PS Evaluation of Mercury Intrusion and Capillary Pressure Results: Development of a New Methodological Approach for Analyzing Carbonates*

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Abstract

Mercury injection capillary pressure (MICP) testing of carbonate rocks has been used extensively in industry and academia to evaluate bulk porosity, pore-throat size, and pore-size distributions for the purpose of reservoir characterization. The integration of MICP data into static and dynamic petrophysical flow models has proven to be a valuable tool in maximizing hydrocarbon recovery. However, inaccuracies in MICP results can significantly impact reservoir volume estimates and projected hydrocarbon recovery. This study quantifies differences in MICP-determined petrophysical properties of representative carbonate rock fabrics found within the Silurian Niagaran pinnacle reef complexes of the Michigan Basin. The objectives of this research are to: (i) characterize pore-throat and pore-size distributions using petrographic and MICP testing; (ii) evaluate the observed lack of hysteresis between intrusion and extrusion data; (iii) assess variability in MICP testing methods, like maximum injection pressure and the equilibration time associated with incremental intrusion pressure intervals. Evaluating the effects of equilibration time from 40 seconds (Trial 1) to 100 seconds (Trial 2) at low pressure (0-100 psi) showed substantial variability. Preliminary analysis of patchy macro-pore dominated fabrics in Trials 1 and 2 showed that the bulk porosity determined by MICP changed from 15.8% to 20.1%, and mean pore diameter changed from 3.03 µm to 2.05 µm, respectively. Furthermore, a 3% difference in pore-throat radius (µm), 25% difference in cumulative Hg saturation, and 74% difference in incremental intrusion sampling (mL/g) were observed between Trials 1 and 2. This study demonstrates how different MICP methodologies can affect the accuracy of petrophysical data that are used to populate static and dynamic models, and perhaps more importantly to make predictions about secondary hydrocarbon recovery.

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ABSTRACT

Mercury injection capillary pressure (MICP) testing of carbonate rocks has been used extensively in industry and academia to evaluate bulk porosity, pore-throat size, and pore-size distributions for the purpose of reservoir characterization. The integration of MICP data into static and dynamic petrophysical flow models has proven to be a valuable tool in maximizing hydrocarbon recovery. However, inaccuracies in MICP results can significantly impact reservoir volume estimates and projected hydrocarbon recovery. This study quantifies differences in MICP-determined petrophysical properties of representative carbonate rock fabrics found within the Silurian Niagaran pinnacle reef complexes of the Michigan Basin. The objectives of this research are to: (i) characterize pore-throat and pore-size distributions using petrographic and MICP testing; (ii) evaluate the observed lack of hysteresis between intrusion and extrusion data; (iii) assess variability in MICP testing methods, like maximum injection pressure and the equilibration time associated with incremental intrusion pressure intervals. Evaluating the effects of equilibration time from 40 seconds (Trial 1) to 100 seconds (Trial 2) at low pressure (0-100 psi) showed substantial variability. Preliminary analysis of patchy macro-pore dominated fabrics in Trials 1 and 2 showed that the bulk porosity determined by MICP changed from 15.8% to 20.1%, and mean pore diameter changed from 3.03 µm to 2.05 µm, respectively. Furthermore, a 3% difference in pore-throat radius (µm), 25% difference in cumulative Hg saturation, and 74% difference in incremental intrusion sampling (mL/g) were observed between Trials 1 and 2. This study demonstrates how different MICP methodologies can affect the accuracy of petrophysical data that are used to populate static and dynamic models, and perhaps more importantly to make predictions about secondary hydrocarbon recovery.

HYPOTHESES & RESEARCH OBJECTIVES

- Does the mercury intrusion and capillary pressure (MICP) measurement parameters affect the porosity measurements?
- Which parameter (pressure or equilibration time) most affect measurements?
- Can the relationship between intrusion and extrusion data be better understood through experimentation with pressure limits and the equilibration time?
- Can MICP parameters (e.g. equilibration time and pressure) induce fracturing or deformation resulting porosity artifacts?
- Can the affects of mineral compressibility by observed following MICP measurements?

