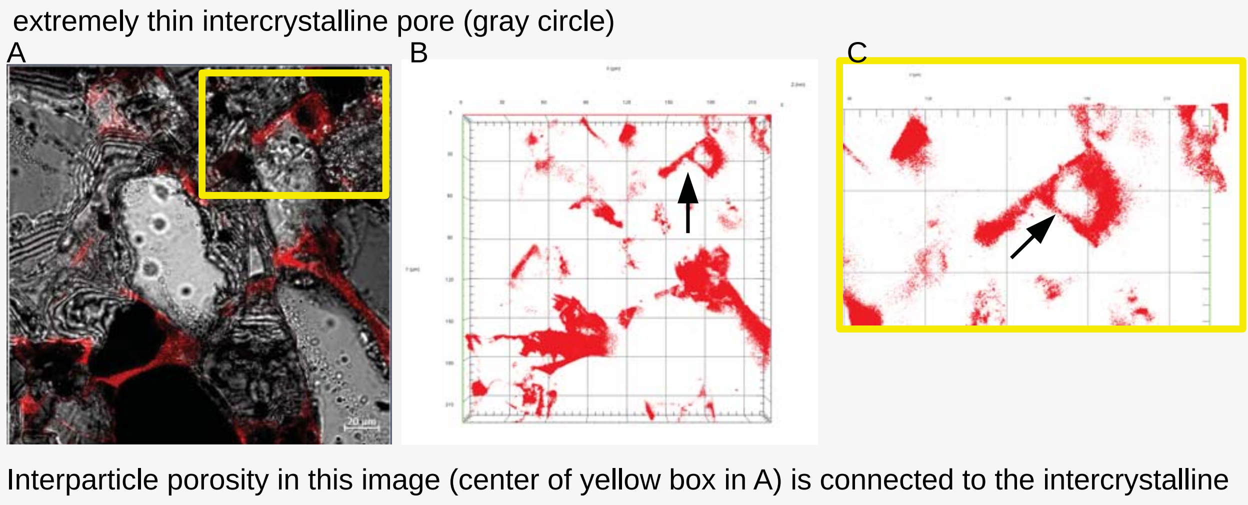




Intercrystalline porosity <20 µm is present (arrows in A, B). This connected intercrystalline pore varies in orientation in the vertical direction (arrow in C)



Dolomite rhomb in center of image exhibits minor intracrystalline porosity at margin (arrow in B). Note the isolated several-micron-scale pore (double-headed arrow in B, C). The pore throats giving it connectivity are likely beyond resolution of confocal method. Also note the extremely thin intercrystalline pore (gray circle)



Interparticle porosity in this image (center of yellow box in A) is connected to the intercrystalline pore network (arrow in B), providing additional storage and connectivity (arrows in B and C)

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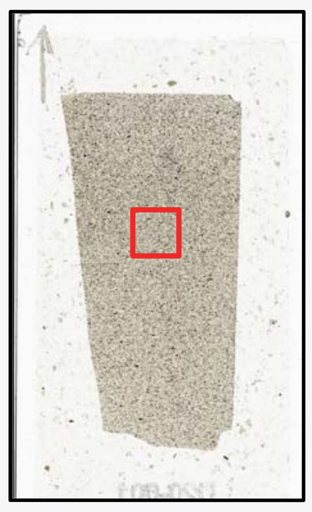
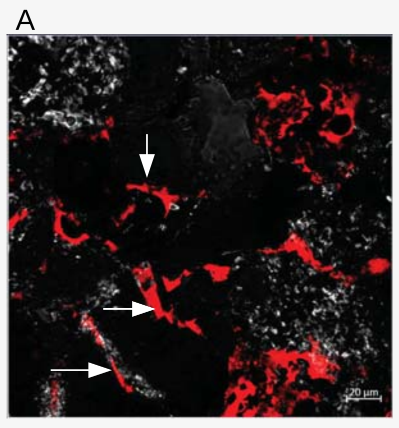
Pore Network Heterogeneity cont.

