Storage Resource Estimates and Seal Evaluation of Cambrian-Ordovician Units in the MRCSP Region*

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Search and Discovery Article #80678 (2019)**
Posted May 27, 2019

*Adapted from oral presentation given at 2018 AAPG 47th Annual AAPG-SPE Eastern Section Joint Meeting, Pittsburgh, Pennsylvania, October 7-11, 2018

DOI:10.1306/80678Medina2019

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Abstract

To evaluate the carbon storage potential of the Midwest Regional Carbon Sequestration Partnership (MRCSP) region, petrophysical analyses of Cambrian-Ordovician strata were conducted, resulting in new estimates of the reservoir targets for carbon storage and the effectiveness of overlying units to serve as seals. The carbon storage resource estimates (SRE) were evaluated using a hierarchy of methods that resulted in different SRE values based on a series of increasingly complex portrayals of the pore system. The simplest analysis follows the United States Department of Energy (USDOE) methodology, whereby a SRE is calculated using a single 'best estimate' of the average porosity of the assessed formations. Additional estimates employ variable porosity models based on a depth-based diagenesis function and effective porosity values derived from geophysical logs. Results from this approach not only illuminate the magnitude of uncertainty that should be expected in SREs as a function of data availability, but also suggest a high potential for storage in deeper Cambrian-Ordovician units.

Capillary pressure data from mercury porosimetry (MICP) were used to evaluate the seal capacity of the Upper Ordovician Maquoketa Group and equivalent units. Geophysical logs (gamma-ray, density, and neutron porosity logs) from multiple well locations in the MRCSP region were used to develop a lithofacies model consisting of five units, revealing a high degree of regional variability within the Maquoketa Group. The distribution of clay-rich lithofacies defines areas having higher potential for effective confinement. Further characterization of porosity, permeability, and the micro- and meso-pore size distribution from MICP suggest high sealing and capillary trapping potential of the Maquoketa Group.

The research was performed under the MRCSP program led by Battelle and funded under USDOE/NETL Cooperative Agreement # DE-FC26-0NT42589.

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Greb, S.F., T.N. Sparks, M. Solis, J. Harper, K. Carter, P. Dinterman, E. Lewis, and C. Medina, 2018, Subsurface Geology for Carbon Storage Along the Ohio River in part of the Midwest Regional Carbon Sequestration Partnership Region: 2018 AAPG 47th Annual AAPG-SPE Eastern Section Joint Meeting, Pittsburgh, Pennsylvania, October 7-11, 2018.

Medina, C.R., M. Mastalerz, and J.A. Rupp, 2018, Pore System Characterization of Cambrian-Ordovician Carbonates Using a New Mercury Porosimetry-Based Petrofacies Classification System: Application to Carbon Sequestration Reservoirs: Greenhouse Gases: Science and Technology, v. 8/5, p. 932-953. doi.org/10.1002/ghg.1806

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Eastern Section, American Association of Petroleum Geologist (ES-AAPG)
Pittsburgh, Pennsylvania, October 2018

MRCSP
MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP

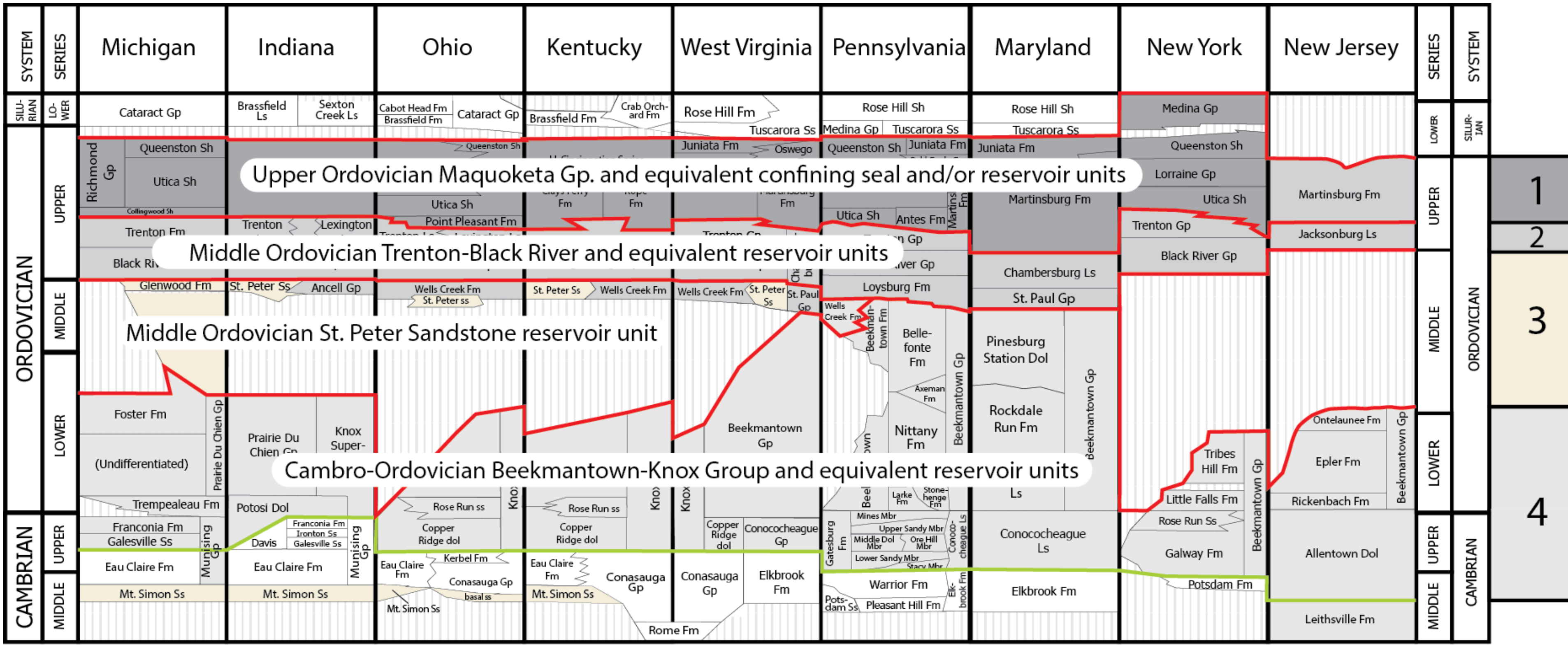
Acknowledgements

Thanks to all colleagues from Battelle, geological surveys, labs, and universities.

Talk Overview

- Methods and results of evaluation of the CO_2 storage potential in saline aquifers of Cambrian-Ordovician strata underlying portions of the MRCSP states
  - We compared five different methodologies to independently generate storage resource estimates (SRE)
  - These methods differ fundamentally in how they estimate values for porosity (Ø)
- Petrophysical evaluation of the Maquoketa Group as a seal (work in progress)
  - Wireline logs used to create a lithofacies model
  - Mercury porosimetry (MICP) analyses in samples from Ohio, Indiana, Kentucky, And Pennsylvania.

Stratigraphy / Units

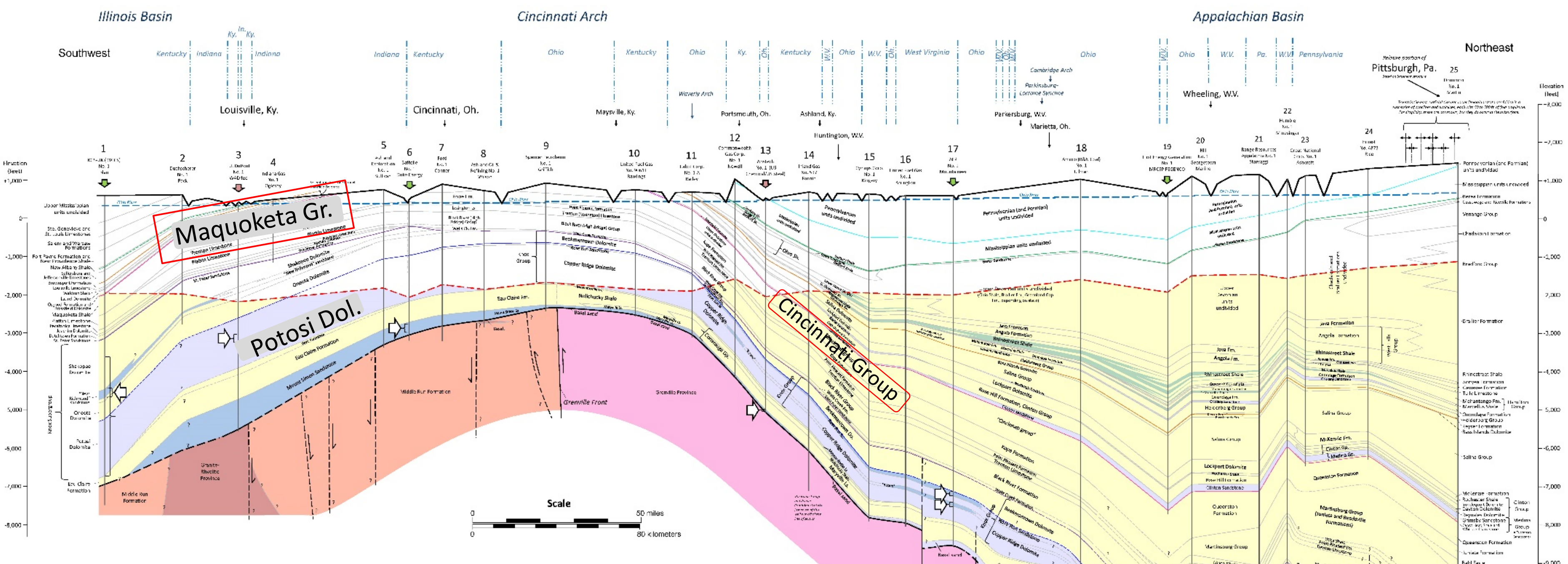


1	Upper Ordovician Maquoketa Gp. and equivalent confining seal and/or reservoir units
2	Middle Ordovician Trenton-Black River and equivalent reservoir units
3	Middle Ordovician St. Peter Sandstone reservoir unit
4	Cambro-Ordovician Beekmantown-Knox Group and equivalent reservoir units

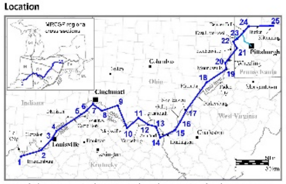
- Unconformity
- Base of Mapped Units

Subsurface geology for carbon storage along the Ohio River in part of the Midwest Regional Carbon Sequestration Partnership Region

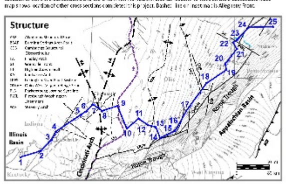
Stephen F. Greb, Thomas N. Sparks, Michael Solis, John Harper, Kristin Carter, Phil Dinterman, Eric Lewis, and Cristian Medina



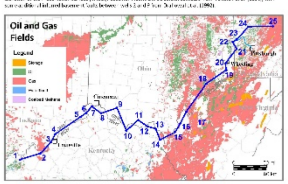
Location



Structure



Oil and Gas Fields



Explanation

The Ohio River is an important industrial and electrical generation corridor, and an area with significant CO_2 emissions. Because future regulations may limit carbon emissions, it is important to understand the potential for safe geologic storage of CO_2 in the subsurface at depth, or for CO_2 use in enhanced oil and gas recovery, in the river area. Geologic storage involves the capture of carbon emissions at the surface and injection of the captured CO_2 under pressure into reservoirs deep underground with sufficient seals and confining zones to prevent migration into shallower strata. This cross section was constructed to help industry, policy makers, and the general public visualize the geology of rock units relative to geologic carbon storage beneath the Ohio River. The cross section extends past the western margin of the Midwest Regional Carbon Sequestration Partnership (MRCSP) on the eastern edge of the Illinois Basin to the Appalachian Basin and the Allegheny structural front, northeast of Pittsburgh, Pennsylvania. It is constructed from 25 deep wells along or near the river. Four of the wells are CO_2-injection test wells and two are Class 1 waste-injection wells, so significant data are available to characterize subsurface reservoirs and confining zones along parts of the section. There are also significant shallower oil and gas wells (not shown) between the deeper wells used in the section. No deep wells were available in the greater Pittsburg area, so wells to the north of the river were used to approximate the subsurface where the Ohio River begins.

Subsurface units in the cross section are color-coded based on a unit's potential as a (1) storage interval (regional saline reservoir), (2) confining interval with local potential reservoirs, (3) confining zone, or (4) organic-rich shale. Units are color-coded at depths greater than 2,600 ft, which is the approximate depth needed for CO_2 to be in a dense supercritical phase. Below this depth, pressures should be great enough to cause CO_2 to dramatically decrease in volume allowing for maximum storage capacity. This depth should also allow CO_2 to be miscible in oil, for efficient use in enhanced oil recovery.

Precambrian basement shallows from 7,000 ft below sea level on the western end of the cross section on the margin of the Illinois Basin, to less than −2,000 ft on the Cincinnati Arch, to nearly −15,000 ft in the Appalachian Basin. Depth to basement is influenced by geologic structures including regional basins and arches, and basement faults.