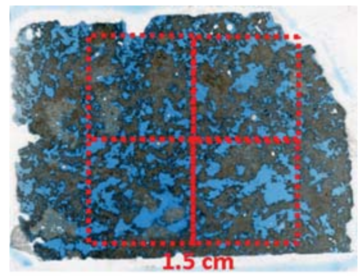
PROBLEM

Previous studies on MICP have evaluated the effects of compressibility and pore shielding. Further, the majority of MICP studies have analyzed coals, shales, sandstone, and experimental work assessing silica compressibility, however, few studies have evaluated the accuracy of MICP measurements of carbonate rocks. No publicly available literature discusses the most appropriate methodology for analyzing carbonates with MICP. Test parameters such as pressure and equilibration time are postulated to significantly affect porosity measurements if not appropriately applied during analyses. Carbonate rocks are highly complex consisting of variable mineralogies and homogeneous or heterogeneous pore architectures. Knowing the appropriate equilibration time to sufficiently fill pores is difficult to assess. Further it is postulated that analyzing carbonates at too high of pressures with too short of equilibration time may induce porosity artifacts due to rate of pressure change. Lastly, the compressibility is not fully understood to the degree to where the compressibility of carbonates may be normalized during MICP analyses.

EXPERIMENT #1: HETEROGENEOUS PORE TYPES

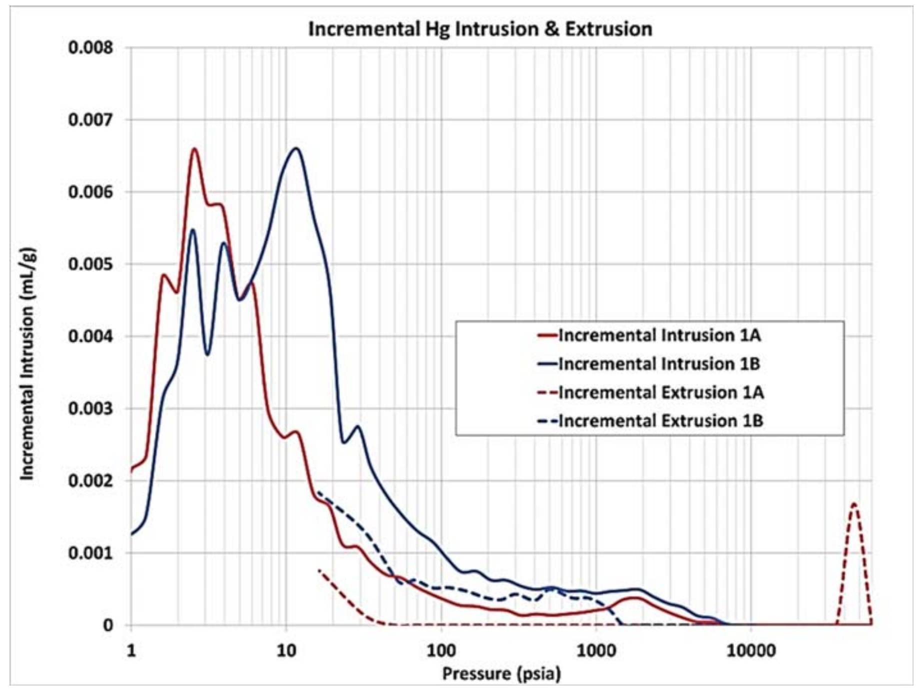
SAMPLE TYPE:

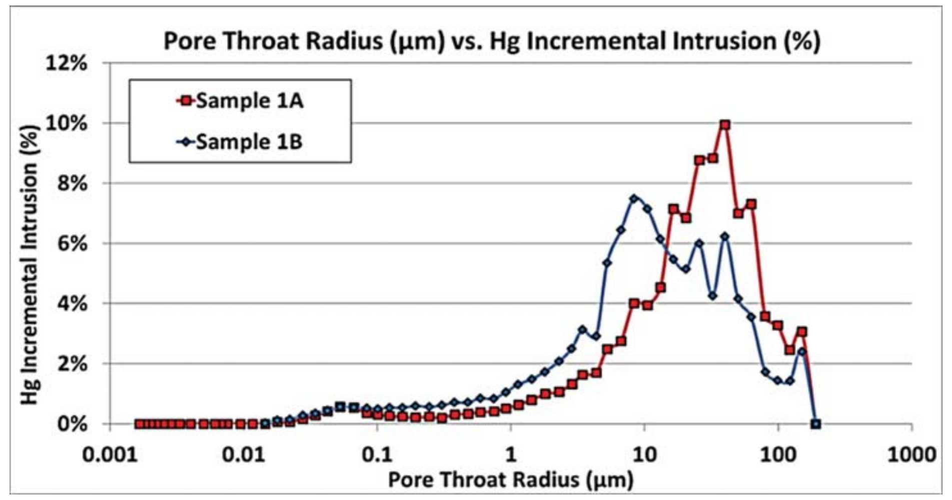
St. Kalkaska 1-21 (#28403) - 6598.8'
Silurian—Brown Niagaran (Guelph Fm.)
Reef Grain Apron Facies
Thin Section Porosity: 26.7%
Core Analysis Porosity: 10.6%
Core Analysis Permeability: 50.15 mD