2. Parkman Sandstone (Powder River Basin)

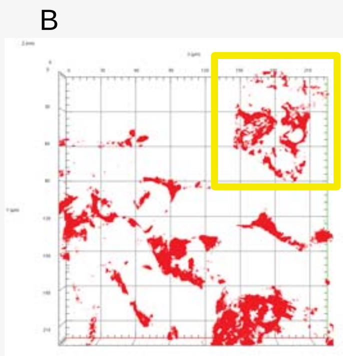
The feldspathic litharenite contains interparticle pores >25 µm. Calcite cement, when present, occludes most primary porosity. The dominant pore type is intercrystalline. These large pores are connected by pores <10 µm in size. Of secondary importance are interparticle pores, found at the margins of rounded vf-f sand grains. Due to the connected nature of intercrystalline and interparticle pores, high-porosity regions contribute to this sample's permeability pathways. Images acquired within area outlined by red box.



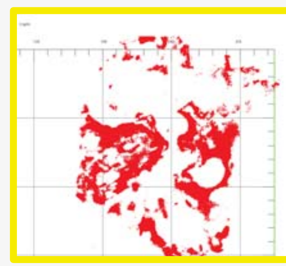
A



B

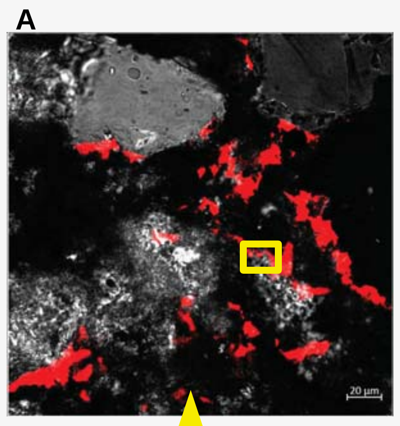


C

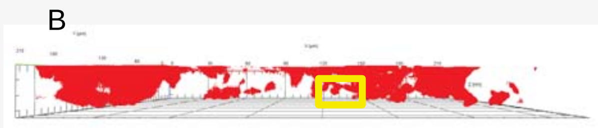


Intercrystalline pores (red) outline the euhedral crystal boundary (middle arrow in A). Interparticle pores (top, bottom arrows in A) are present. A rare region of intracrystalline pores present (C)

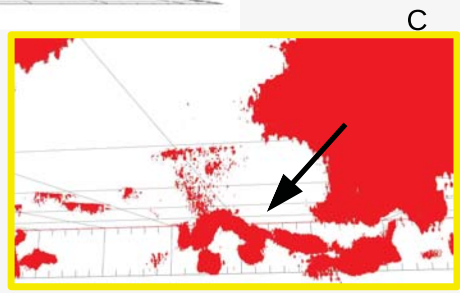
A



B

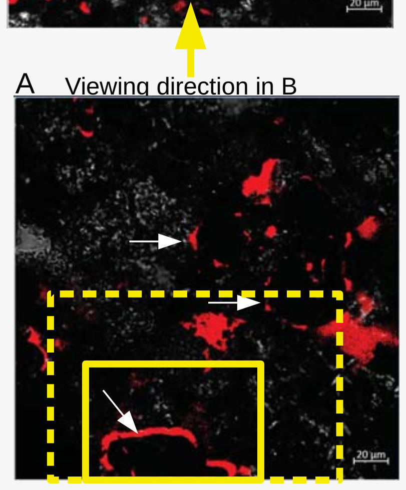


C

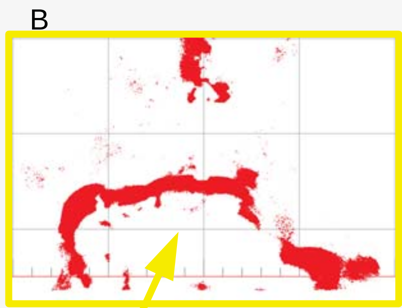


Similar to sample location above, this image shows connected intercrystalline pores (see arrow in C). The intercrystalline pores are variable in orientation in 3D and do not exhibit consistent width