The Cambrian Mount Simon Sandstone was the primary injection zone of the Battelle No. 1 Duke Energy well (no. 6 on section) southwest of Cincinnati on the Cincinnati Arch. This well was an experimental CO_2 injection test drilled by the MRCSP, and the first carbon storage test in the Mount Simon Sandstone in the United States. Approximately 1000 tonnes (1100 short tons) were injected and monitored (Battelle, 2011a). The Mount Simon thins toward the Cincinnati Arch and was absent in the Kentucky Geological Survey No. 1 Blan well (no. 1 on the section). Eastward the Basal sand, and Potsdam Sandstone are approximately correlative units and may have potential for carbon storage.

Cambrian Knox carbonates and sandstones were primary test horizons in several CO_2 wells in both basins. A sandstone in the middle Knox Group (originally considered the Gunter Sandstone, but possibly the New Richmond Sandstone) and vuggy Knox carbonates were the test horizon in the Kentucky Geological Survey No. 1 Blan well (no. 1 on section). A total of 293 tonnes (323 short tons) of CO_2 was injected into Knox reservoirs. This was the first demonstration of CO_2 injection in the Knox in the United States (Greb et al., 2012; Bowersox et al., 2013; Bowersox and Williams, 2014). The Copper Ridge Dolomite, Knox Group, was the reservoir for the DuPont No. 1 waste acid disposal well (no. 3 on section) near Louisville, Kentucky (Clark et al., 2005; Greb et al., 2009; 2012). Significant testing was done on the Basal sand, Knox carbonates, and the Rose Run Sandstone in the Aristech No. 1 Chemicals well (no. 13 on section), an industrial waste disposal well (Ohio Division of the Geological Survey data). The Copper Ridge B zone and Rose Run Sandstone were the primary reservoirs tested in the AEP No. 1 well (no. 17 on the section) at the Mountaineer power plant (Bacon et al., 2007; 2009). An extensive, multi- year testing program was conducted and 37,000 tonnes (40,785 short tons) of CO_2 were injected as part of a U.S. Department of Energy integrated carbon sequestration project (Gupta et al., 2013).

Eastward in the Appalachian Basin, where Cambrian and Ordovician horizons are more than 10,000 ft beneath the surface, shallower reservoirs in Silurian and younger strata would need to be considered for future carbon storage (Wickstrom et al., 2005; Carter et al., 2010). The First Energy FEGENCO well (no. 19 on section) was a CO_2 test well that found insufficient injectivity in Silurian stata at depth beneath the Burger power plant for CO_2 storage (Battelle, 2011b; Gupta et al., 2011; Wickstrom et al., 2011). Sandstones in the Silurian Clinton-Medina Group, however, are significant oil and gas producers near the Kentucky-West Virginia-Ohio border and north of the Ohio River in Ohio and Pennsylvania (McCormac et al., 1996; Carter et al., 2010), and the Silurian Keefer Sandstone is locally productive south of the river in northeastern Kentucky (Noger et al., 1996), so have local porosity and permeability. Several gas fields are developed in upper Devonian sandstones beneath or southeast of the Ohio River in West Virginia and Pennsylvania including the Venango (Boswell et al., 1996a), Bradford (Boswell et al., 1996b) and Elk (Boswell et al., 1996c) Sandstones. In the future, CO_2 could be used for secondary recovery in some of these fields with ultimate storage in depleted fields (Riley et al., 2010). Likewise, gas is produced from the upper Devonian Ohio Shale along and south of the river in eastern Kentucky and West Virginia (Boswell, 1996; Milici, 1996). Aside from providing confinement for deeper reservoirs, organic-rich Devonian shales are being investigated for their potential use in CO_2-enhanced gas recovery and storage (Nuttall, 2010). More information about the CO_2 storage and enhanced oil and gas possibilities with CO_2 in the region are available at the MRCSP website (mrcsp.org).

References

Source: Greb et al., 2018

Part I: CO_2 storage potential

"The **volumetric methods** require the area of the target formation or horizon along with the formation's thickness and porosity…"

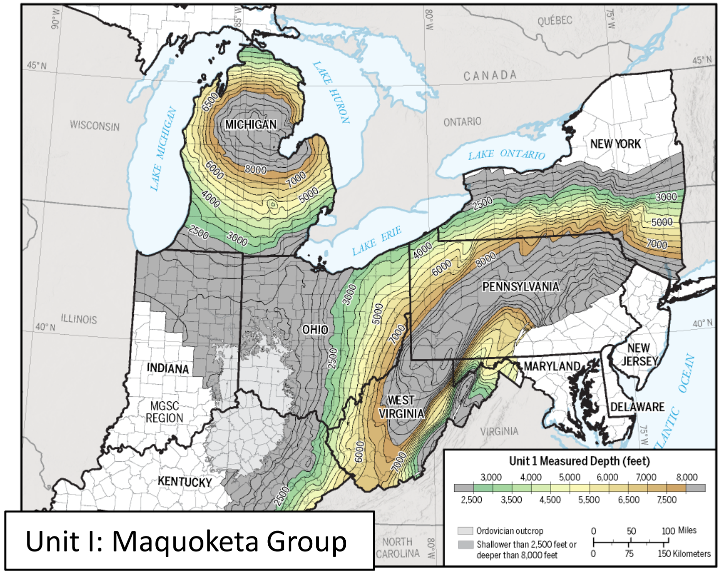
Source: DOE Carbon Storage Atlas, Fifth Edition (2015)

- The DOE methodology uses a single value for all basic parameters

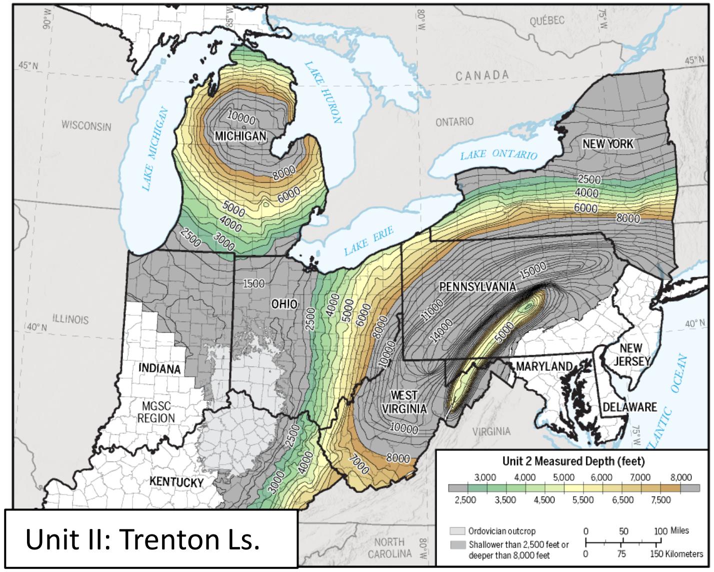
Storage Resource Estimate (SRE):

$$SRE_{CO_2} = Area * Thickness * Porosity * Density_{CO_2} * E_{saline}$$

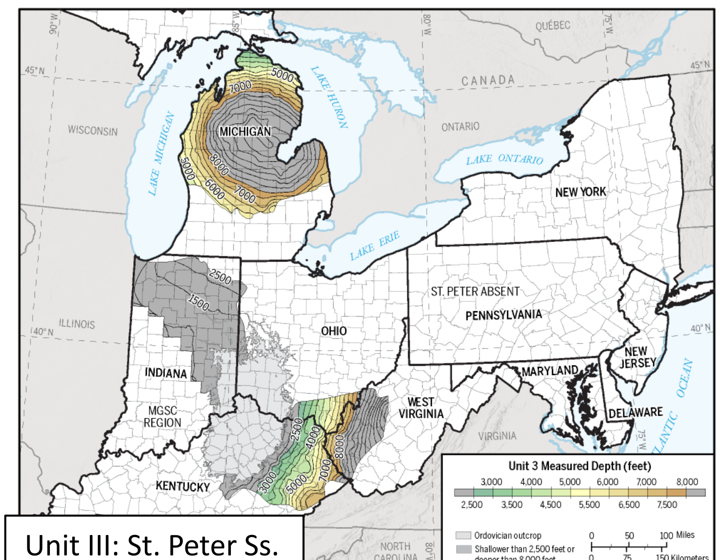
Depth Considerations (2500’ and 8000’)



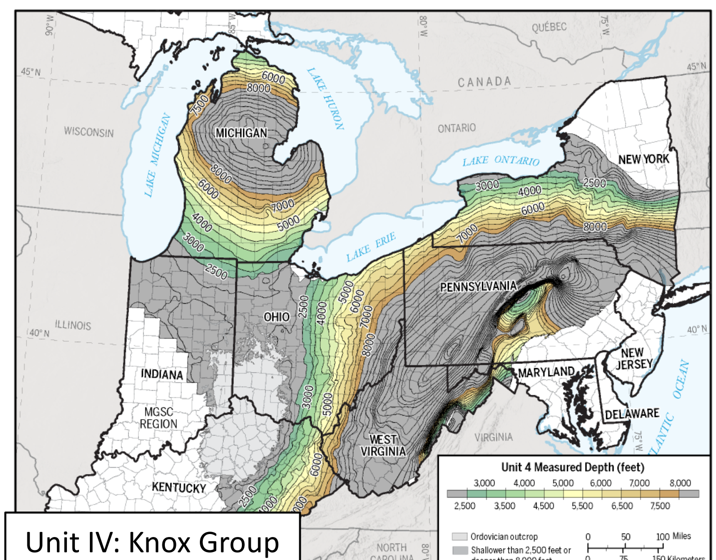
Unit I: Maquoketa Group



Unit II: Trenton Ls.

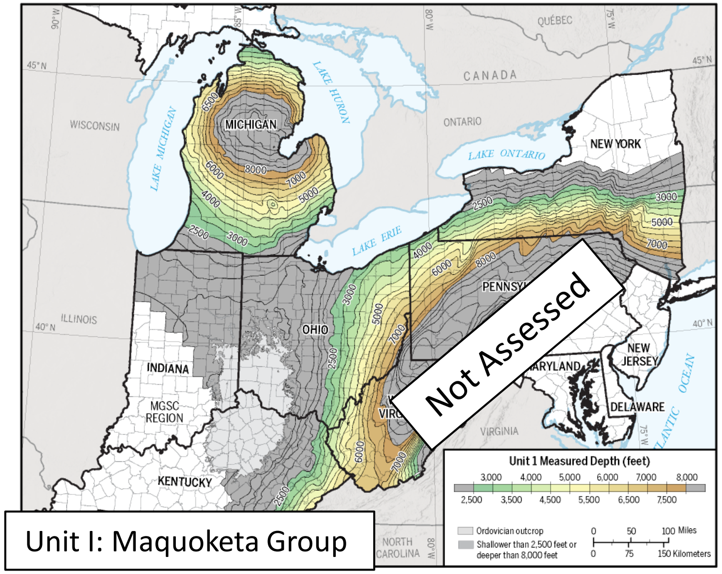


Unit III: St. Peter Ss.

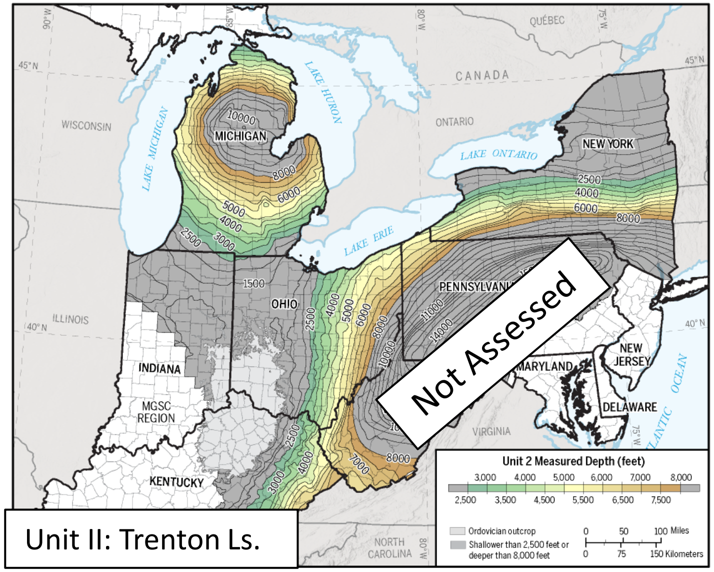


Unit IV: Knox Group

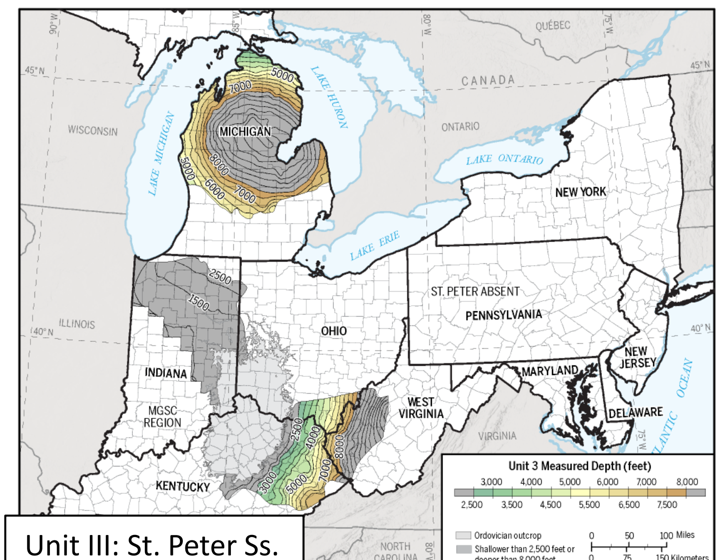
Depth Considerations (2500’ and 8000’)



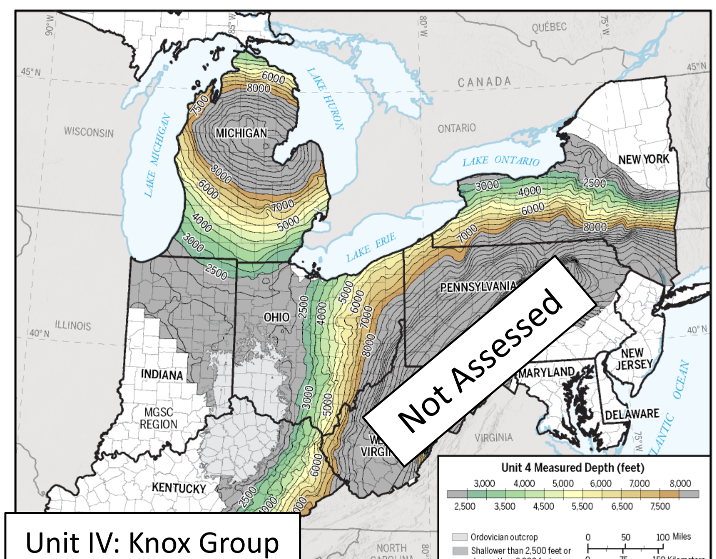
Unit I: Maquoketa Group



Unit II: Trenton Ls.