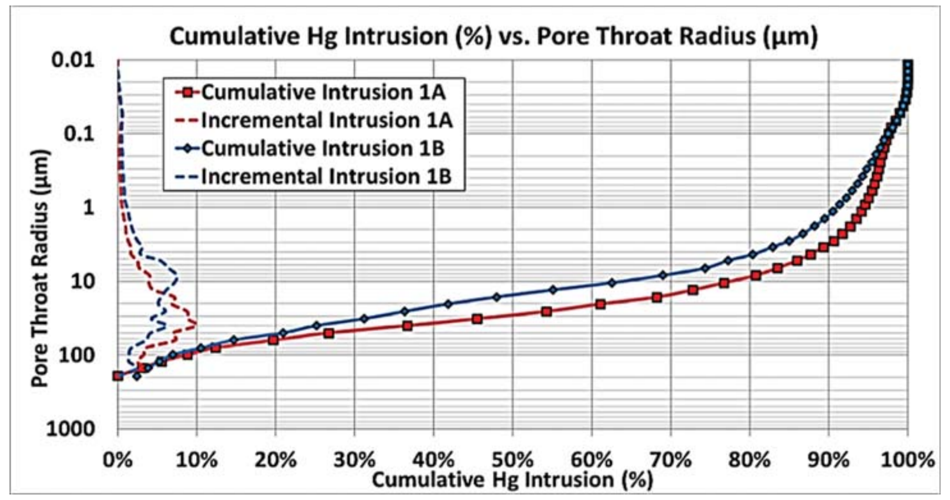


Thin Section Scan at 6400 DPI.

Dolomite w/ Patchy Touching Vugs







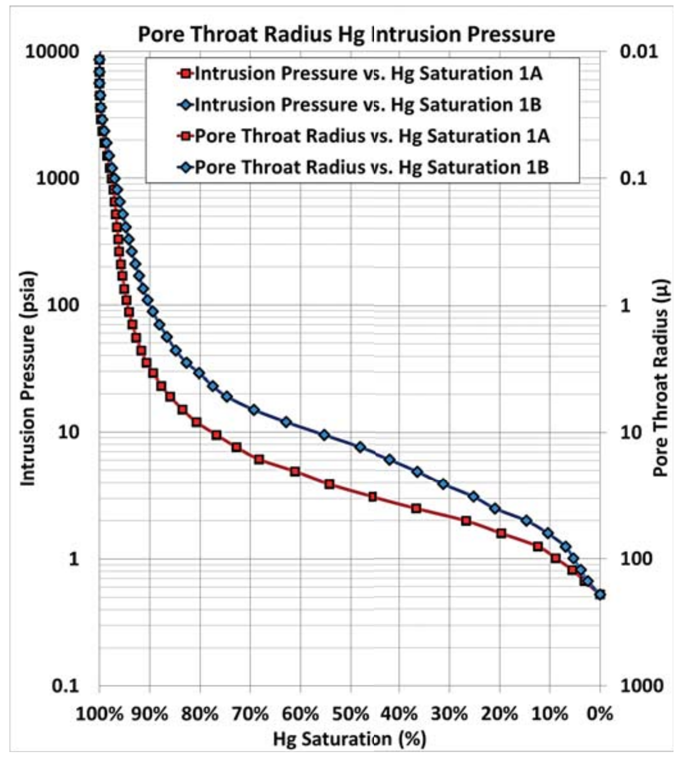
(Above) Sample 1A shows a greater incremental intrusion observed at a lower pressure with a shorter equilibration time when compared to Sample 1B