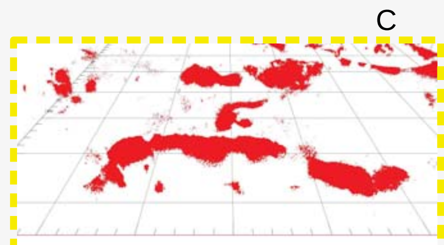
A



B



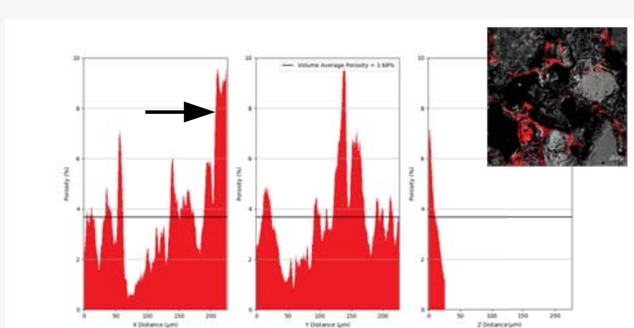
C

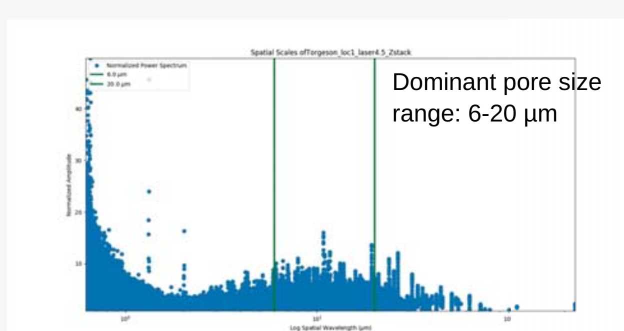


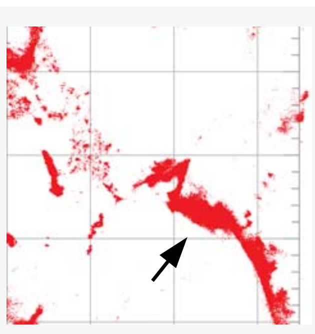
This image shows interparticle pores, along the margins of rounded silt grains (arrows in A). These comprise much of the potential storage for the sample, but may not contribute to connectivity. Dashed yellow box shows approximate field of view of (C).

Porosity Quantification

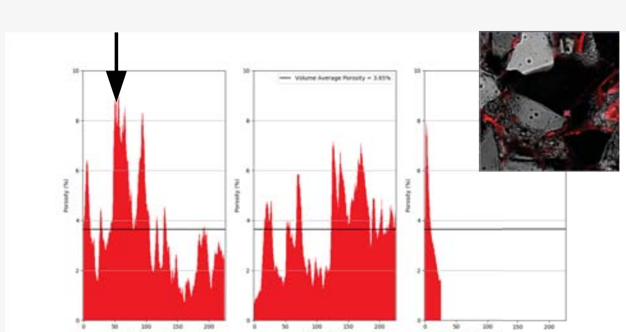
1. Bakken Formation (Williston Basin)