Unit III: St. Peter Ss.



Unit IV: Knox Group

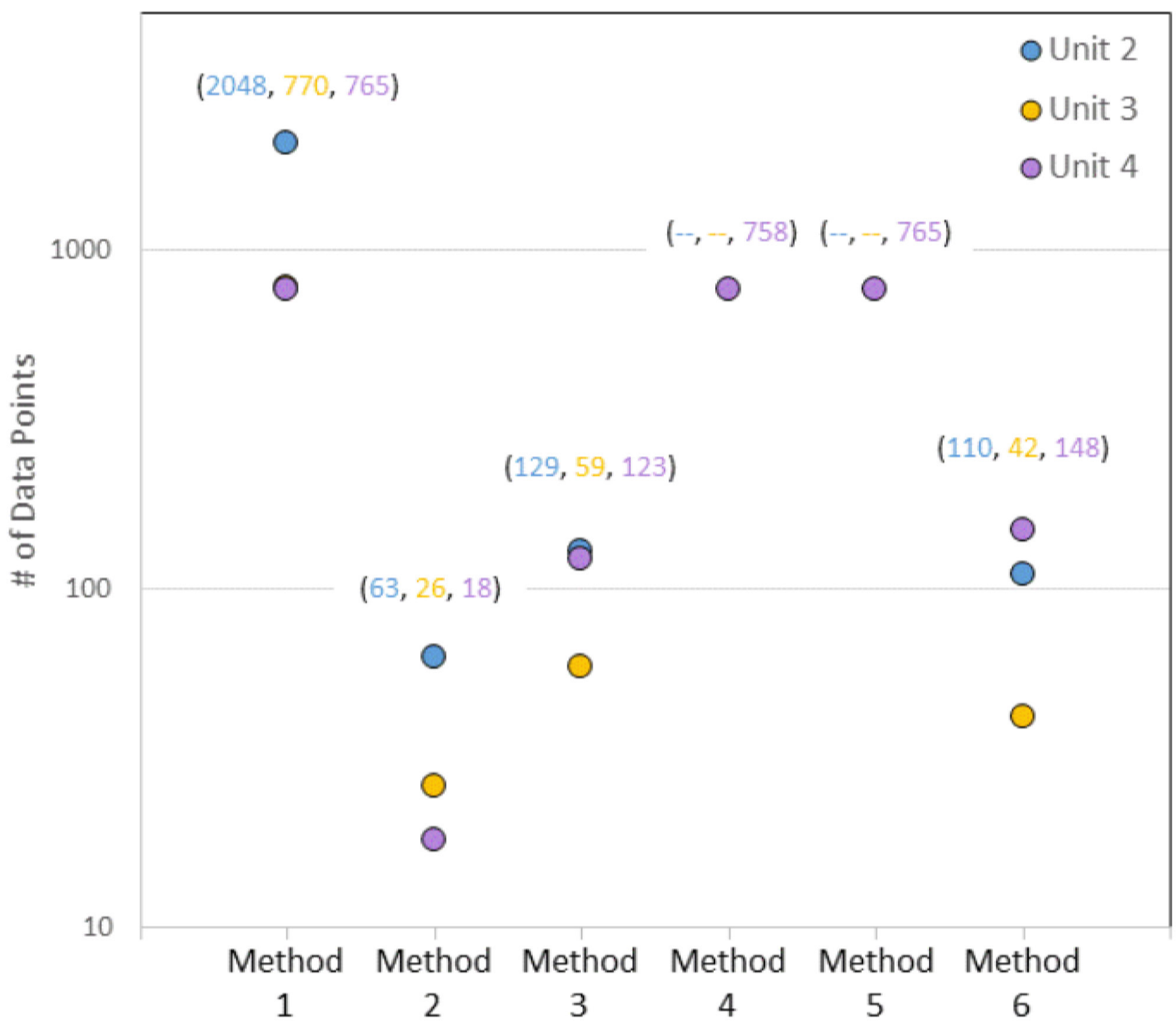
This Work's Methodology

Increasing in sophistication/complexity of porosity data

Method I	Method II	Method III	Method IV	Method V	Method VI
Average ϕ = 10%	ϕ from core analysis	Uses ϕ from wireline logs	Uses a diagenetic model that assumes an exponential decrease of porosity as a function of depth	Uses MICP data to define petrofacies	SCREEN (NETL)
Similar to DOE methodology		Logs used include neutron, sonic, and density			(Storage prospeCtive Resource Estimation Excel aNalysis)
Robust dataset	Limited data	Robust dataset	Robust dataset	Limited data	Limited data

- To facilitate comparison of results among methods, the efficiency factor was held constant
- Results are reported in tonnes of CO_2 /km^2
- Number of data points depends on methodology.

This Work's Methodology



Methods I, II, III

- Method I: Assumes average porosity in all units (ϕ_{tot}= 10%)→ DOE Methodology
- Method II: Uses average porosity from core analysis (ϕ_{core})
- Method III: Consists of the processing of wireline-derived porosity (such as neutron, sonic, or density logs) in Petra Software to estimate SRE.

These methods follow a volumetric equation (ie, methodology published in Atlas by DOE-NETL, 2010)

$$SRE_{CO_2} = A_t * h_g * \emptyset_{tot} * \rho_{CO_2} * E_{saline}$$

<u>Where:</u>

A_t *is the area of a given county*

h_g *is the average thickness, in the county, of unit under assessment*

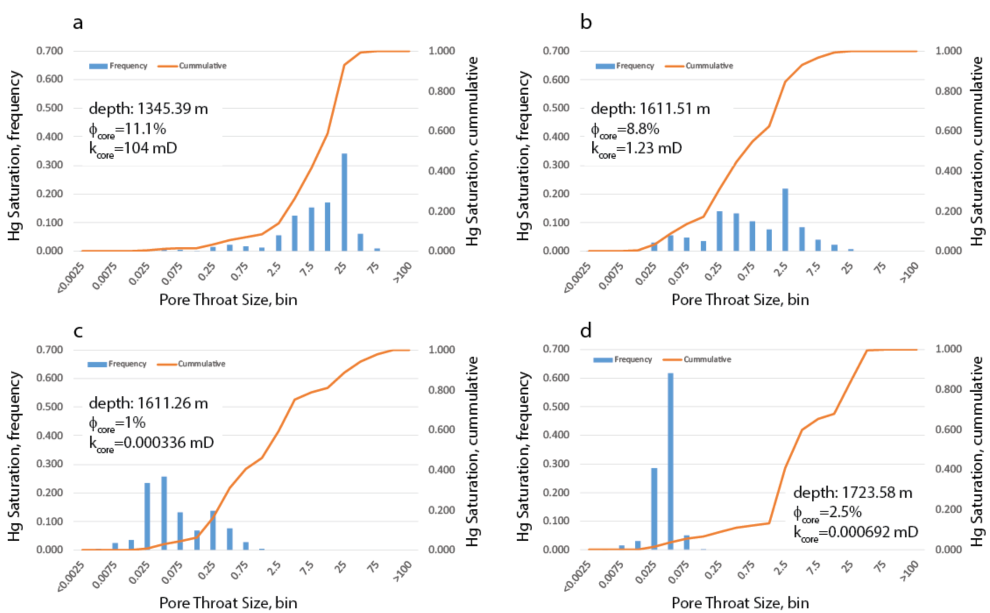
$\emptyset_{tot}$ *is the average porosity (10%)*

ρ_{CO_2} *is CO_2 density at reservoir conditions (0.73 tonnes/m^3)*

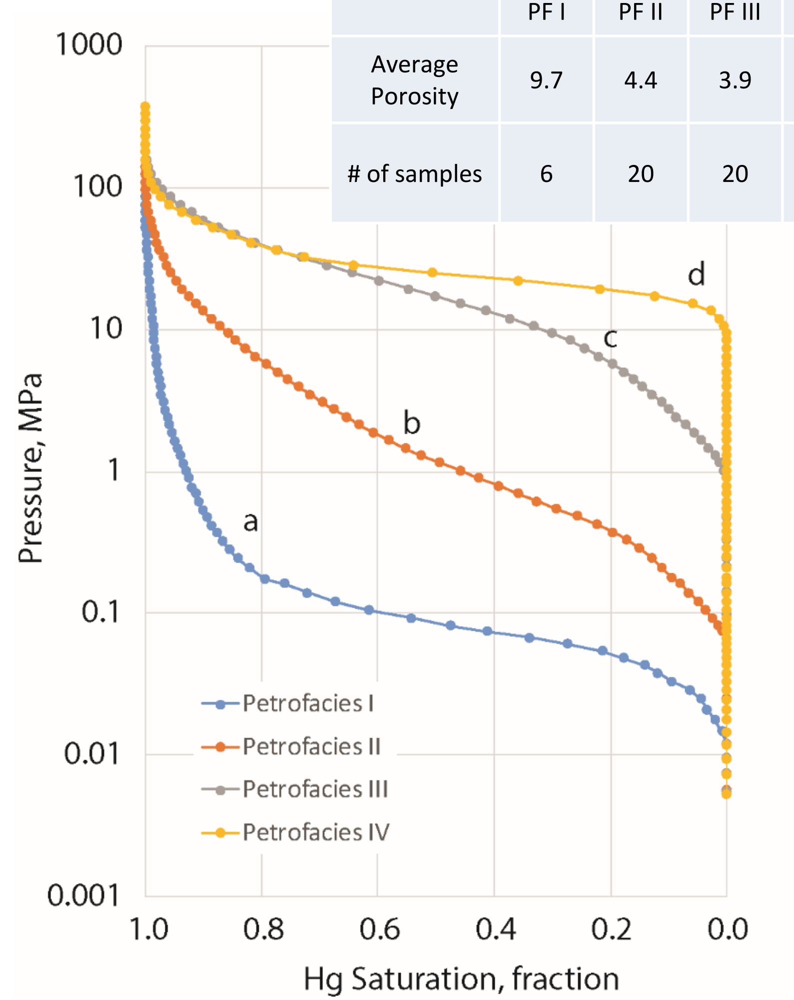
E_{saline} is the efficiency factor (1% and 4% used, respectively)