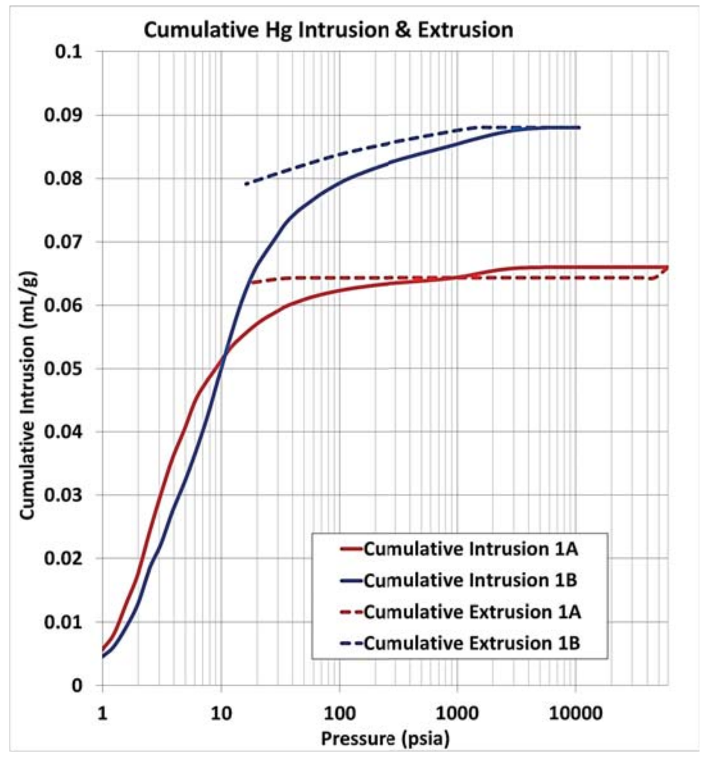
(Top-Left) Sample 1A shows a greater incremental intrusion into pores with larger pore throats corresponding with the lower pressures illustrated in the figure above.

(Middle-Left) Composite of cumulative and percent incremental intrusion and their respective pore throat radii.

(Bottom-Left) Percent cumulative intrusion at each pressure increment and the dominant pore throat radius being invaded at the respective pressure increment. Significant difference in cumulative intrusion at pressures below the atmospheric pressure.

(Below) Cumulative Hg intrusion and extrusion curves.