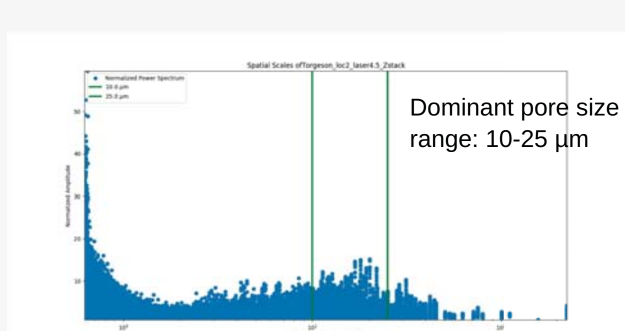


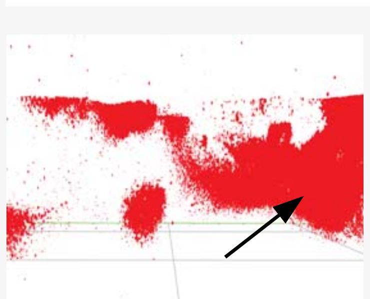




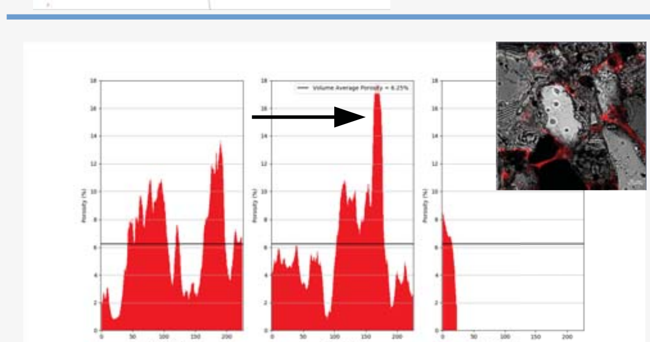
- Average porosity of imaging region (inset above) is 3.68%
- Porosity varies from above 10 (see arrow above) to below 2%
- Small end of the pore size range comprises isolated intraparticle and intracrystalline pores as well as thin, linear intercrystalline pores
- Large end of the pore size range comprises large intercrystalline pores as pictured in image on left

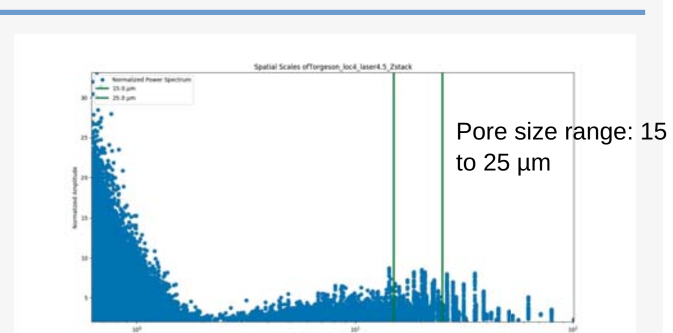


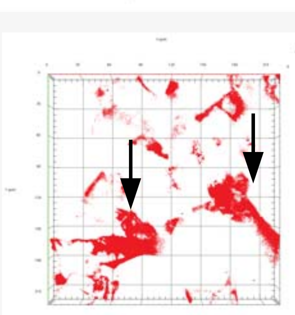




- Average porosity of imaging region (inset) is 3.65%
- High-porosity streaks reach 8% (arrow above), low-porosity streaks below 1%
- Unlike neighboring imaging location above, this location is dominated by larger pores, especially intercrystalline pores at the edge of the large euhedral dolomite crystal (arrow at left)
- Isolated-appearing round pore on the <10 µm scale (left) are uncommon







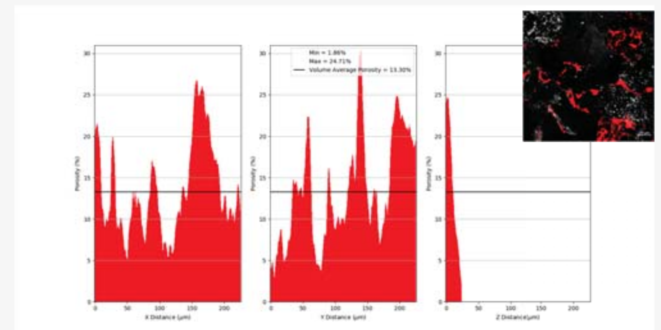
- Average porosity is 6.25%
- High-porosity streaks reach 18% (arrow above); Low-porosity streaks reach 2%
- Note high variance in porosity
- Dominant pore size is in a tight range: 15 to 25 µm
- This imaging area is dominated by larger, possibly dissolution-related pores (see arrows at left)