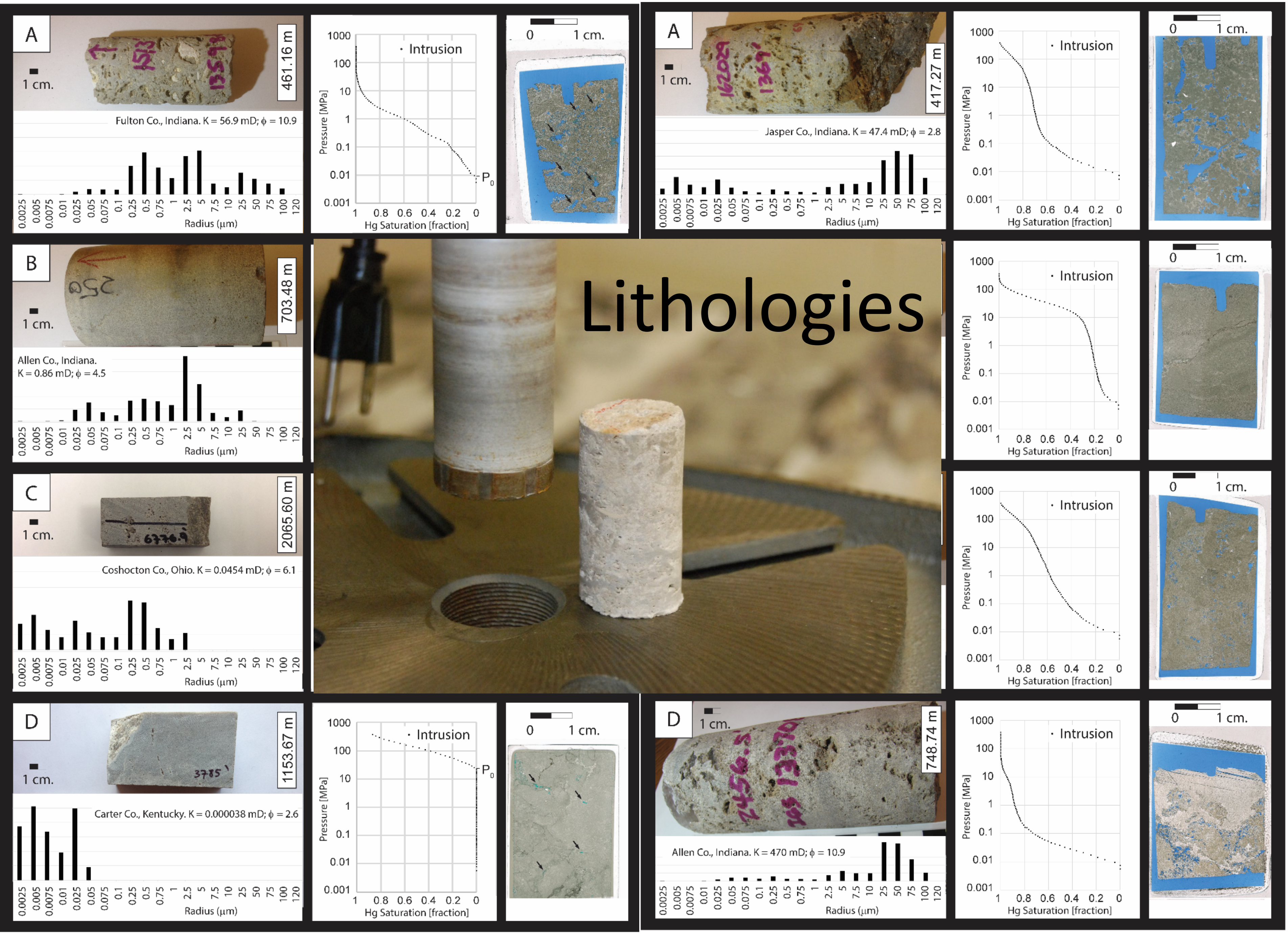
Method V

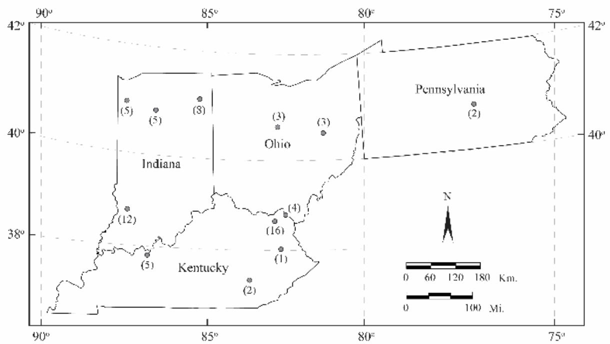
- Uses data from Mercury Injection Capillary Pressure (MICP) to define characteristic pore size distribution curve. An average porosity is derived from each type petrofacies.

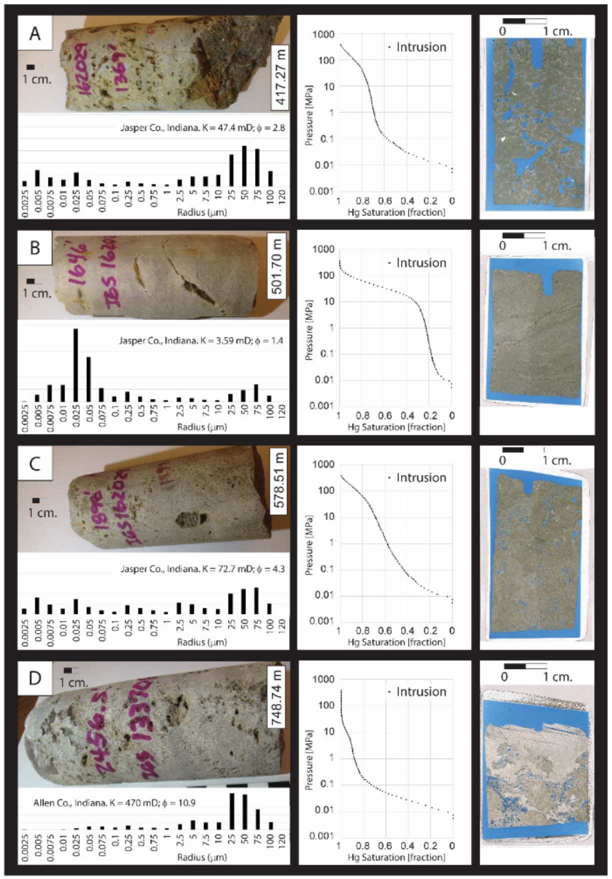


	PF I	PF II	PF III	PF IV
Average Porosity	9.7	4.4	3.9	3.6
# of samples	6	20	20	18




Lithologies
A
1 cm.
461.16 m
Fulton Co., Indiana. K = 56.9 mD; ϕ = 10.9
Radius (μm)
Pressure [MPa]
Intrusion
P0
Hg Saturation [fraction]
0 1 cm.
B
1 cm.
703.48 m
Allen Co., Indiana.
K = 0.86 mD; ϕ = 4.5
C
1 cm.
2065.60 m
Coshocton Co., Ohio. K = 0.0454 mD; ϕ = 6.1
D
1 cm.
1153.67 m
Carter Co., Kentucky. K = 0.000038 mD; ϕ = 2.6
A
1 cm.
417.27 m
Jasper Co., Indiana. K = 47.4 mD; ϕ = 2.8
D
1 cm.
748.74 m
Allen Co., Indiana. K = 470 mD; ϕ = 10.9
0.0025 0.005 0.0075 0.01 0.025 0.05 0.075 0.1 0.25 0.5 0.75 1 2.5 5 7.5 10 25 50 75 100 120
1000 100 10 1 0.1 0.01 0.001
1 0.8 0.6 0.4 0.2 0





Original Research Article

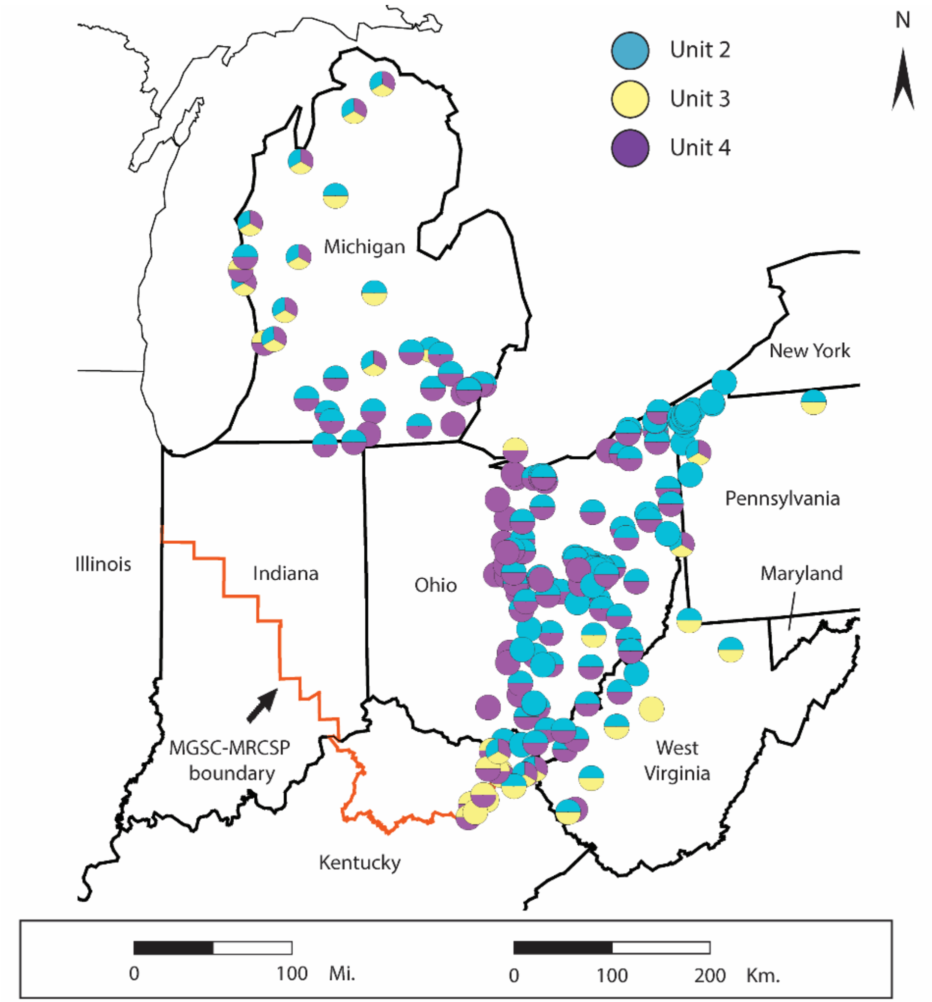
Pore system characterization of Cambrian-Ordovician carbonates using a new mercury porosimetry-based petrofacies classification system: application to carbon sequestration reservoirs

Cristian R. Medina, Department of Earth and Atmospheric Sciences, Indiana University, Bloomington, Indiana, USA and Indiana Geological and Water Survey, Indiana University, Bloomington, Indiana, USA
Maria Mastalerz and John A. Rupp, Indiana Geological and Water Survey, Indiana University, Bloomington, Indiana, USA

Abstract: To better understand injection and post-injection flow processes and the entrapment of supercritical CO_2 during geological carbon sequestration in a carbonate reservoir, the pore system was analyzed in 66 Cambrian-Ordovician carbonate samples from several locations in the midwestern USA. This work employed standard microphotography from thin sections, helium porosimetry for porosity and permeability, and mercury injection capillary pressure analysis, aiming to understand which elements of the pore system dominantly control the overall flow and CO_2 storage potential in the subsurface. In particular, mercury injection capillary pressure analysis has been fundamental in understanding several petrophysical properties of rocks, including porosity, permeability, and the pore-size distribution of the samples under study. This work analyzes mercury injection capillary pressure data and proposes a petrophysical subdivision of the samples into four petrofacies, based on values of porosity, permeability, and capillary entry pressure. This system aims to predict the portions of the studied carbonate sequence that are more likely to have a higher potential for injectivity and storage, and to better understand how porosity, permeability, capillary entry pressure, and pore size all play a role in ensuring both buoyant and capillary trapping mechanisms to secure the injected supercritical CO_2. Results from this investigation suggest that in these Cambrian-Ordovician carbonate reservoirs, pore size inversely correlates with capillary entry pressure, and that permeability does not

Source: Medina et al., 2018

Method VI: SCREEN (DOE-NETL)



Data Inputs

1

General Information	
Researcher Name	Cristian Medina
Formation Name	Trenton
Date	6/6/2017
Run ID	SRE MRCSP