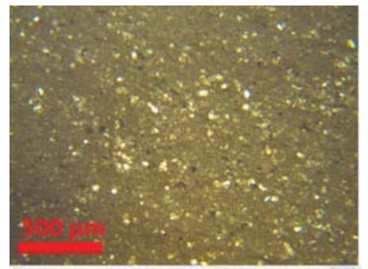


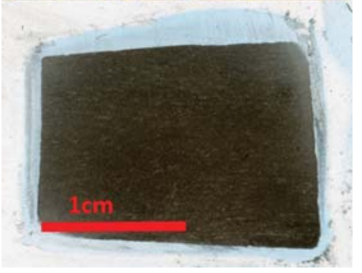


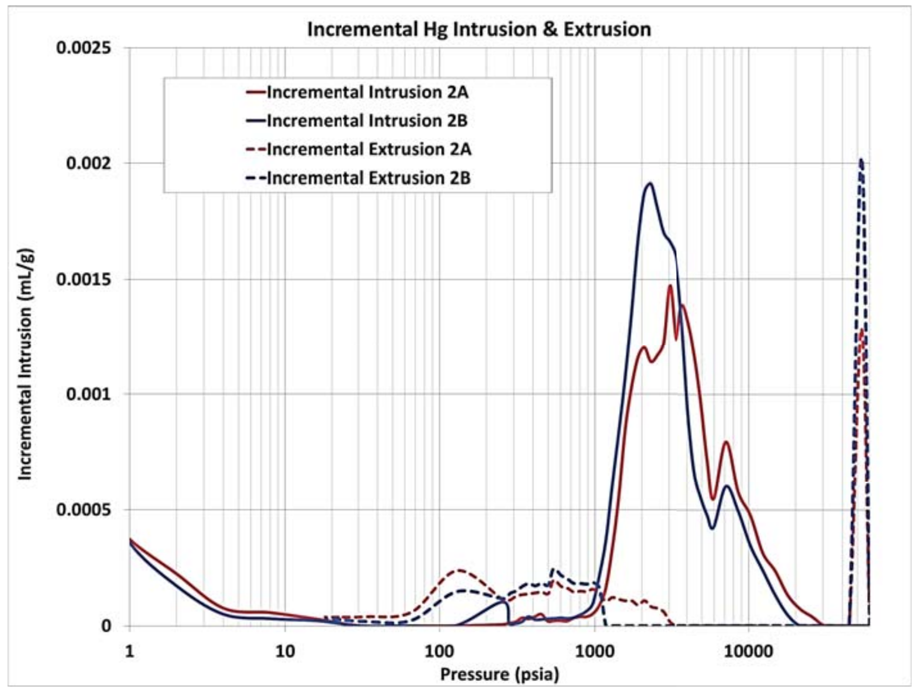
EXPERIMENT #2: HOMOGENEOUS PORE TYPES

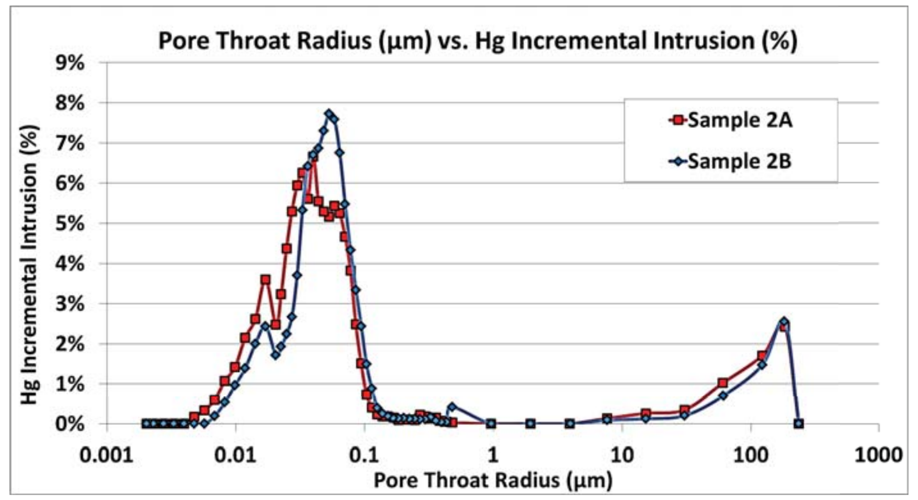
SAMPLE TYPE:

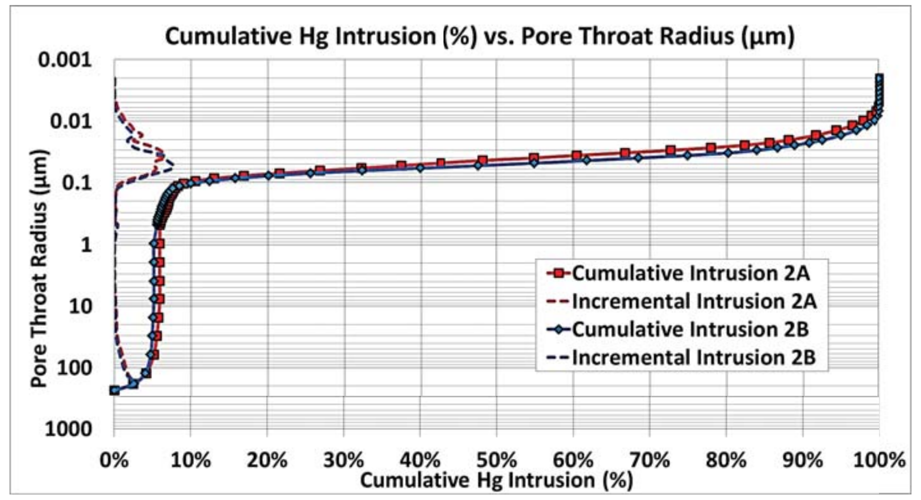
Benchley 1-29 (#31186) - 5095.5'
Devonian—Black Lime (Amherstburg Fm.)
Subtidal Fine Grain Mud Facies
Thin Section Porosity: 0.18%