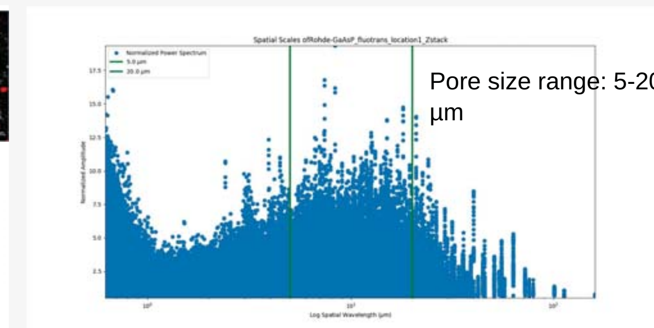
Porosity Quantification cont.

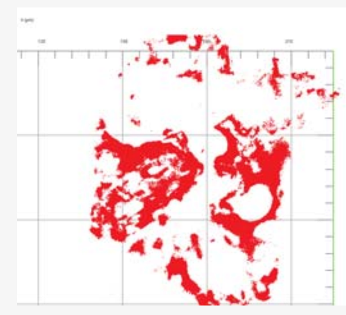
2. Parkman Sandstone (Powder River Basin)

Comparison to independent measurements

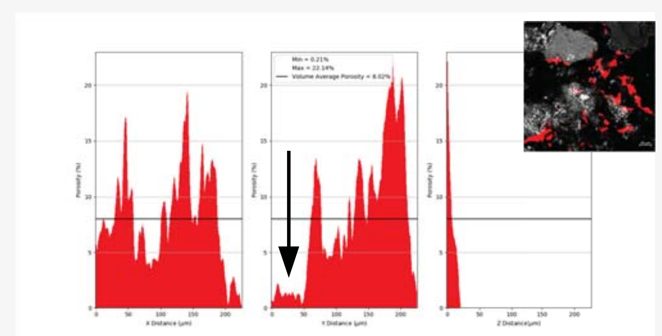
- Ambient porosity: **8.0%**
- Average porosity from three confocal imaging volumes: **10.1%**

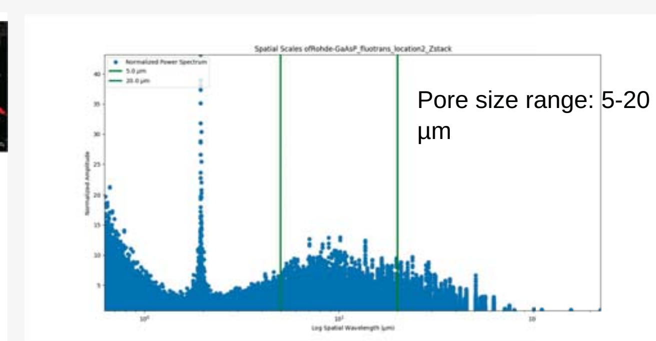


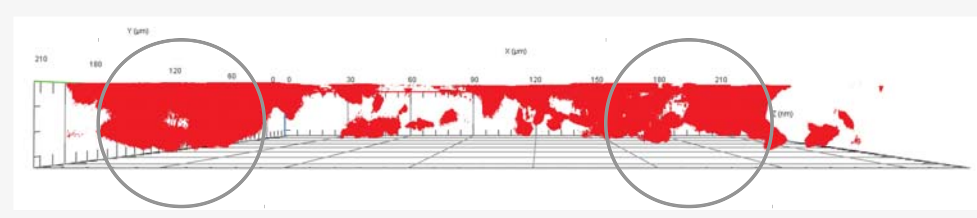




- Average porosity is 13.3%
- High porosity streaks reach 30%; low-porosity streaks below 5%
- The pore network in this sample is highly heterogeneous
- High porosity regions in the X and Y directions appear controlled partly by the large region of intracrystalline porosity (at left)