2

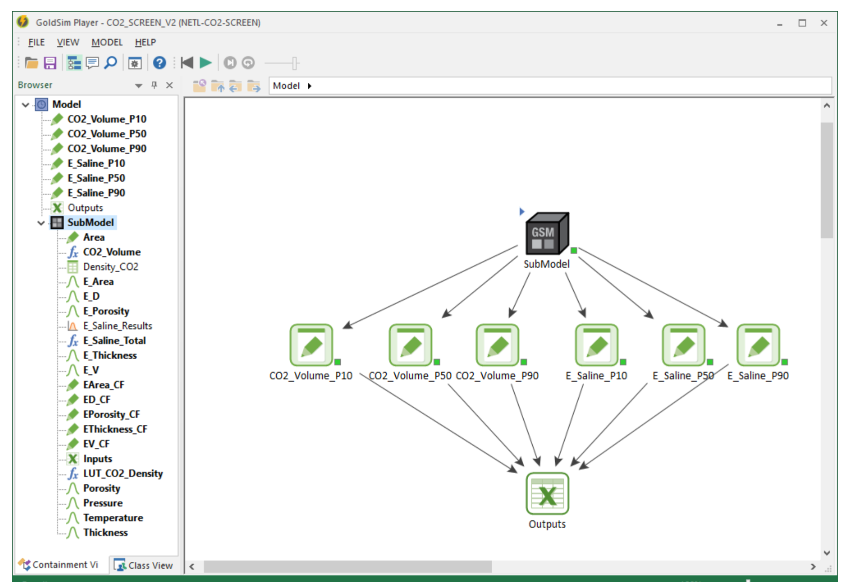
Storage Efficiency Factors

Auto-populate: Choose lithology and depositional environment

User Specified: Directly enter P_{10} and P_{90} values

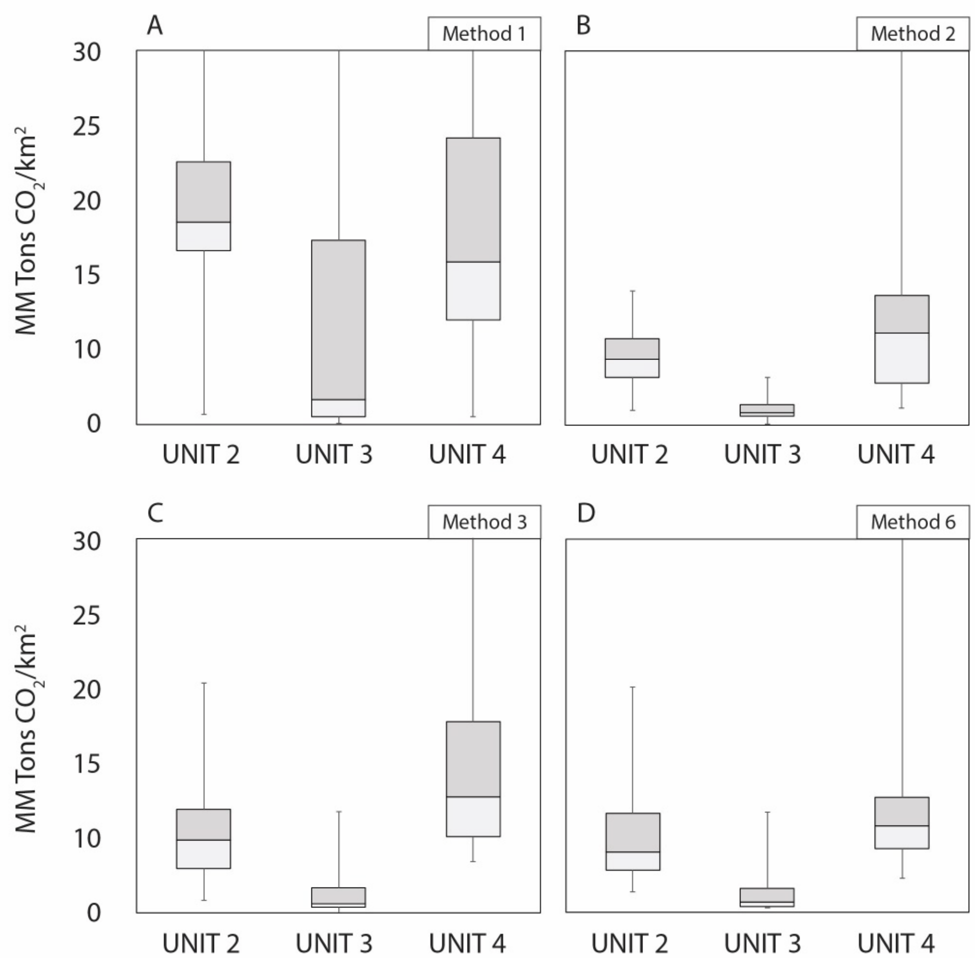
Lithology and Depositional Environment	Limestone: Unspecified

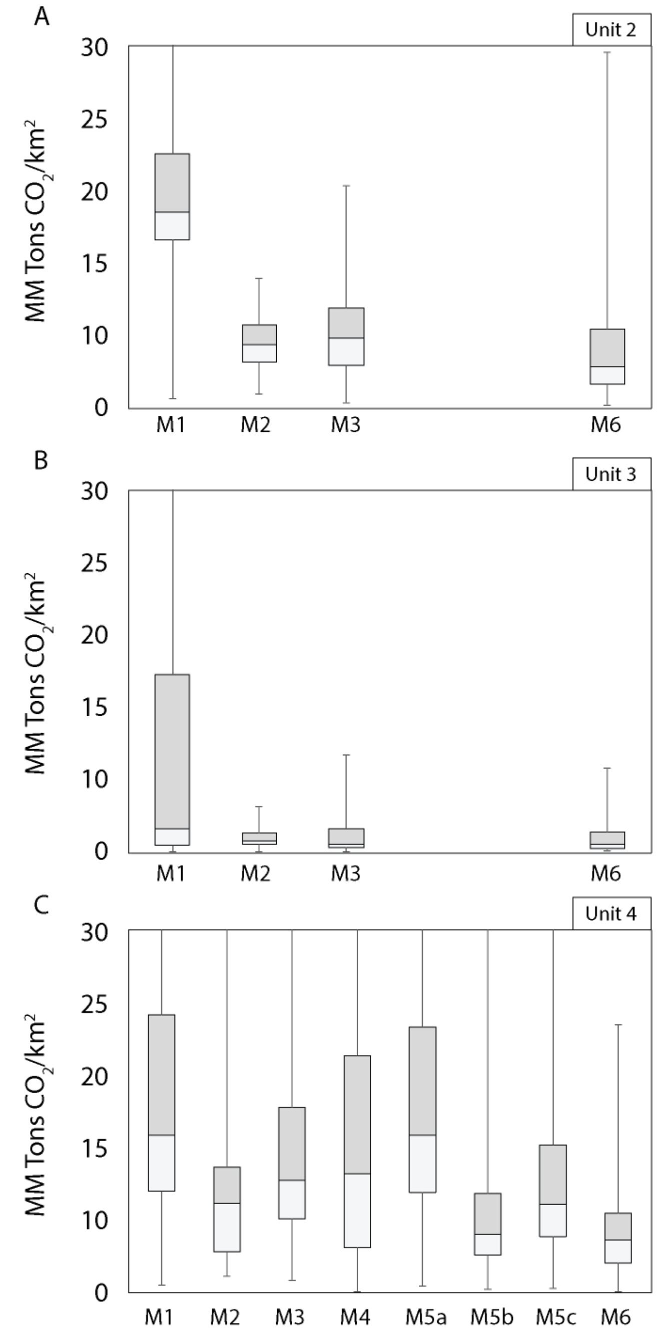
	Auto-populated		User Specified					
	P_{10}	P_{90}	P_{10}	P_{90}	X_{10}	X_{90}	μ_x	σ_x
Net-to-Total Area	0.20	0.80	0	0	-1.39	1.39	0.00	1.08
Net-to-Gross Thickness	0.13	0.62	0	0	-1.90	0.49	-0.71	0.93
Effective-to-Total Porosity	0.64	0.75	0	0	0.58	1.10	0.84	0.20
Volumetric Displacement	0.33	0.57	0	0	-0.71	0.28	-0.21	0.39
Microscopic Displacement	0.27	0.42	0	0	-0.99	-0.32	-0.66	0.26



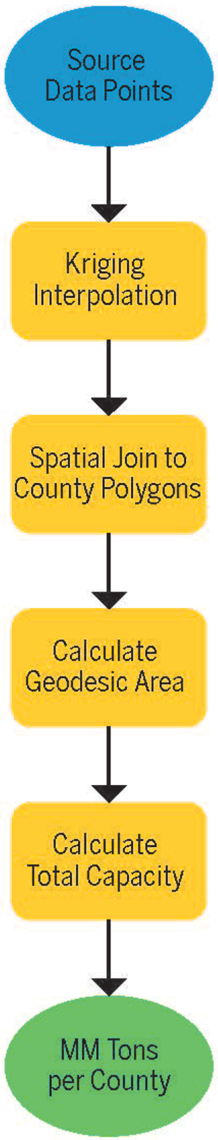
- Units deeper than 2500’
- Units shallower than 10000’
- Output in Mt/km^2

Results
(Raw values, E=1)





Results: GIS Workflow



Data imported from excel tables and converted to point features.

Interpolation of the analytical surfaces were created with simple kriging. Each surface was processed with an output cell size of 5000.

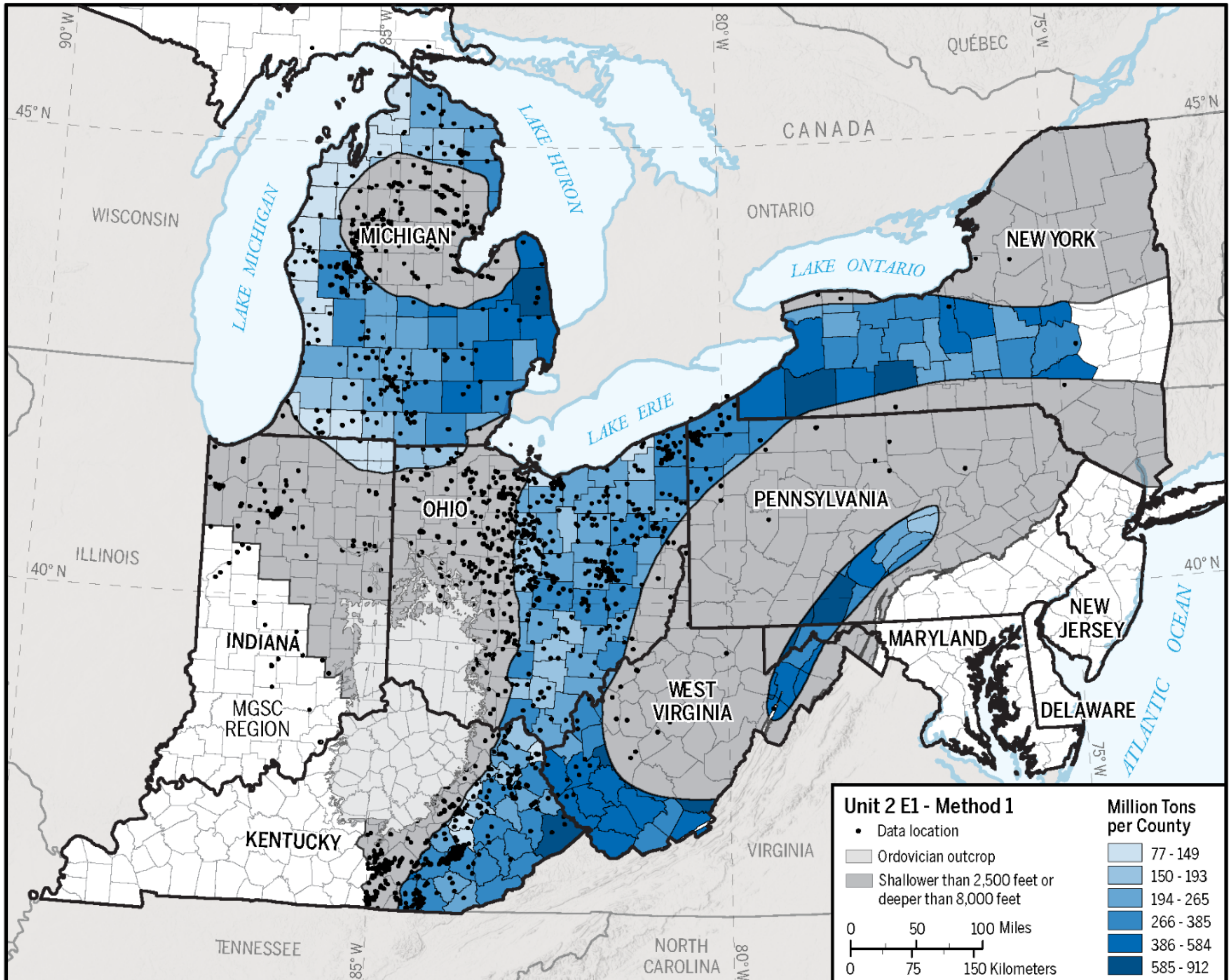
Raster output was then joined to county boundary polygons.

The geodesic area of each county polygon was then calculated.

Finally, the total capacity is calculated by multiplying the aggregated million tons of CO_2 per square kilometer by the area of each county in square kilometers.

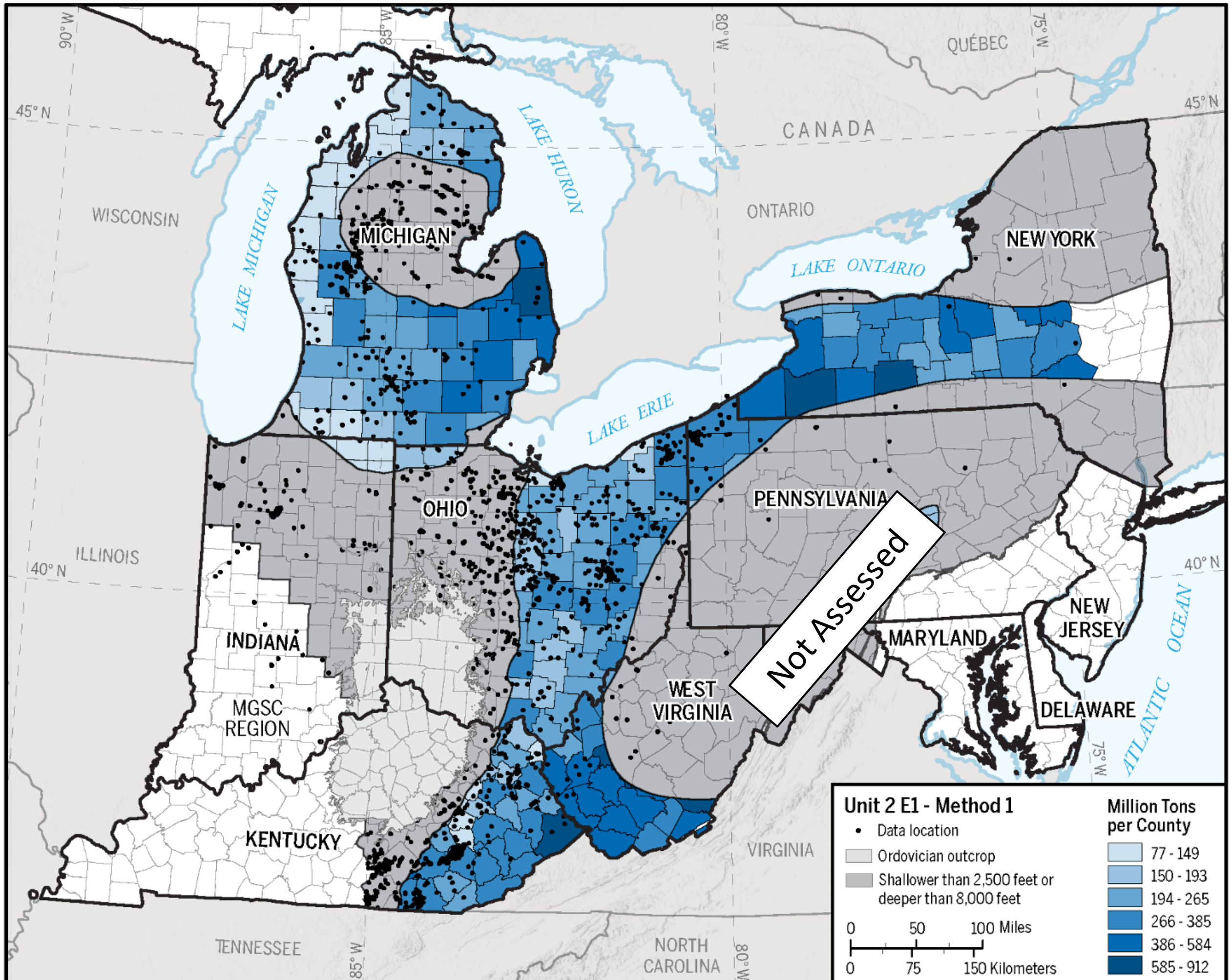
Source: Kevin Russell, IGWS

Unit II (Trenton/Black River) E1 Results (E=0.01)