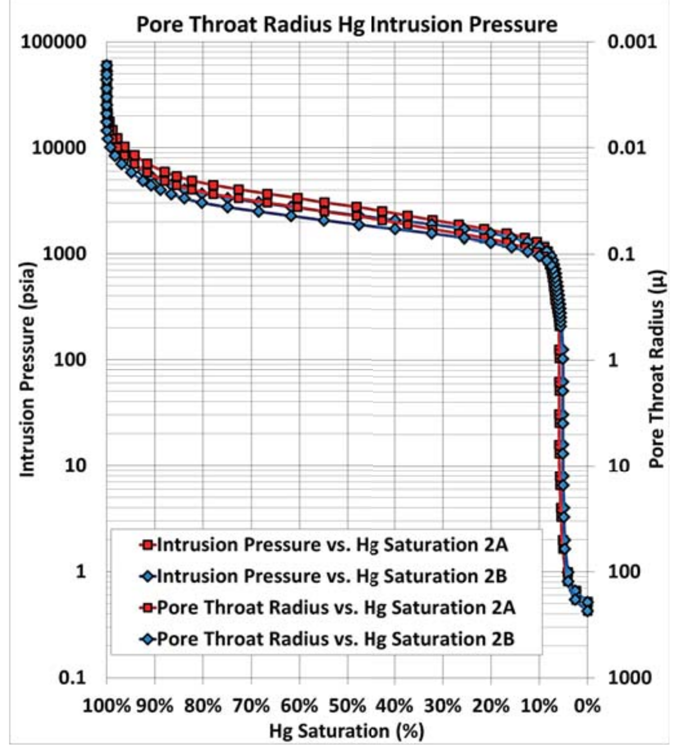


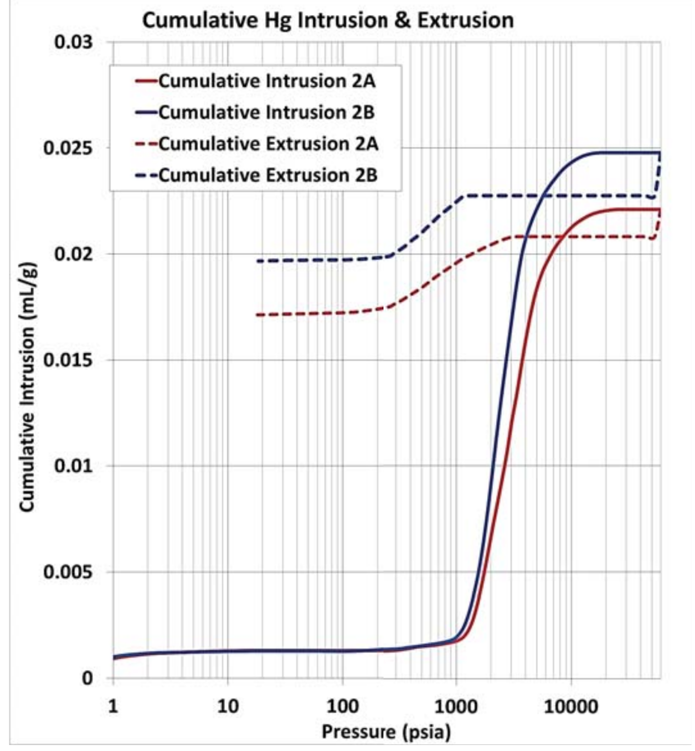
(Above) Sample 2B shows a greater incremental intrusion observed at lower pressure with a shorter equilibration time when compared to Sample 2A.

(Top-Left) Sample 2B shows a greater incremental intrusion than Sample 2A for pore throat radii ranging for 0.1 to 0.01 µm into pores with larger pore throats corresponding with the pressures illustrated in the figure above.

(Middle-Left) Composite of cumulative and percent incremental intrusion and their respective pore throat radii.

(Bottom-Left) Percent cumulative intrusion at each pressure increment and the dominant pore throat radius being invaded at the respective pressure increment. A similar intrusion trend is observed with differences in the cumulative saturation at the same pressure increment. (Below) Cumulative Hg intrusion and extrusion curves.