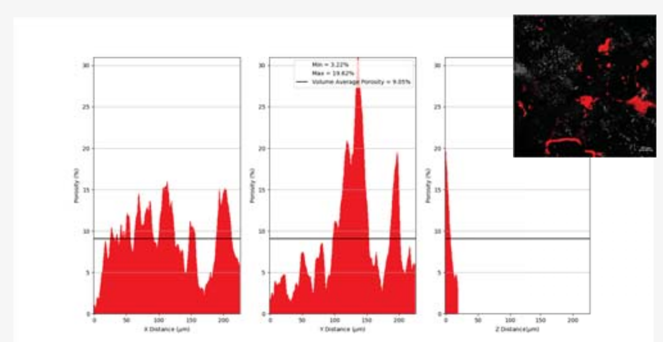


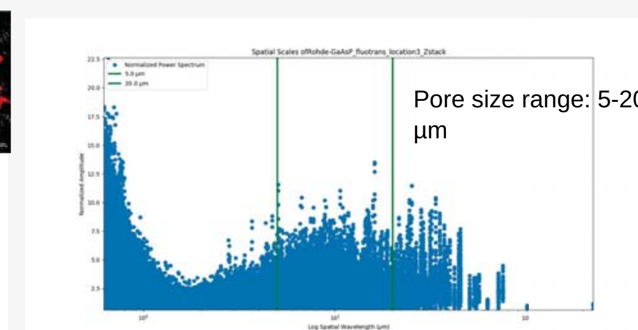


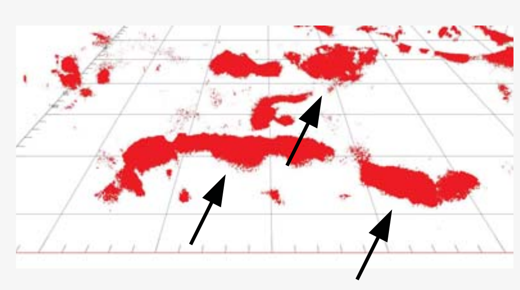


Note the large pores (gray circles) comprising the upper end of the pore size distribution in the profile at left

- Average porosity is 8.02%
- Porosity is heterogeneous, with near-0 porosity zones (see arrows above)







- Average porosity is 9.05%
- Porosity less varied in the X direction in this sample: lower pore network heterogeneity
- Porosity variance in the Y direction dominated by a peak of near 30%: a high-porosity, high-permeability streak on the 20-micron scale related to large interparticle pores (arrows at left) common in this image location

Discussion

1. Sample Comparison

- Both samples are the primary reservoir facies of their respective basins
- Both are lithologically similar: arenitic composition, with primary porosity occluded by carbonate replacement and cement
- The Williston Basin Bakken sample is dominated by a larger, more heterogeneous pore size distribution: 6 to 25 µm, while having lower, less heterogeneous volumetric porosity (4.5% average, ranging from ~18% to 1%.
- The Powder River Basin Parkman Sandstone sample has a homogeneous pore size distribution across imaging regions (5 to 20 µm) while exhibiting more heterogeneous and greater porosity (10.1% average, ranging from ~30% to ~2%).
- Both samples are dominated by intercrystalline pores associated with replacement dolomite and dolomite cement in the Bakken sample and calcite cement in the Parkman Sandstone sample.
- However, low porosity and larger pore sizes in the Bakken sample indicate dolomite replacement successfully occluded intercrystalline pores vital for pore network connectivity

2. Implications for Reservoir Performance

- The presence of high-porosity streaks of up to an order magnitude greater porosity than the average porosity indicates a contribution of those streaks to flow paths at the several-micron-scale
- The Parkman Sandstone sample would host better flow due to its relatively higher porosity and the contribution of small intercrystalline micropores to connecting larger pores

Conclusions

- Pore distribution in all samples is heterolithic in both horizontal and vertical space
- The pore network of both samples is dominated by intercrystalline pores
- The Parkman Sandstone sample exhibits larger range of porosity
- The Bakken sample pore size distribution is from **6 to 25 µm;** porosity varies from 18% to <1%, with an average for all locations of **4.5%**
- The Parkman Sandstone sample pore size distribution is from **5 to 20 µm**; porosity varies from >30% to <2% with an average of **10.1%**

Acknowledgements

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