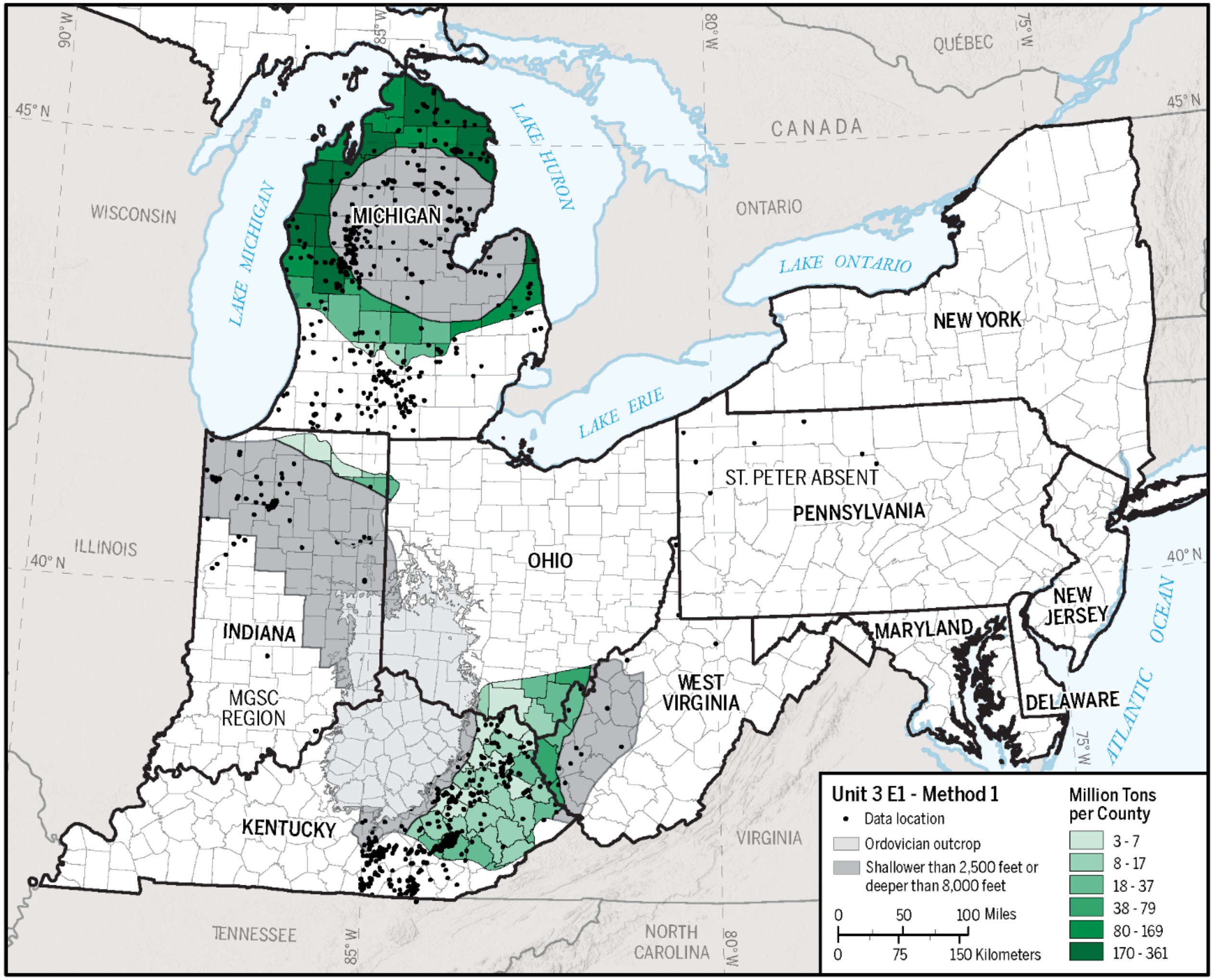
*Method 2 (core analysis) has limited data to show in maps.

Unit II (Trenton/Black River) E1 Results (E=0.01)

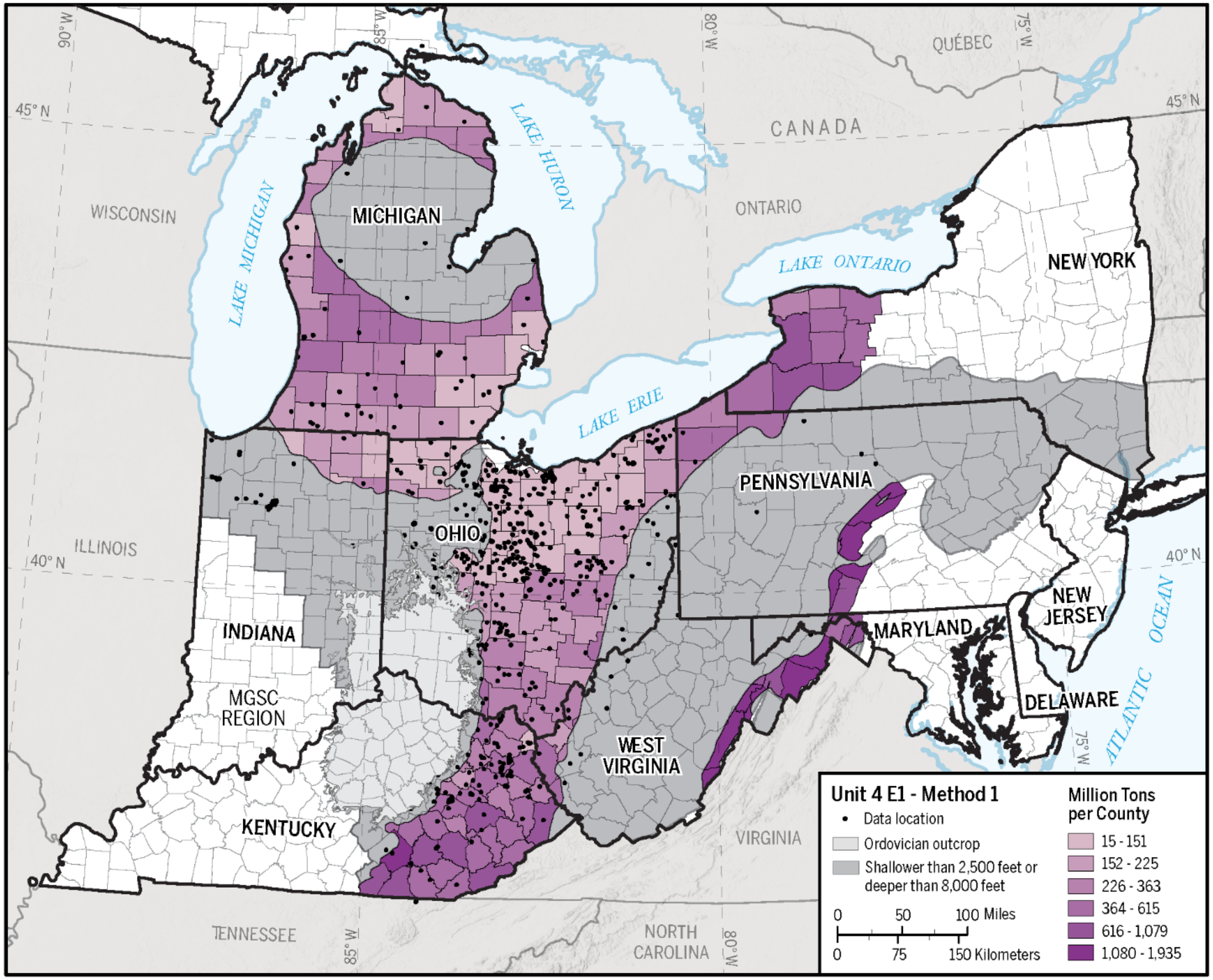


*Method 2 (core analysis) has limited data to show in maps.

Unit III (St. Peter SS) Reorder Think about order.



Unit IV (Knox Supergroup)

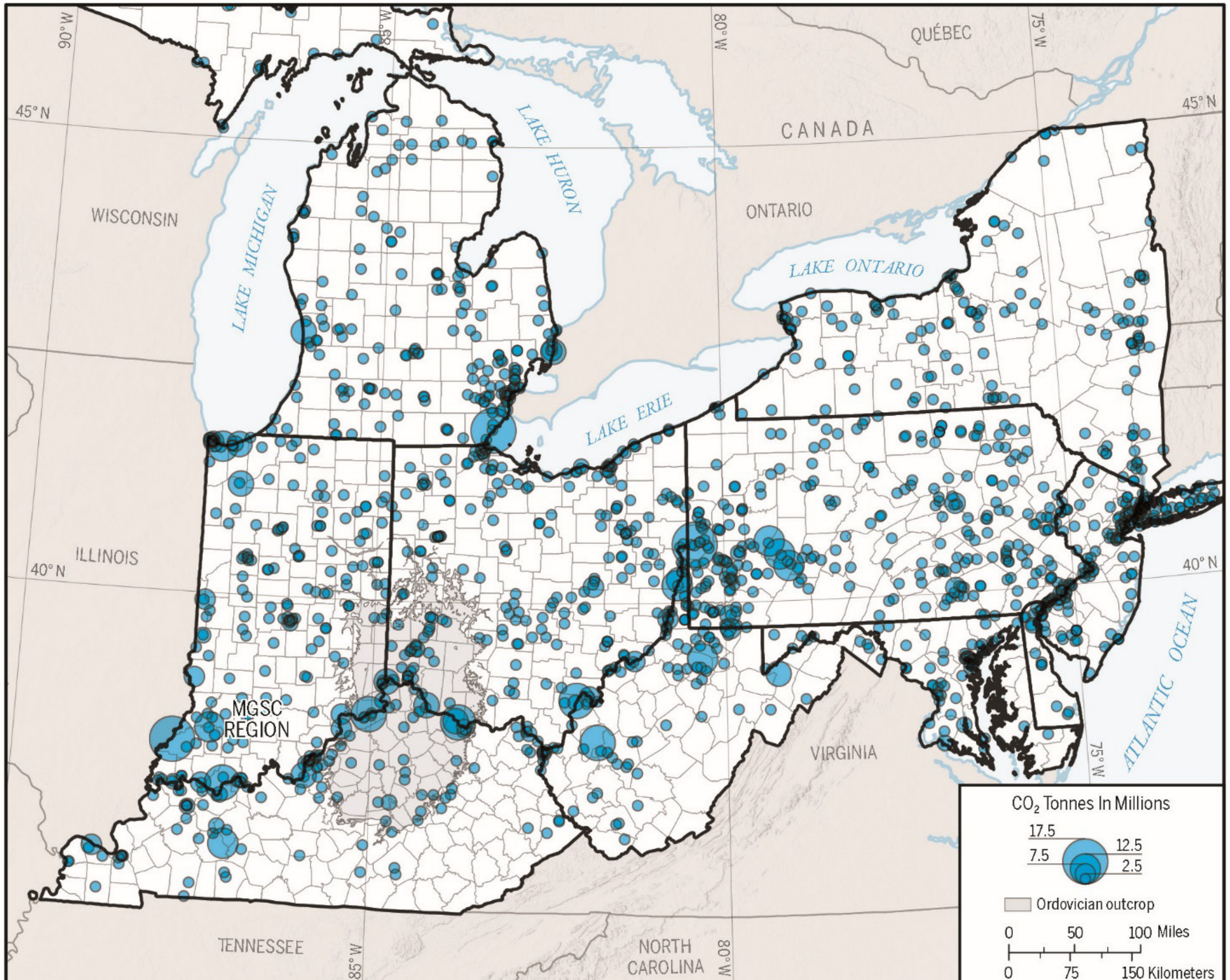


Total SRE estimated using method IV (E=1-4%): 14,935-59740 [MMTons] = 26-100 [yrs] [E=1-4%]

How do these SREs compare with Emissions from Point Sources?