RESULTS

Table 1—Comparison of MICP Results for Samples 1A and 1B

	Sample 1A	Sample 1B	% Difference
Equilibration Time (Seconds) =	40 Low; 100 High	100 Low; 100 High	
Sample Weight (g) =	2.956	2.644	-10.55%
Total Intrusion Volume (mL/g) =	0.066	0.088	33.33%
Total Pore Area (m^2/g) =	0.087	0.172	97.70%
Median Pore Diameter (Volume) (nm) =	57615.1	24543.9	-57.40%
Median Pore Diameter (Area) (nm) =	120.5	129.8	7.72%
Average Pore Diameter (4V/A) (nm) =	3028.4	2046.8	-32.41%
Bulk Density at 0.52 psia (g/mL) =	2.3936	2.2827	-4.63%
Apparent (skeletal) Density (g/mL) =	2.8429	2.8561	0.46%
Porosity (%) =	15.8034	20.0782	27.05%
Stem Volume Used (%) =	51	60	17.65%
Threshold Pressure (psia) =	1.75	1.84	5.14%
Characteristic length (nm) =	113793.4	108261	-4.86%
Conductivity formation factor =	0.048	0.044	-8.33%
Permeability constant =	0.00442	0.00442	0.00%
Permeability (mD) =	2771.5567	2278.9421	-17.77%
BET Surface Area (m^2/g) =	230	230	0.00%
Pore shape exponent =	1	1	0.00%
Tortuosity factor =	2.062	2.006	-2.72%
Tortuosity =	3.9082	3.8156	-2.37%
Percolation Fractal dimension =	2.997	2.995	-0.07%
Backbone Fractal dimension =	2.949	2.888	-2.07%

Table 2—Comparison of MICP Results for Samples 2A and 2B

	Sample 2A	Sample 2B	% Difference
Equilibration Time (Seconds) =	100 Low; 100 High	40 Low; 40 High	
Sample Weight (g) =	2.996	2.996	0.00%
Total Intrusion Volume (mL/g) =	0.0221	0.0248	12.22%
Total Pore Area (m^2/g) =	1.269	1.165	-8.20%
Median Pore Diameter (Volume) (nm) =	85.6	103.3	20.68%
Median Pore Diameter (Area) (nm) =	56.9	73.8	29.70%
Average Pore Diameter (4V/A) (nm) =	69.7	85.1	22.09%
Bulk Density at 0.52 psia (g/mL) =	2.6748	2.6453	-1.10%
Apparent (skeletal) Density (g/mL) =	2.8429	2.8308	-0.43%
Porosity (%) =	5.9132	6.5545	10.85%
Stem Volume Used (%) =	18	21	16.67%
Threshold Pressure (psia) =	1830.42	2011.62	9.90%
Characteristic length (nm) =	133.1	121.1	-9.02%
Conductivity formation factor =	0.021	0.034	61.90%
Permeability constant =	0.00442	0.00442	0.00%
Permeability (mD) =	0.0016	0.0022	37.50%
BET Surface Area (m^2/g) =	230	230	0.00%
Pore shape exponent =	1	1	0.00%
Tortuosity factor =	0	2.167	
Tortuosity =	1562.2925	1403.0892	-10.19%
Percolation Fractal dimension =	2.345	2.564	9.34%
Backbone Fractal dimension =	N/A	N/A	N/A

CONCLUSION

- MICP results for both heterogeneous and homogeneous pore types show similar trend in their pore size distribution, however, the frequency and distribution of various pore sizes appears to be skewed. This is attributed to the difference in equilibration time resulting in insufficient equilibration time to fill pores of a comparable size.
- A greater cumulative volume of Hg intruded into heterogeneous samples with a longer equilibration time conversely greater volumes of Hg intrude into homogeneous samples with a shorter equilibration time.
- MICP parameters, pressure and equilibration time affect the resulting porosity measurements, pore-throat size and frequency distribution.
- The appropriate equilibration time for carbonate samples is still poorly understood, but future experiments will provide insights on the sufficient equilibration time to fill pore.
- In samples postulated to be nearly identical there are observed shifts dominant pore throat sizes and the volume of Hg intruded, it is postulated to have resulted from the MICP testing parameters which ultimately resulted in 10.85% difference between porosity measurements.