Total CO_2 emissions: 559 [MMTons/Year]*

***Source: NATCARB (2014)**



More than 100 years worth of storage!**

Part II:
Sealing Efficiency of The Maquoketa Group

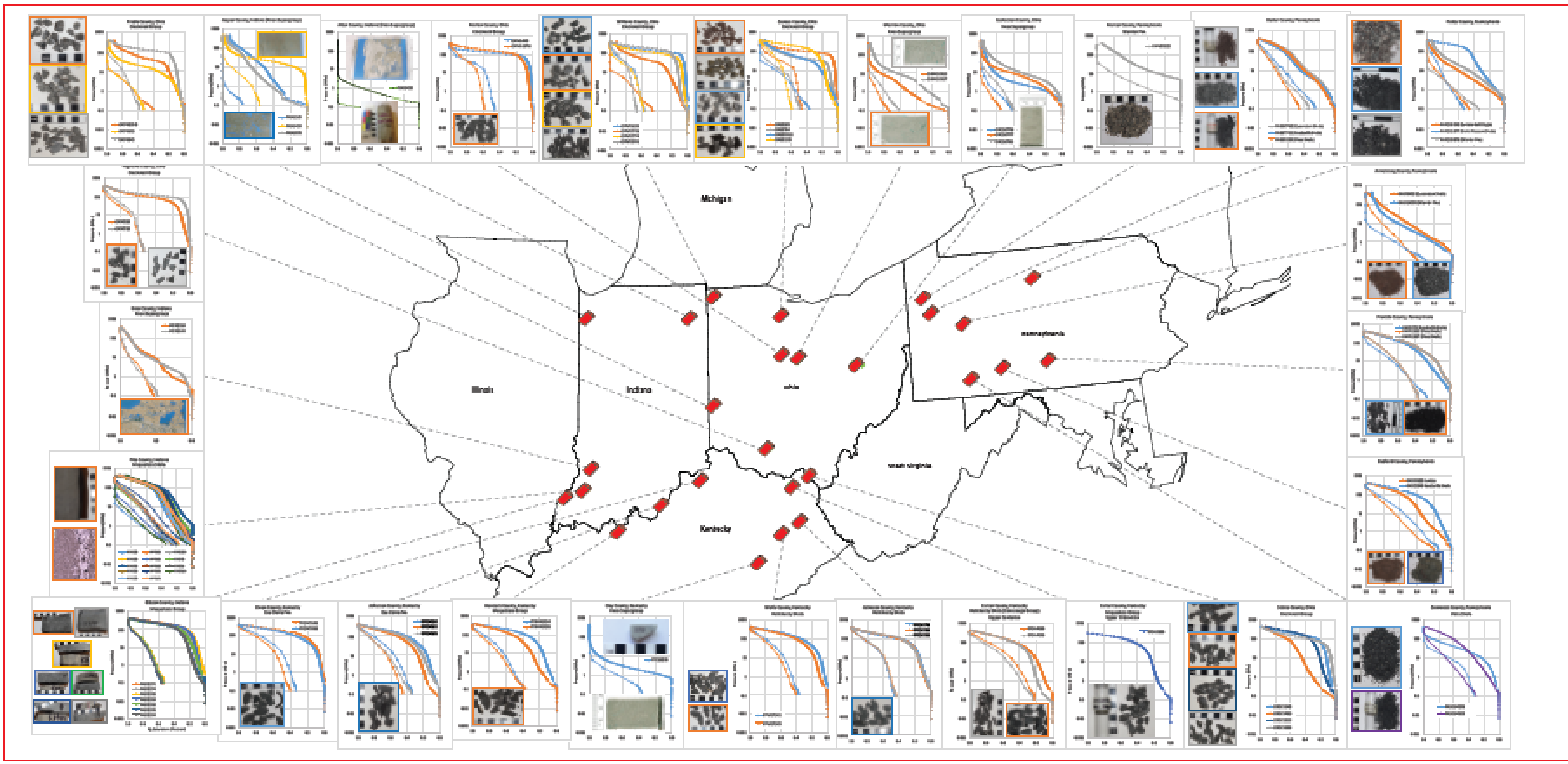
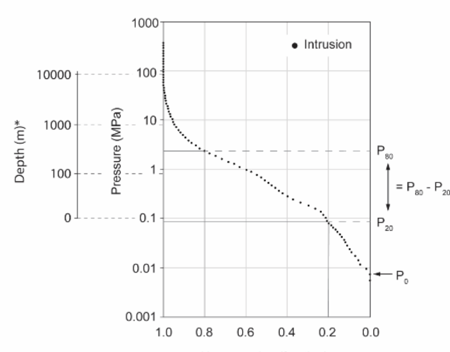
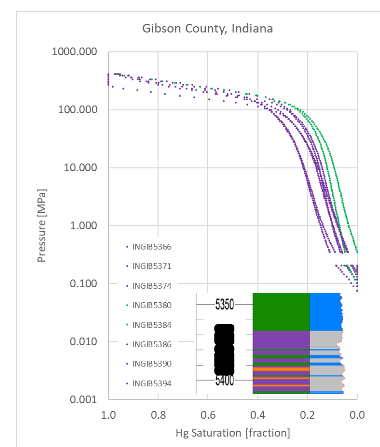


Image: Spatial distribution of MICP samples, sample photographs, and MICP data

Sealing Efficiency of The Maquoketa Group

- We sampled the Maquoketa Group (and equivalent units) from wells in Indiana, Kentucky, Ohio, and Pennsylvania. We used samples from cores and cuttings when available.
- Analysis of 32 samples using a Micromeritics' Autopore mercury porosimeter (MICP).
- Studied pore size distribution, permeability, and capillary entry pressure of Maquoketa samples and related these values to a representative CO_2 column.
- We put these results in context of the CO_2 column that the samples would be able to hold (density-gravity driven upward flow) .

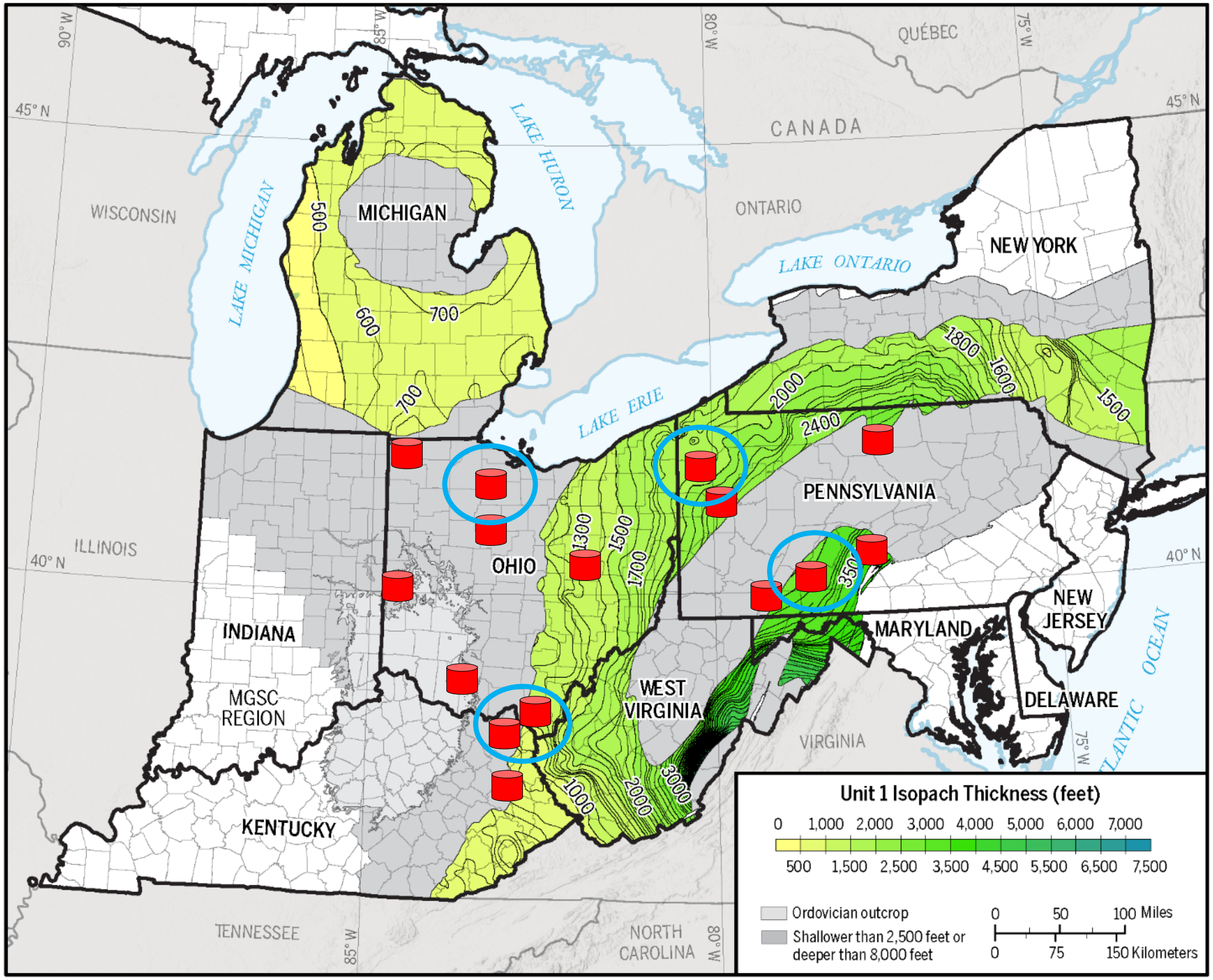




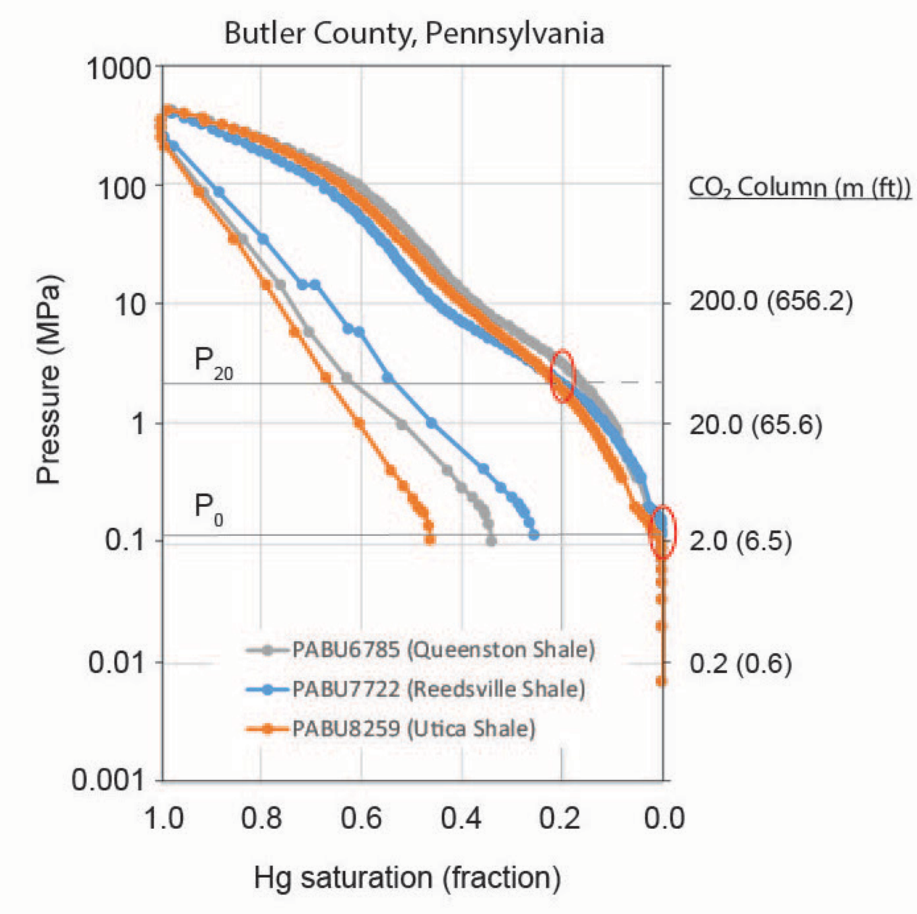
Maquoketa Group and equivalent Units Isopach and Samples Location

Sample Location

Example Wells to Show in this Talk



MICP Analyses



Assumptions:

1. Hg to CO_2 capillary Pressure conversion: factor of 12.4:

$$P_{C_{Hg-air}} = 12.4\ x\ P_{C_{CO2-Brine}}$$

2. Hydrostatic pressure gradient: 0.49 (psi/ft) – 0.022 (MPa/m)

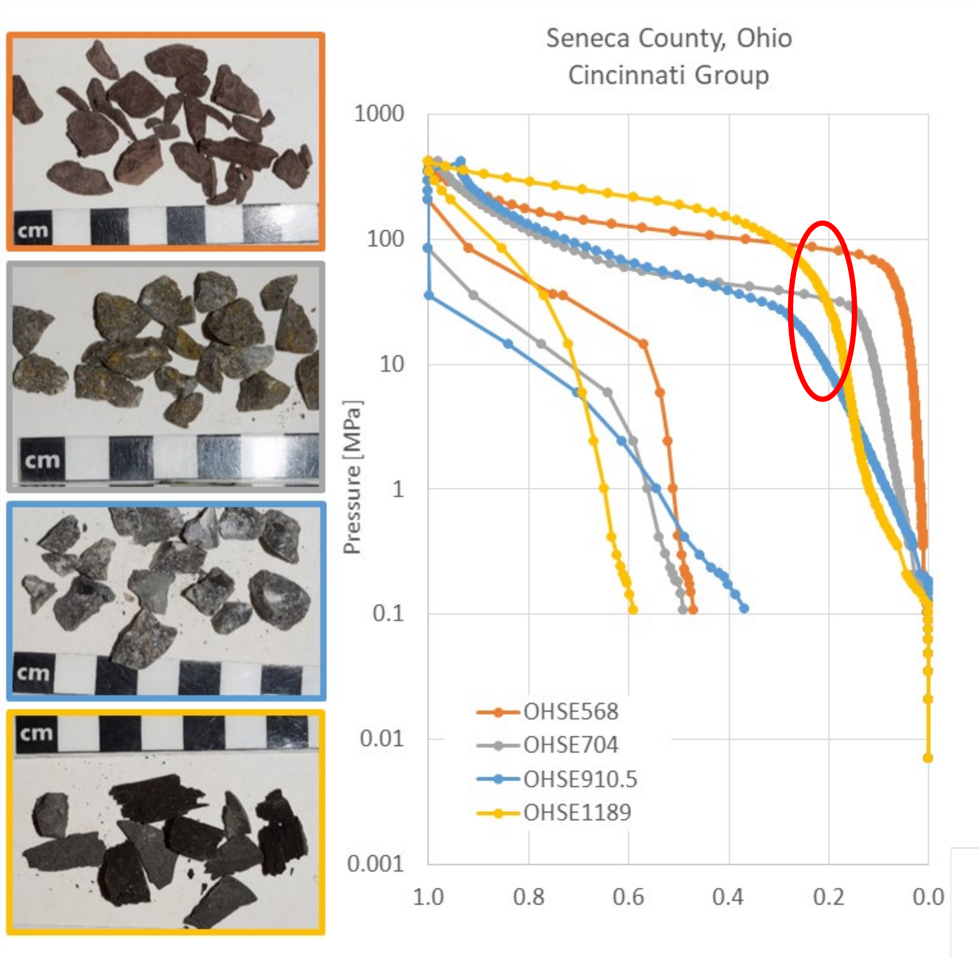
3. CO_2 density:

$\rho_{co2}(kg/m^3) = 712.88 + 0.4427 * P(Mpa)$

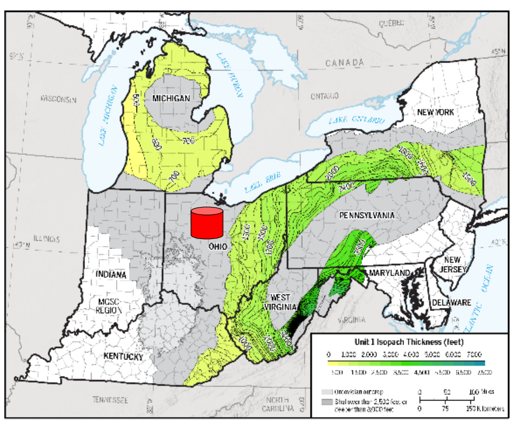
4. CO_2 column (h):

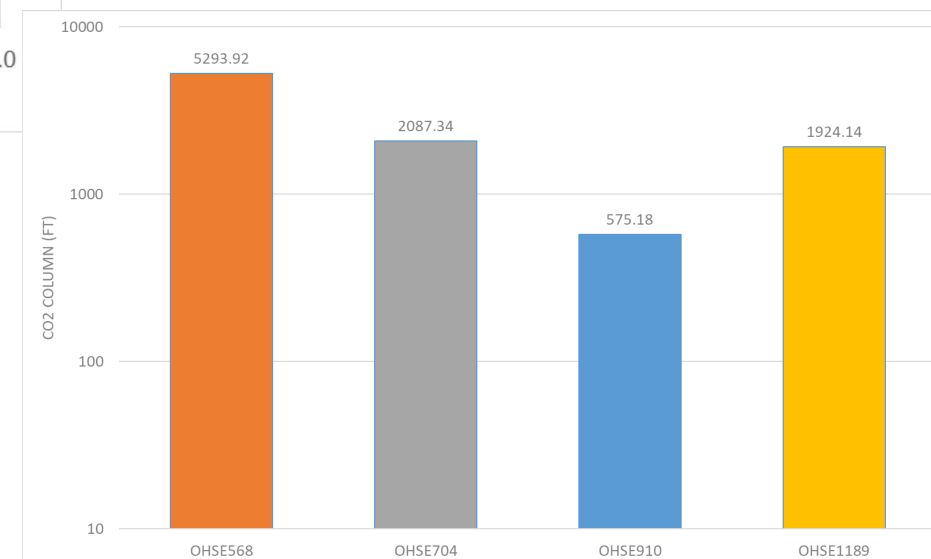
$$\Delta P = (\rho_{brine} - \rho_{CO2})gh:$$

$$h_0(m) = \frac{P_0}{9.8 * 12.4 * (\rho_{brine} - \rho_{CO_2})}$$

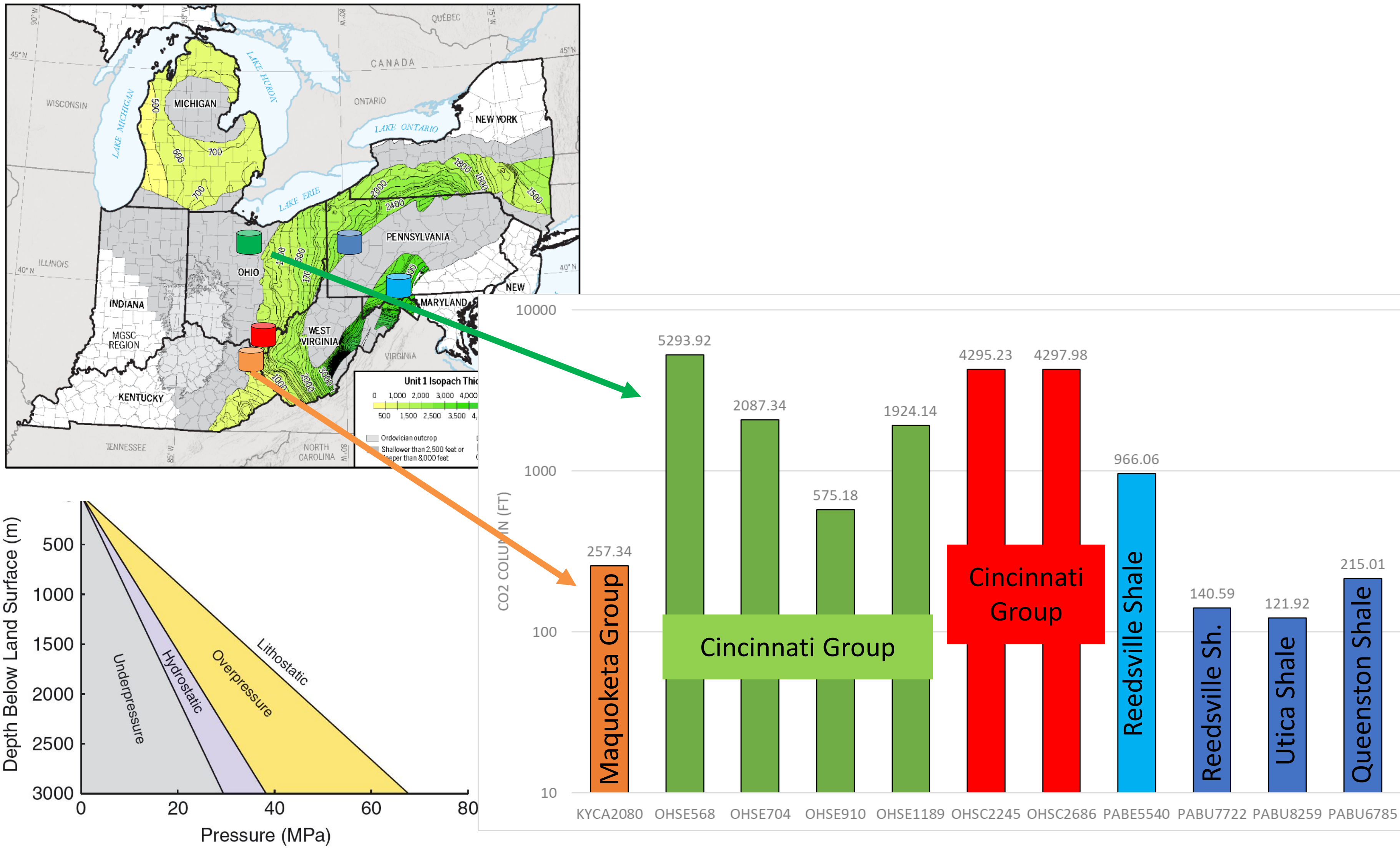


- Near 900 ft. thickness of the Maquoketa Group at this location.
- High values of P_{20} are translated into 500-5000 ft. of CO_2 column (20% entry).

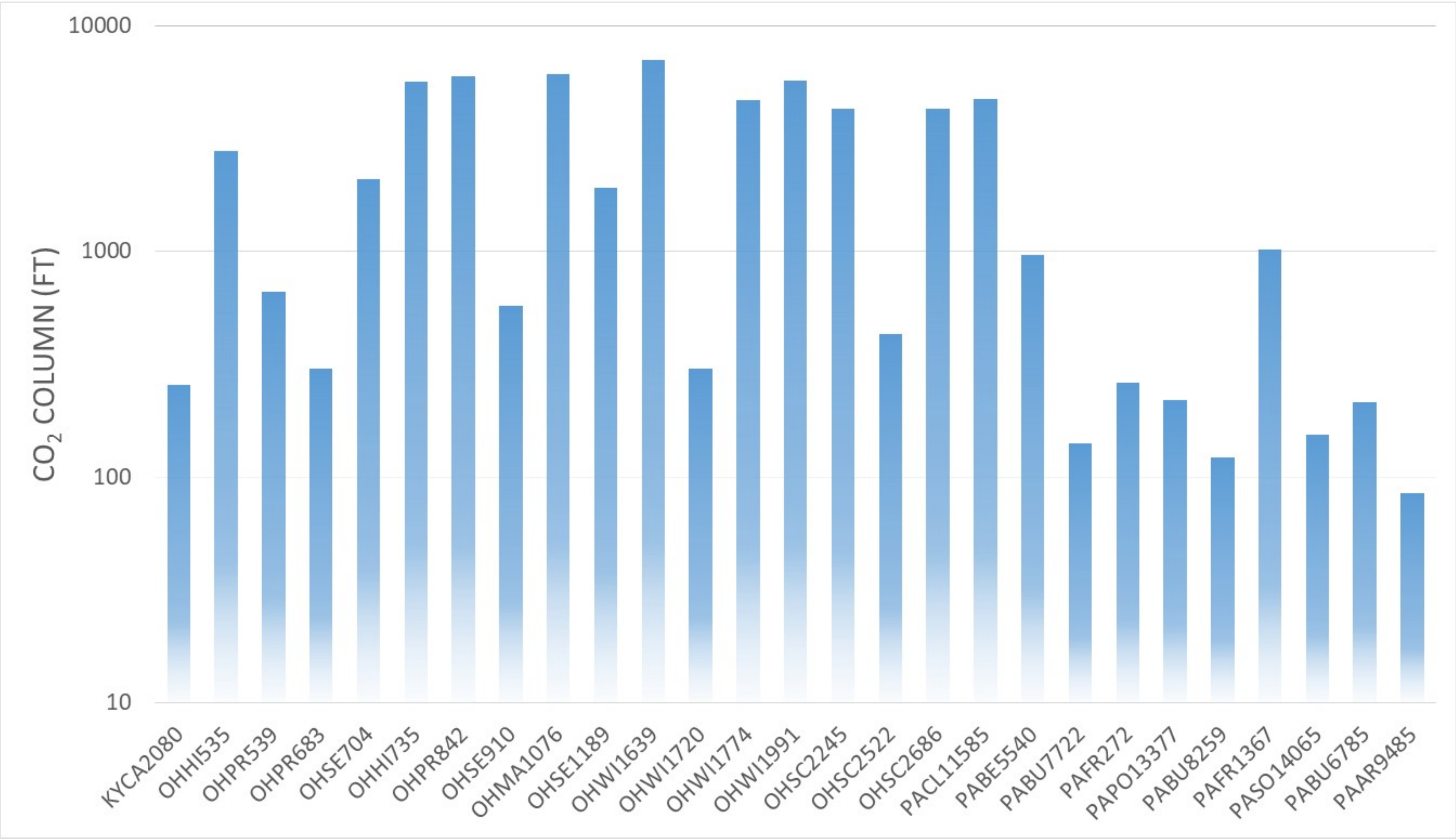




CO_2 Column at 5 Wells assuming 20% of Pore-Volume Saturation (P_{20})



CO_2 Column (ft.) associated with P_{20} invasion



Conclusions

- The MRCSP region exhibits sufficient geologic storage capacity in the Cambrian-Ordovician carbonate reservoirs in the Midwestern region. Considering CO_2 emissions from stationary sources in the region result in +100 years of storage.
- Methodologies suggest that using a single value for porosity of 10% (Method 1) results in overestimation of SRE.
- This SRE assessment does not include local factors that should be included in site-scale analysis (i.e., details of the local geology).
- This study is exploratory in nature and does not intend to determine which method is "better" or "worse than", but rather, sets the stage for future consideration of integration of different methods based on robustness and availability.
- The Maquoketa Group exhibit capillary pressure profiles from MICP analysis that, along with thickness of the sequence, suggest good sealing potential in the MRCSP region (work in progress).

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Storage Resource Estimates and Seal Evaluation of Cambrian-Ordovician Units in the MRCSP Region

Thank you!

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MRCSP
MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP