Hierarchical Evaluation of Geologic Carbon Storage Resource Estimates: Cambrian-Ordovician Units within the MRCSP Region*

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Abstract

The Midwest Regional Carbon Sequestration Partnership (MRCSP) aims to study the regional distribution and geologic storage suitability of units within the Cambrian-Ordovician sequences, including the Knox Supergroup, St. Peter Sandstone, Trenton and Lexington Limestones, and equivalent units across the MRCSP region.

To date, we have compiled a comprehensive data set of wireline logs and petrophysical information that include core analysis for porosity and permeability and mercury injection capillary pressure (MICP) analyses. Using these data, carbon storage resource estimates (SRE) are evaluated using a hierarchical approach that addresses uncertainty in the estimates by incorporating different models of formation porosity based on a series of increasingly complex portrayals of the pore system. The simplest analysis follows the USDOE methodology whereby a SRE is calculated using a single value for porosity in the assessed formation. Additional estimates follow the same general methodology but employ increasingly precise spatially variable porosity models based on formation diagenesis (depth-dependent function), reservoir suitability (effective porosity), distinct petrofacies (advanced reservoir characterization), and multiple realizations of porosity using data-driven geostatistical methods.

Results from this hierarchical approach help illuminate the magnitude of uncertainty that should be expected in SREs as a function of data availability and the level of reservoir characterization that is achievable for a given formation. A semi-probabilistic SRE calculation methodology using Monte Carlo simulations to create models for porosity generally tends to underestimate the range of uncertainty in storage resource. Conceivably, the higher the order model, the lower the uncertainty in the SRE. Ongoing research is investigating whether improved precision implicit in higher orders of the hierarchy are generating more accurate estimates of storage volumes.

Selected References

DOE Carbon Storage Atlas, 2015, Fifth Edition, 114 p. https://www.netl.doe.gov/File%20Library/Research/Coal/carbon-storage/atlasv/ATLAS-V-2015.pdf. Website accessed November 2016.

DOE-NETL, 2010, Carbon Sequestration Atlas of the United States and Canada: DOE National Energy Technology Laboratory, Third Edition, 160 p.

NATCARB, 2014, National Carbon Sequestration Database and Geographic Information System (NATCARB) Sources spatial database of stationary sources of atmospheric carbon dioxide (CO_2) emissions: https://databasin.org/datasets/8f9de65926ab4e32bbe763df100a1398. Website accessed November 2016.

Websites Cited

https://geologictimepics.com/. Website accessed November 2016.

www.lawmerallarm.org/. Website accessed November 2016.

INDIANA GEOLOGICAL SURVEY

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MRCSP MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP

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Kentucky Geological Survey UNIVERSITY OF KENTUCKY

Outline

- Purpose
- Midwest Regional Carbon Sequestration Partnership (MRCSP)
- Stratigraphy
- Reservoir characterization
- Methods
- Results
- Conclusions

Purpose

- To evaluate the CO_2 storage potential in saline aquifers of Cambrian-Ordovician strata underlying portions of the MRCSP states

- To explore the use of five different methodologies to independently generate storage resource estimates (SRE)

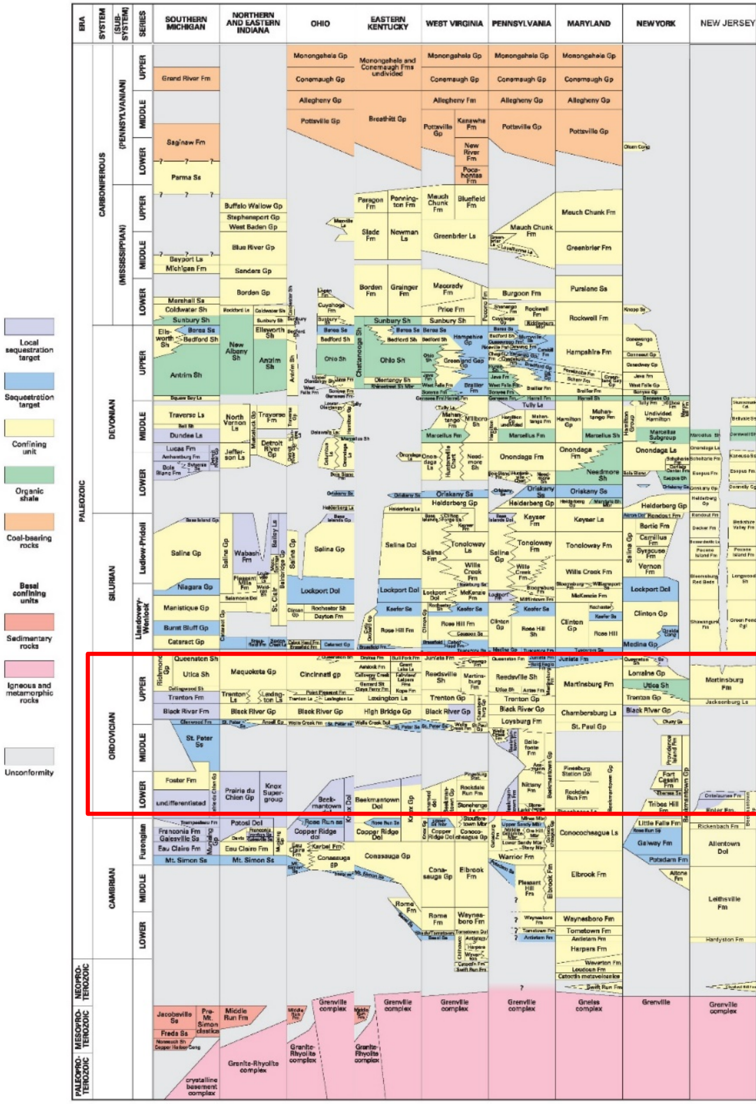
  - The methods differ fundamentally in how they estimate values for porosity (Ø)

- To compare the various results and assess how each of the different methods yield SREs with various magnitudes and explore the reasons for "inter-method" variability

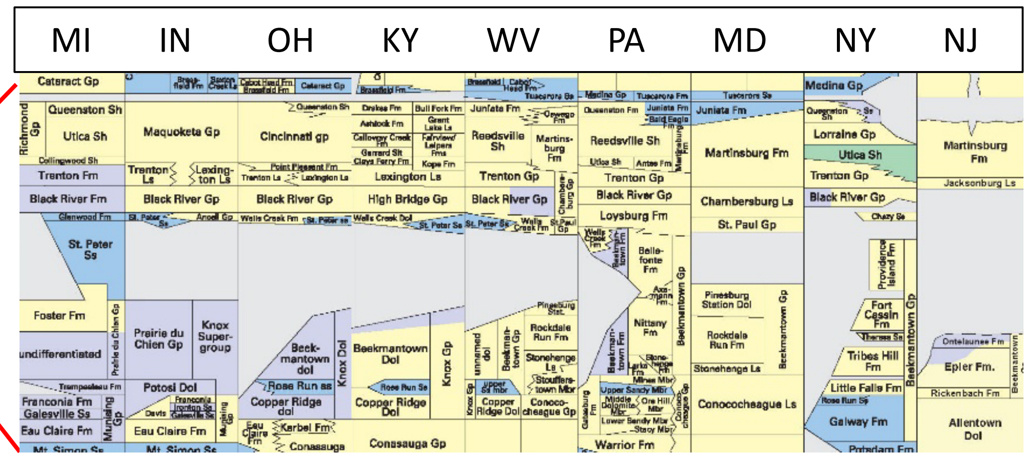
Midwest Regional Carbon Sequestration partnership (MRCSP)

- One of the seven partnerships in US and Canada
- 10 states
- This work focuses on saline aquifers in Indiana, Michigan, Ohio, Kentucky, West Virginia, and Pennsylvania

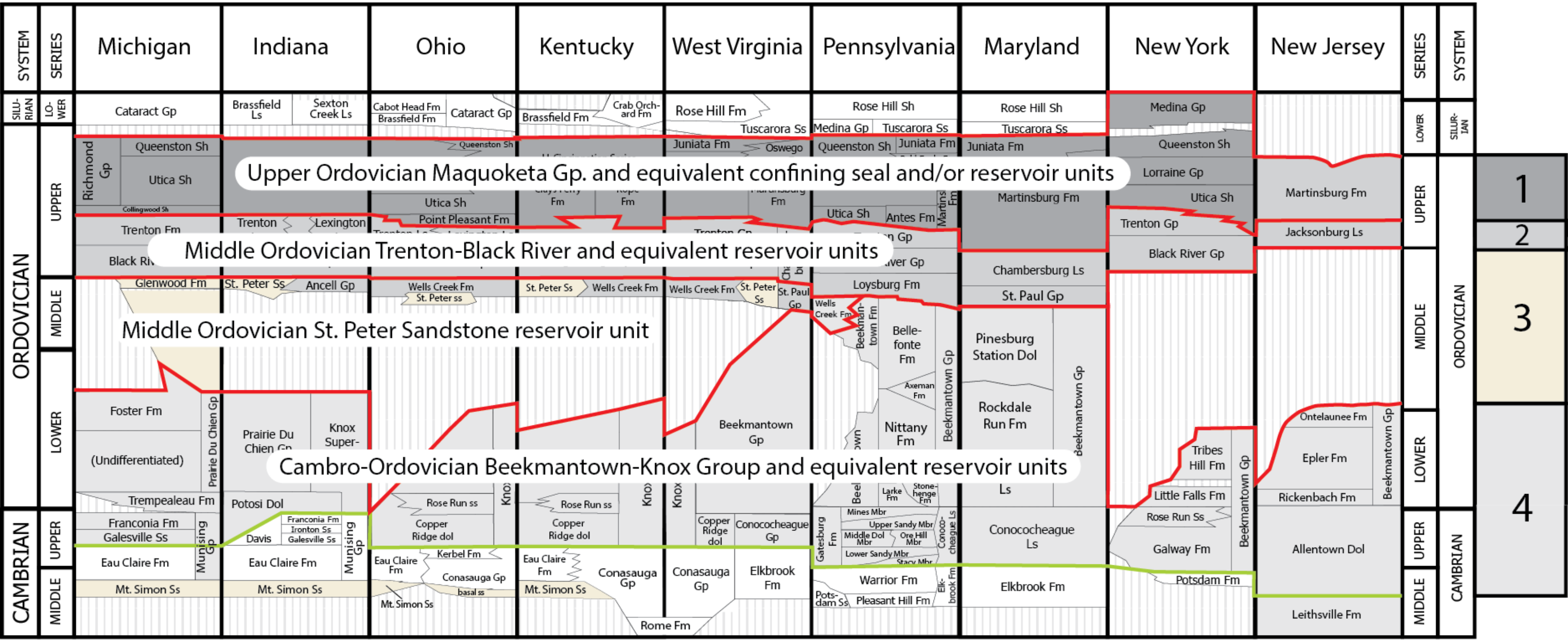
Stratigraphy / Units



Seal vs. Reservoir (Knox Supergroup)



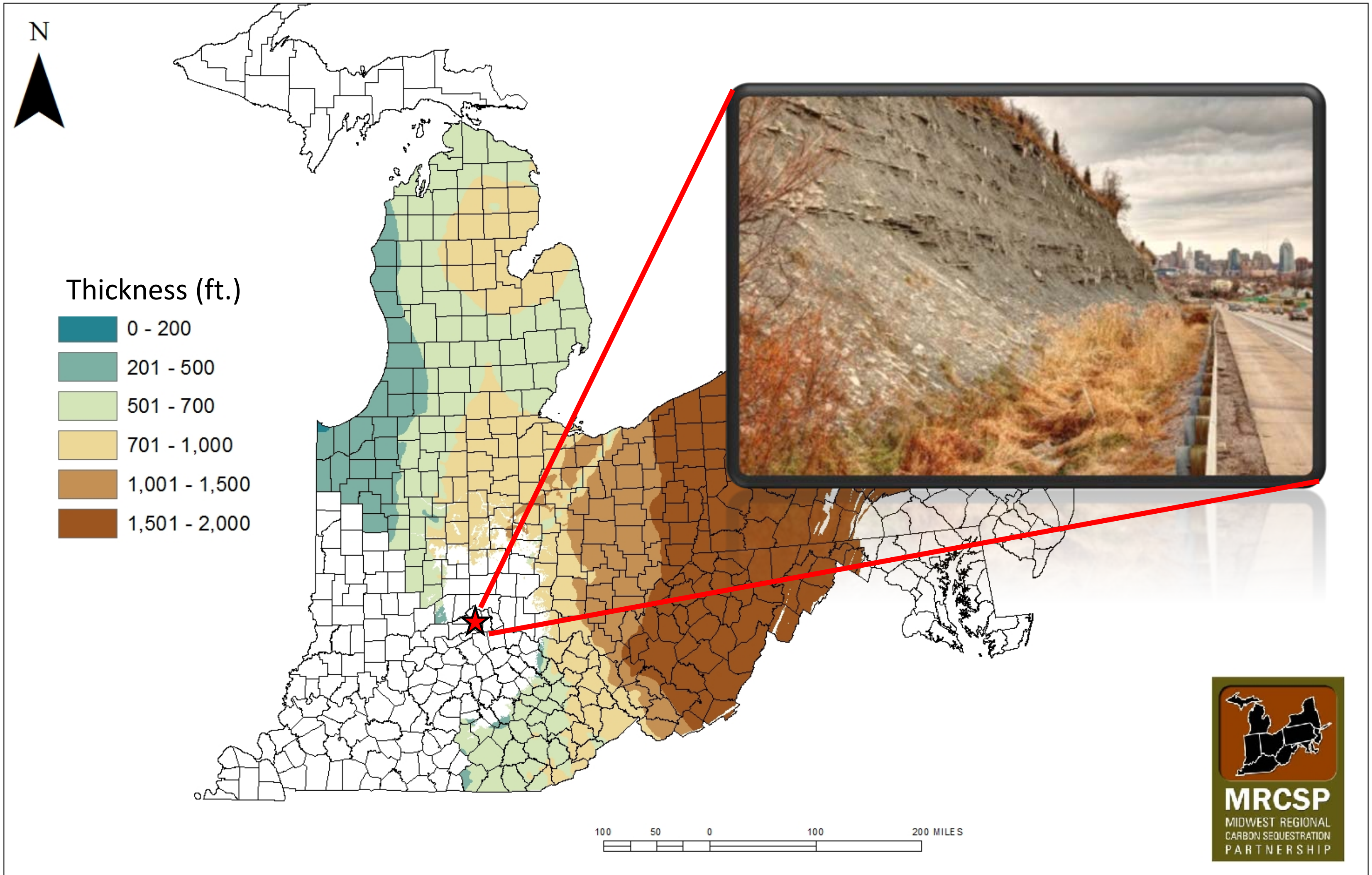
Stratigraphy / Units



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

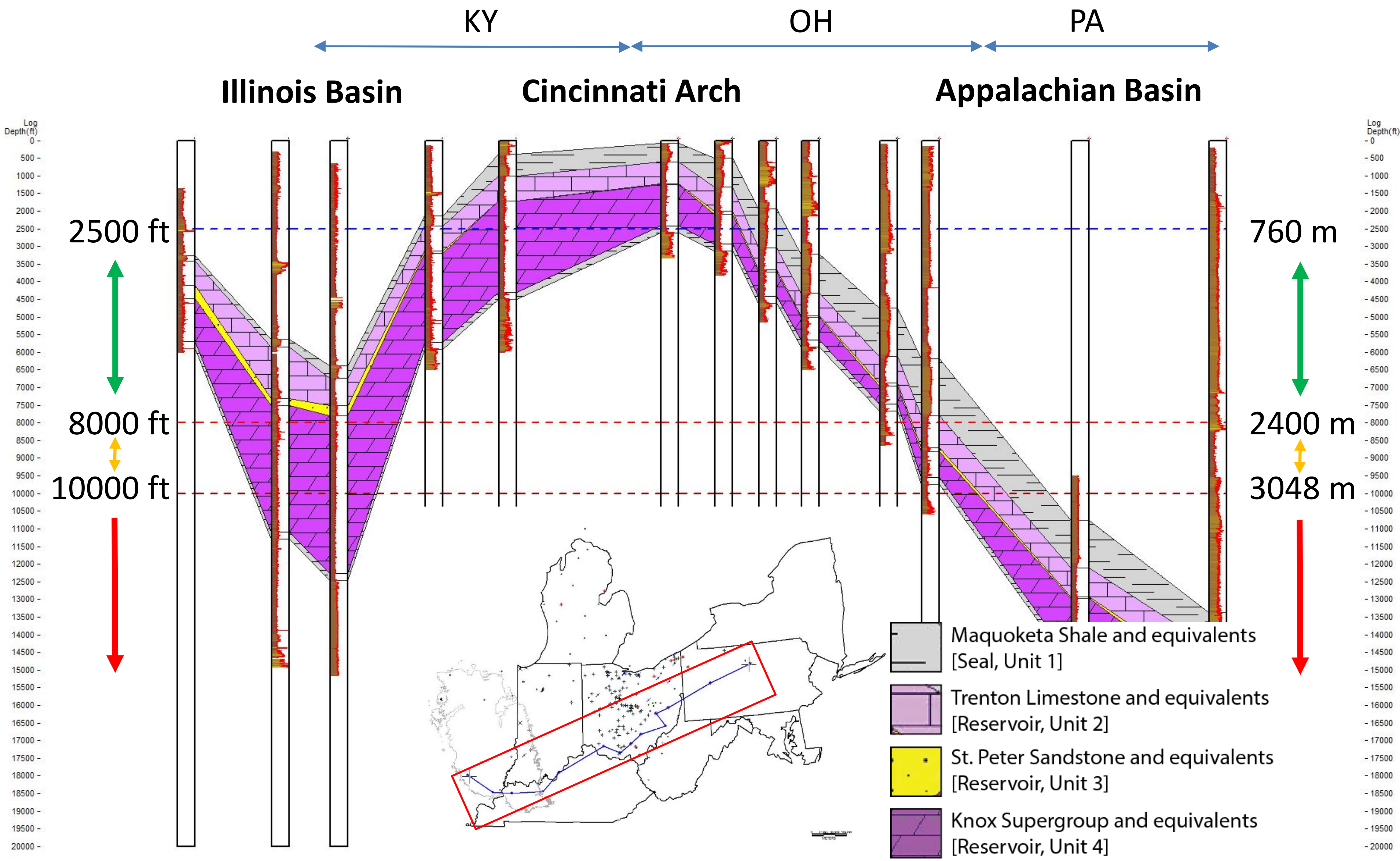
Unconformity
Base of Mapped Units

Isopach of Primary Reservoir Seal: Maquoketa Group and Equivalents

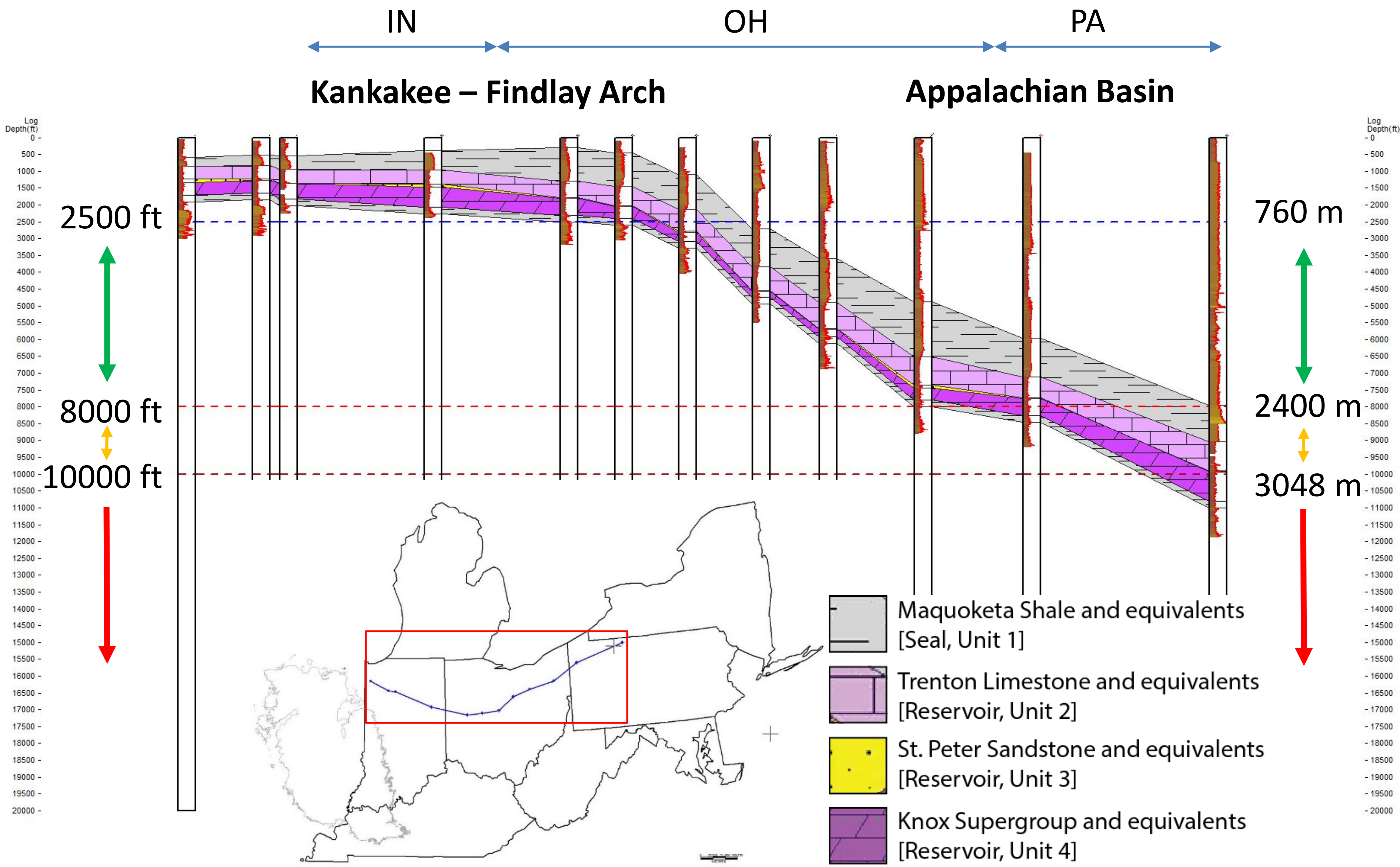


Source: https://geologictimepics.com/

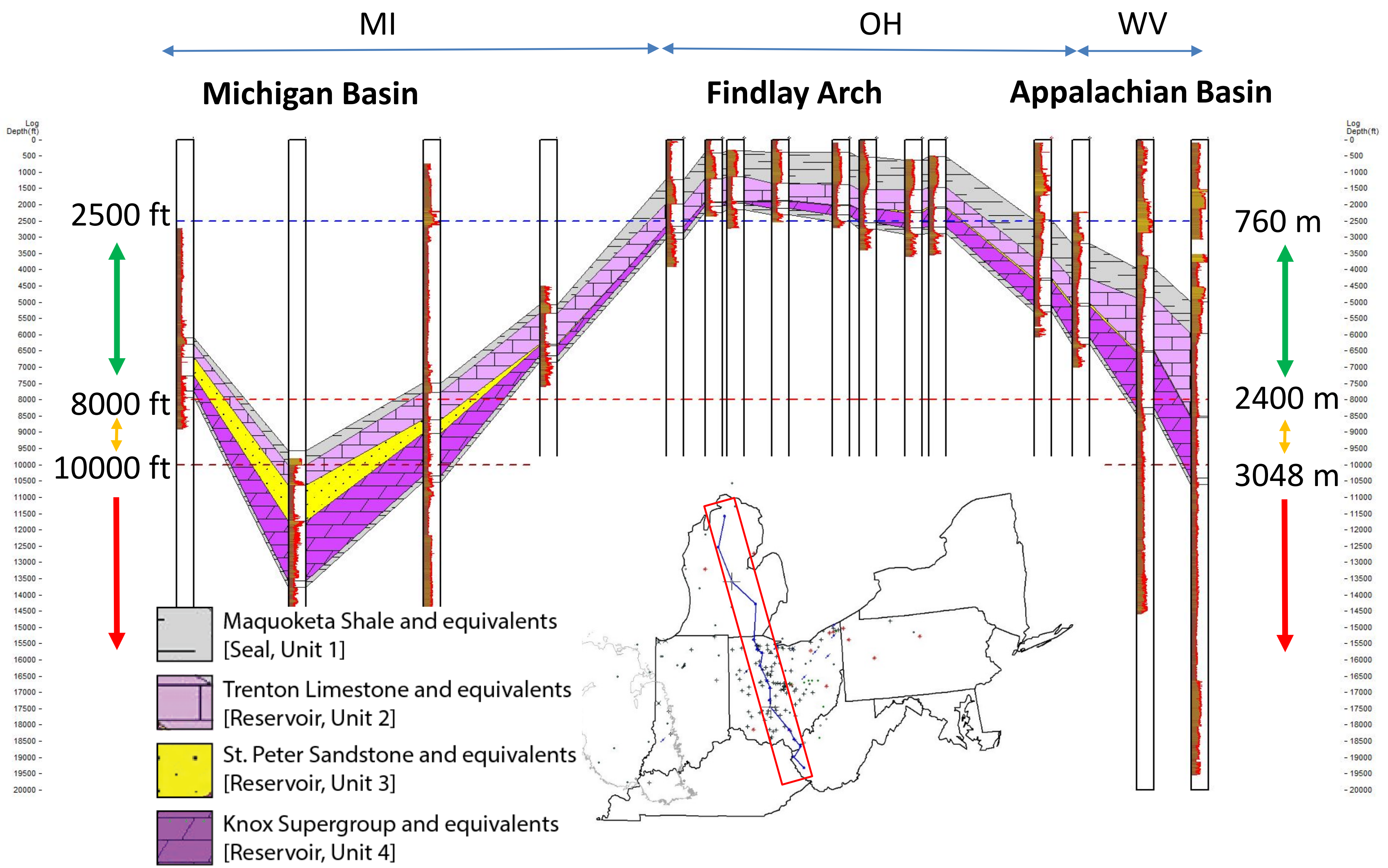
Cross Section I (SEE-NEE)



Cross Section II (W-E)



Cross Section III (N-S)



DOE Methodology

"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)

- Designed to be reconnaissance or highest level estimation of potential storage volumes
- Uses a single value for all basic parameters

Storage Resource Estimate (SRE):

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

Efficiency Factor

Employs an “efficiency factor” (**E_{saline}**) to account for the lack of accuracy caused by variability in factors

Efficiency factor uses “widely accepted assumptions about in-situ fluid distributions in porous formations and fluid displacement processes commonly applied in the petroleum and groundwater science fields”

In saline aquifers, because of the high degree of uncertainty in estimates (96 to 99 %), the resultant volumes are highly discounted (4 to 1% of the calculated values)

* However, when any of the factors in the basic volumetric equation are “enhanced” with more accurate, less uncertain data, the efficiency factors need to be modified (increased) to account for these changes.

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

where

$$\mathrm{E_{saline}} = \mathrm{E_{An/At}}\ \mathrm{E_{hn/hg}}\ \mathrm{E_{\phi e/\phi tot}}\ \mathrm{E_v}\ \mathrm{E_d}$$

This Work's Methodology

Increasing in sophistication/complexity of porosity data

Method I	Method II	Method III	Method IV	Method V
Assumes average porosity in all units (ϕ = 10%) Similar to DOE methodology	Uses average porosity from core analysis	Uses porosity from wireline logs Logs used include neutron, sonic, and density	Uses a diagenetic model that assumes an exponential decrease of porosity as a function of depth	Uses MICP data on pore size distribution patterns to define 'petrofacies' models
Robust dataset	Limited data	Robust dataset	Robust dataset	Limited data

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

Method I

- Assumes average porosity in all units (ϕ_{tot}= 10%)
- Follows a volumetric equation (ie, methodology published in Atlas by DOE-NETL, 2010)

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

$$SRE_{CO_2} = A_t * h_g * \mathbf{0.10} * 0.73 * [0.01, 0.04]$$

<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 II

- Uses average porosity from core analysis (ϕ_{core})
- Follows volumetric equation (DOE-NETL, 2010)

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

Where:

A_t *is the area of a given county*

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

$\emptyset_{core}$ *is the average porosity from core analysis*

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 III

- Consists of the processing of wireline-derived porosity (such as neutron, sonic, or density logs) in Petra Software to estimate SRE.

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

Where:
A_t *is the area of a given county*
h_g *is the average thickness, in the county, of unit under assessment*
$\emptyset_{log}$ *is the wireline-derived porosity*
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 IV

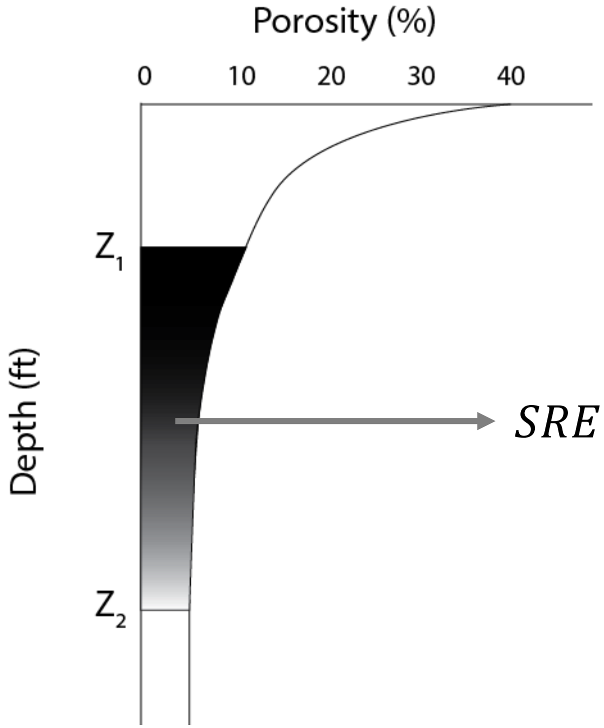
- Uses depth-dependent porosity model based on the previous studies that suggest that porosity decreases with depth ($\phi(d)=A*e^{-depth*B}$)

$$SRE_{CO_2} = A_t * h_g * \emptyset(d) * \rho_{CO_2} * E_{saline}$$

Where:
A_t *is the area of a given county*
h_g *is the average thickness, in the county, of unit under assessment*
$\emptyset$ *(d) is porosity as a function of depth*
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 IV

$$SRE_{well} = \int_{z_{top}}^{z_{bottom}} \emptyset(z)dz = \int_{z_{top}}^{z_{bottom}} 0.1497 * e^{-0.00023*z} dz$$



$$SRE = 650.8 * (e^{-0.00023*z_1} - e^{-0.00023*z_2})$$

Method V

- Uses data from Mercury Injection Capillary Pressure (MICP) to define petrofacies. These petrofacies have characteristics values of porosity (and permeability).

$$SRE_{CO_2} = A_t * h_g * \emptyset(\boldsymbol{petrofacies}) * \rho_{CO_2} * E_{saline}$$

Where:

A_t *is the area of a given county*

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

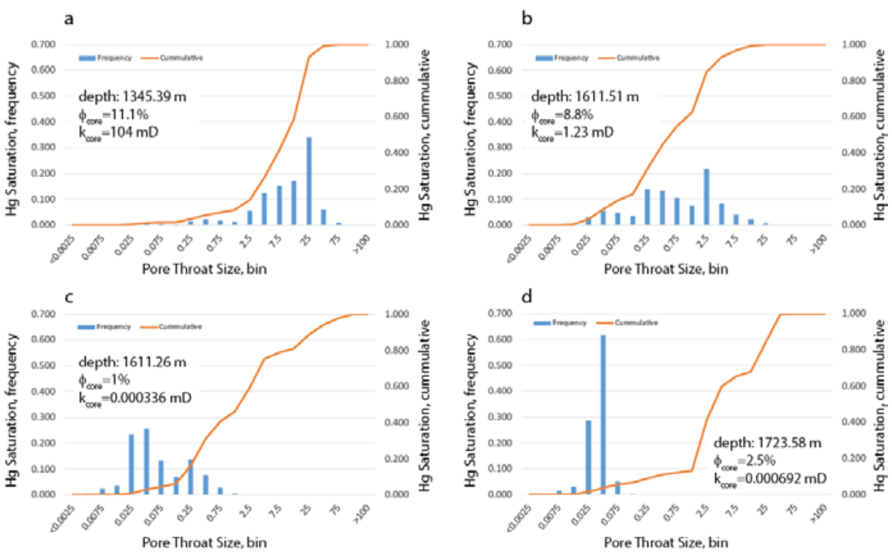
$\emptyset$ *(petrofacies) is porosity associated to petrofacies*

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

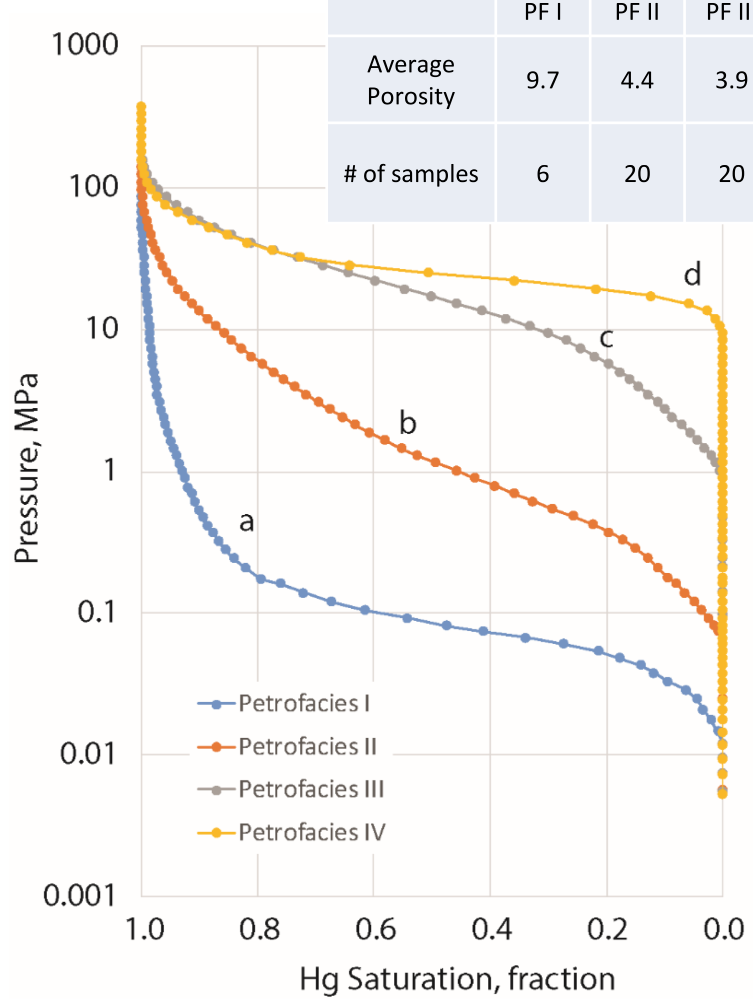
E_{saline} is the efficiency factor (1% and 4% used, respectively)

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

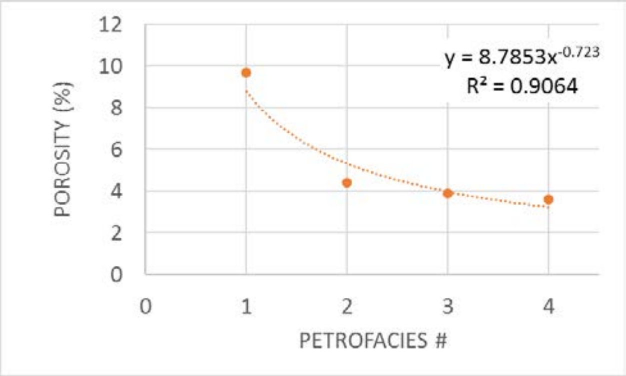


Petrofacies in Cores

Petrofacies #1

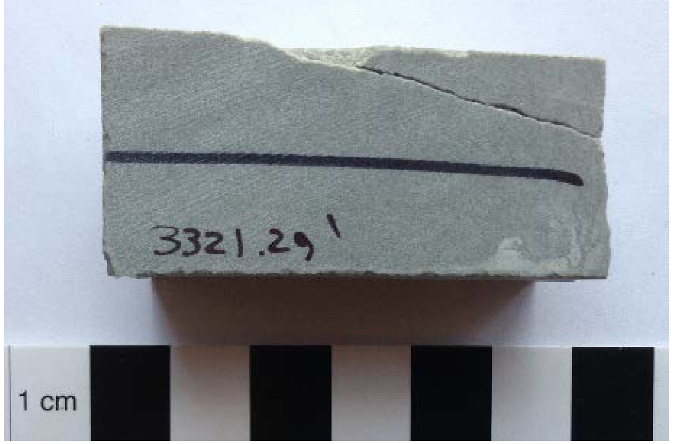
Petrofacies #2

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



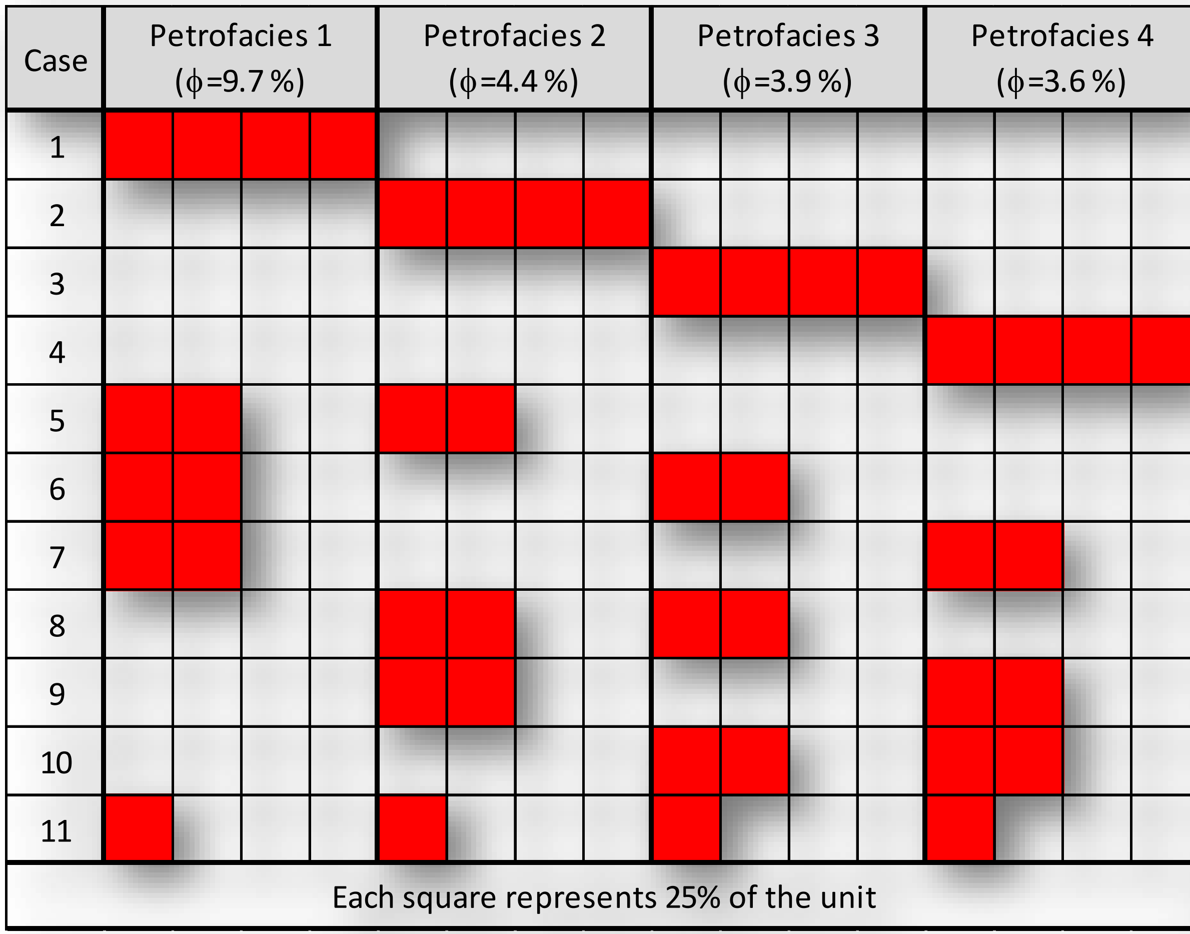
Petrofacies #3

Petrofacies #4



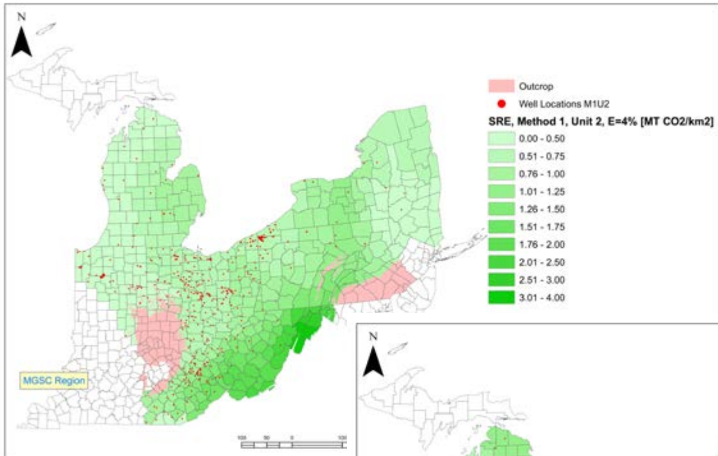
Method V

Each well is assumed a different scenario of abundance of petrofacies (porosity based on current study)

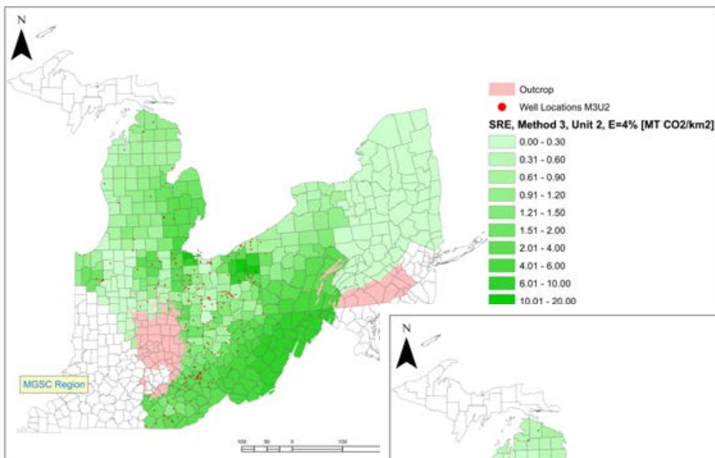


Results

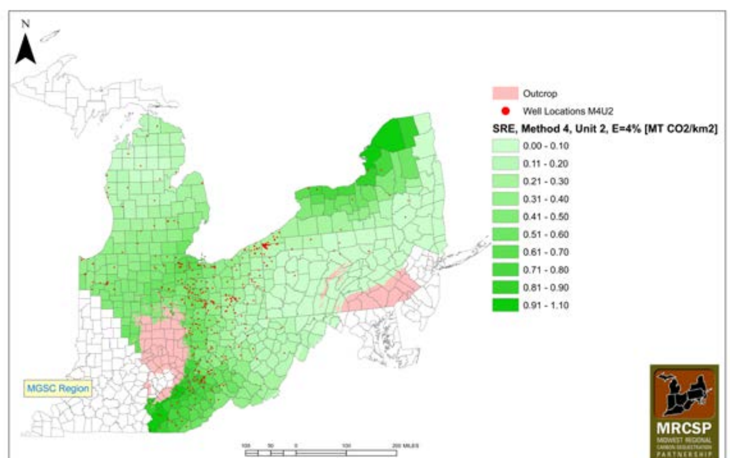
Unit II (Trenton/Black River): Results* (E = 4%)



Method 1 (ϕ = 10%)
Controlled by:
Thickness



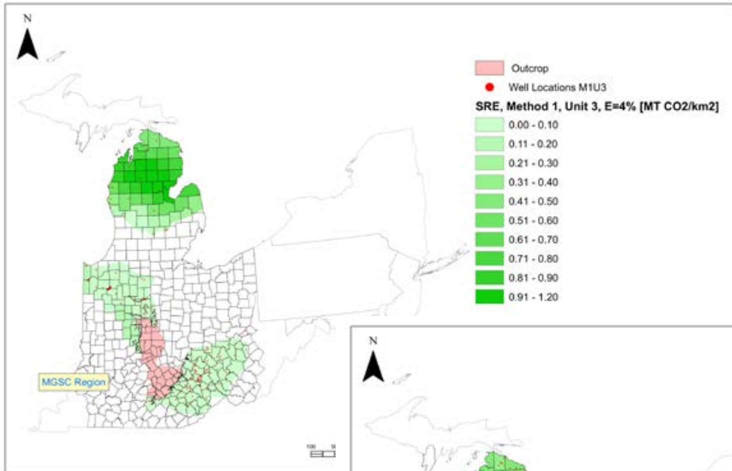
Method 3 (porosity from wireline logs)
Controlled by:
Thickness and logs



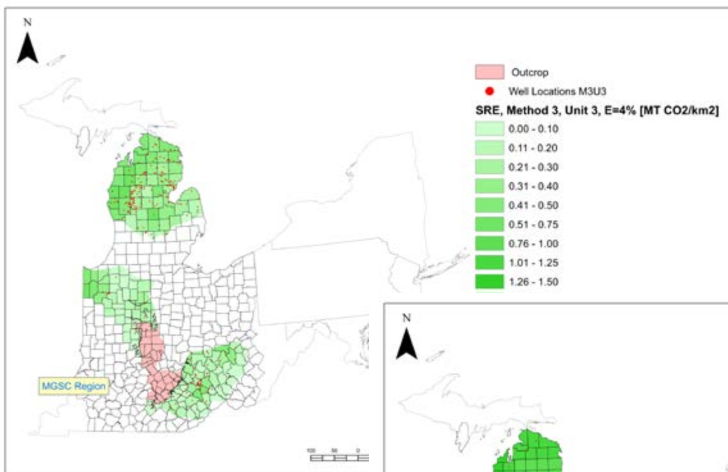
Method 4 (diagenetic model).
Controlled by:
Depth and Thickness

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

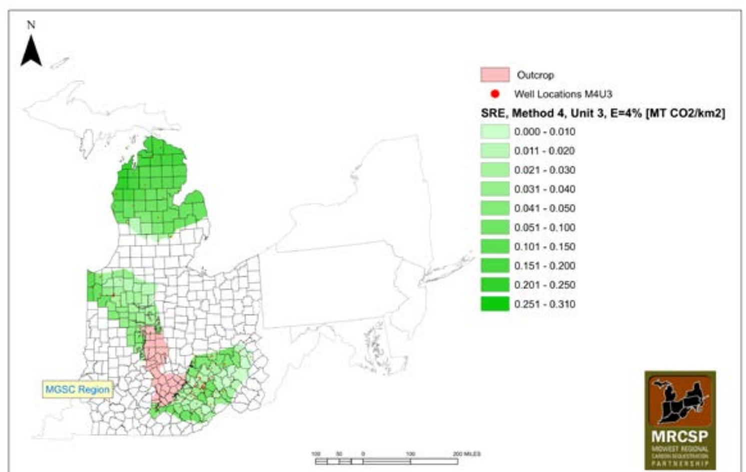
Unit III (St. Peter SS): Results (E = 4%)



Method 1
(constant porosity)



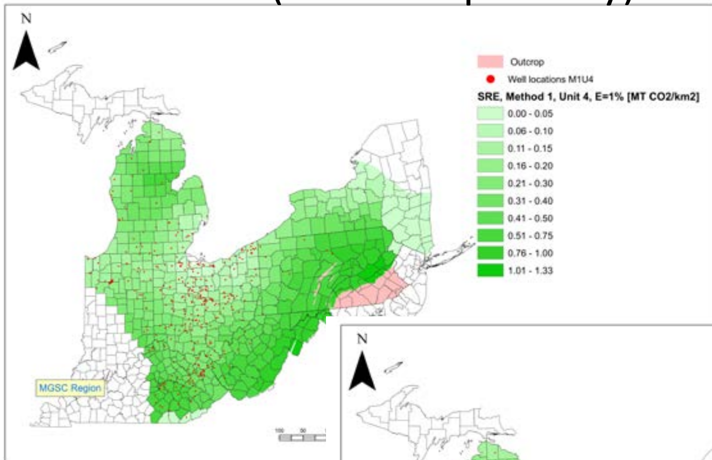
Method 3
(porosity from
wireline logs)



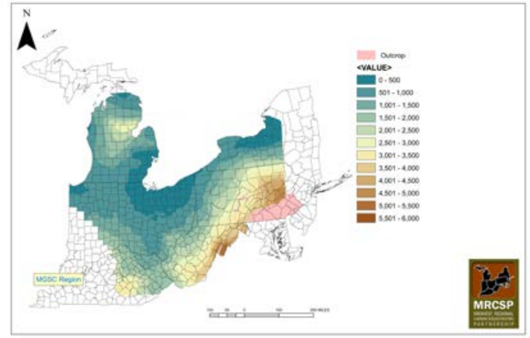
Method 4
(diagenetic
model)

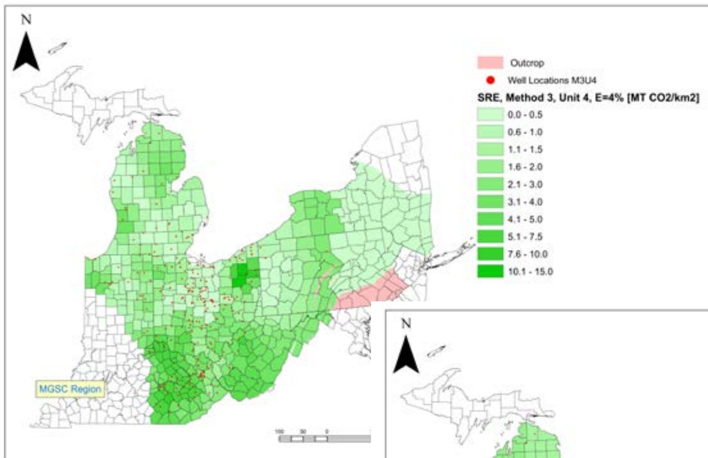
Unit IV (Knox): Results (E = 4%)

Method 1 (constant porosity)

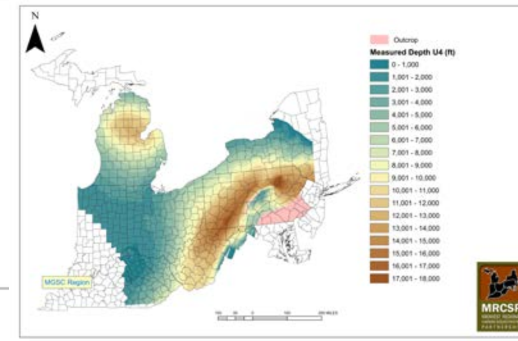


Thickness-controlled SRE

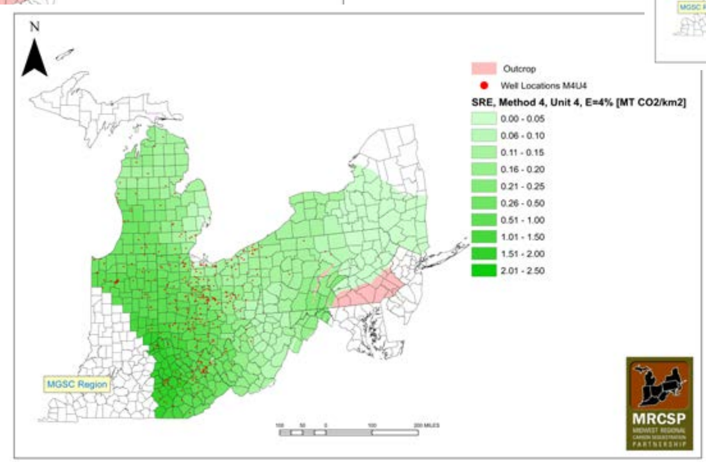




Thickness-controlled SRE



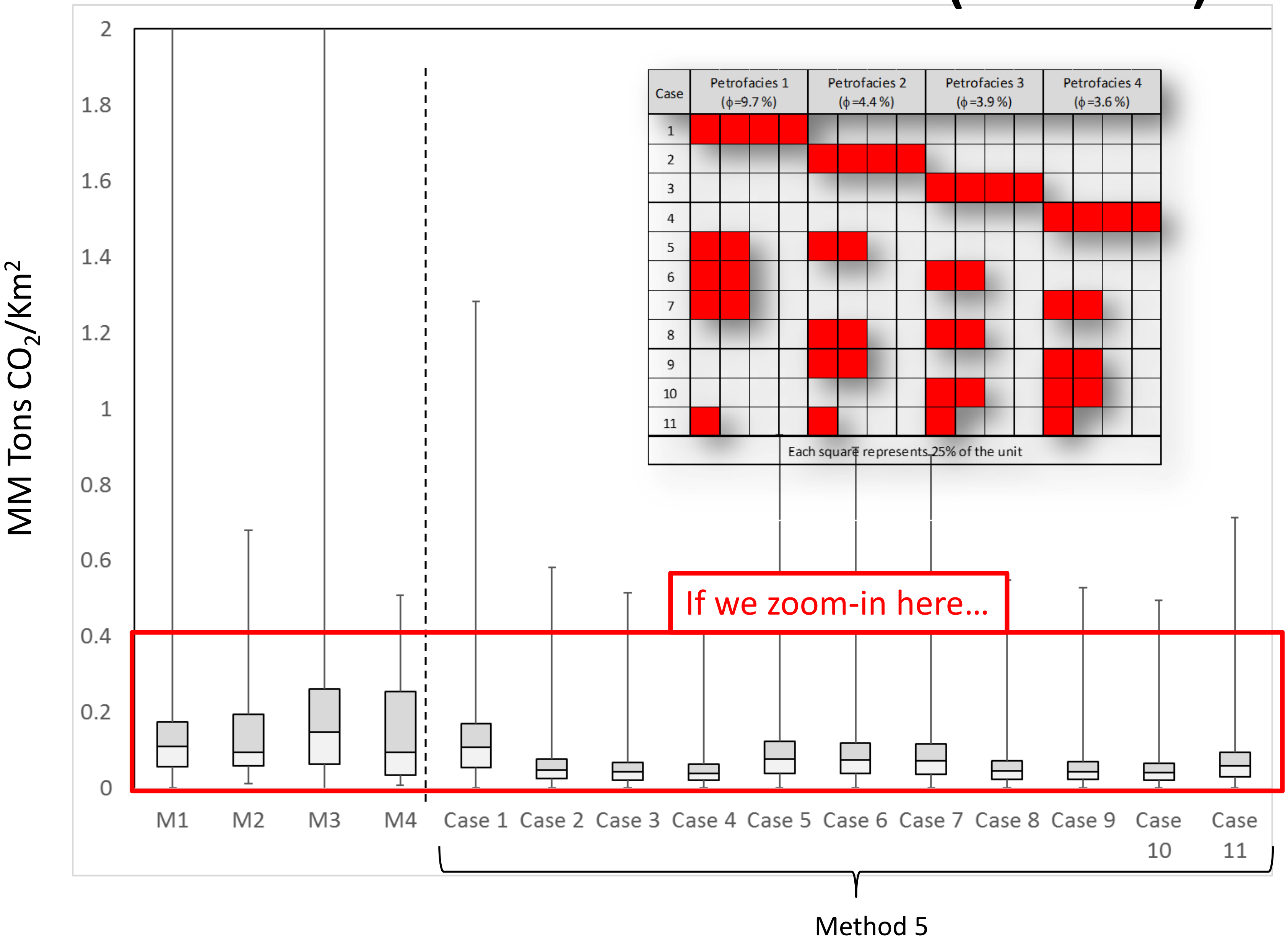
Method 3 (porosity from wireline logs)



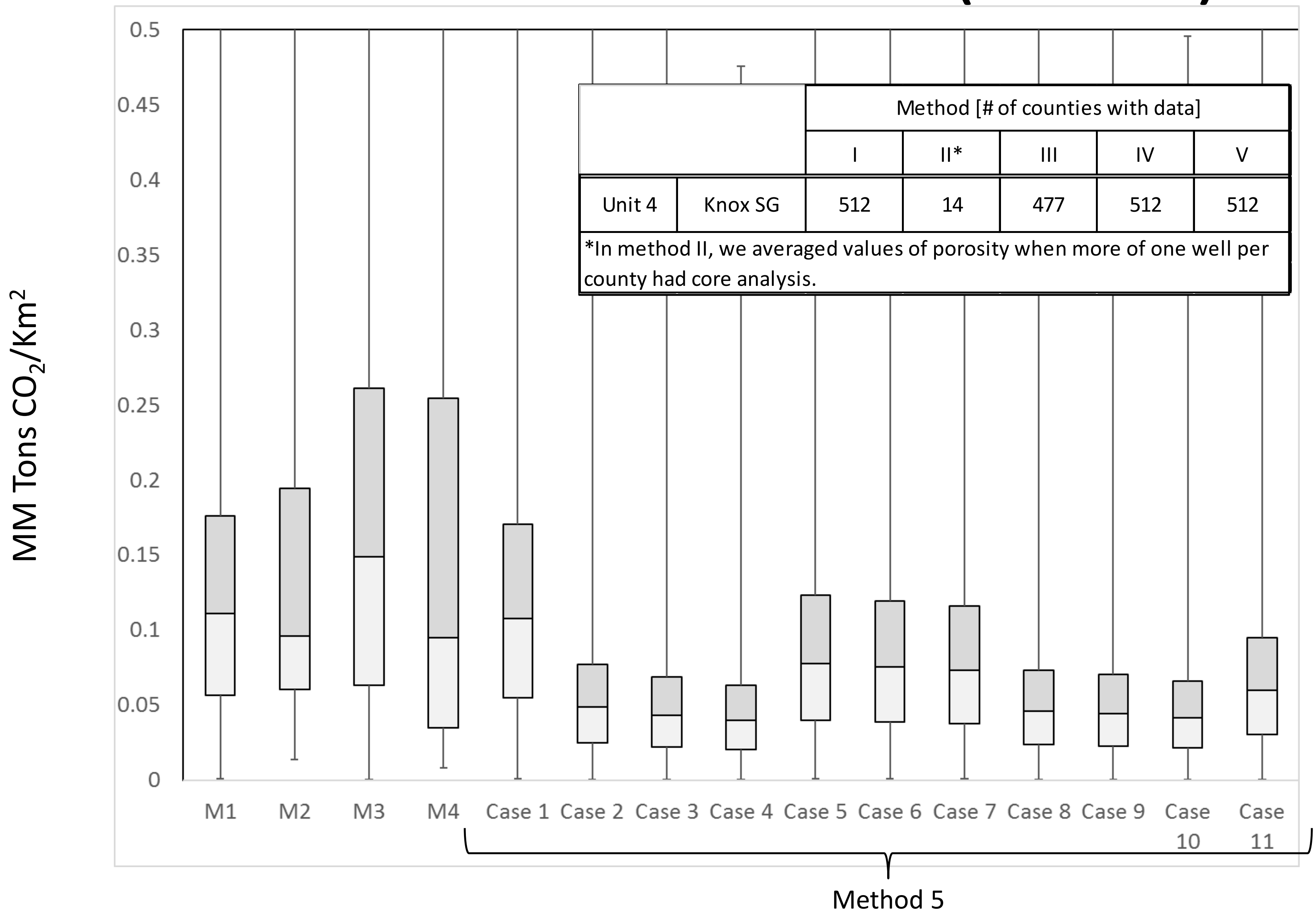
Thickness and Depth-controlled SRE

Method 4 (diagenetic model)

Results: All Methods (Unit 4)



Results: All Methods (Unit 4)



		Method [# of counties with data]				
		I	II*	III	IV	V
Unit 4	Knox SG	512	14	477	512	512

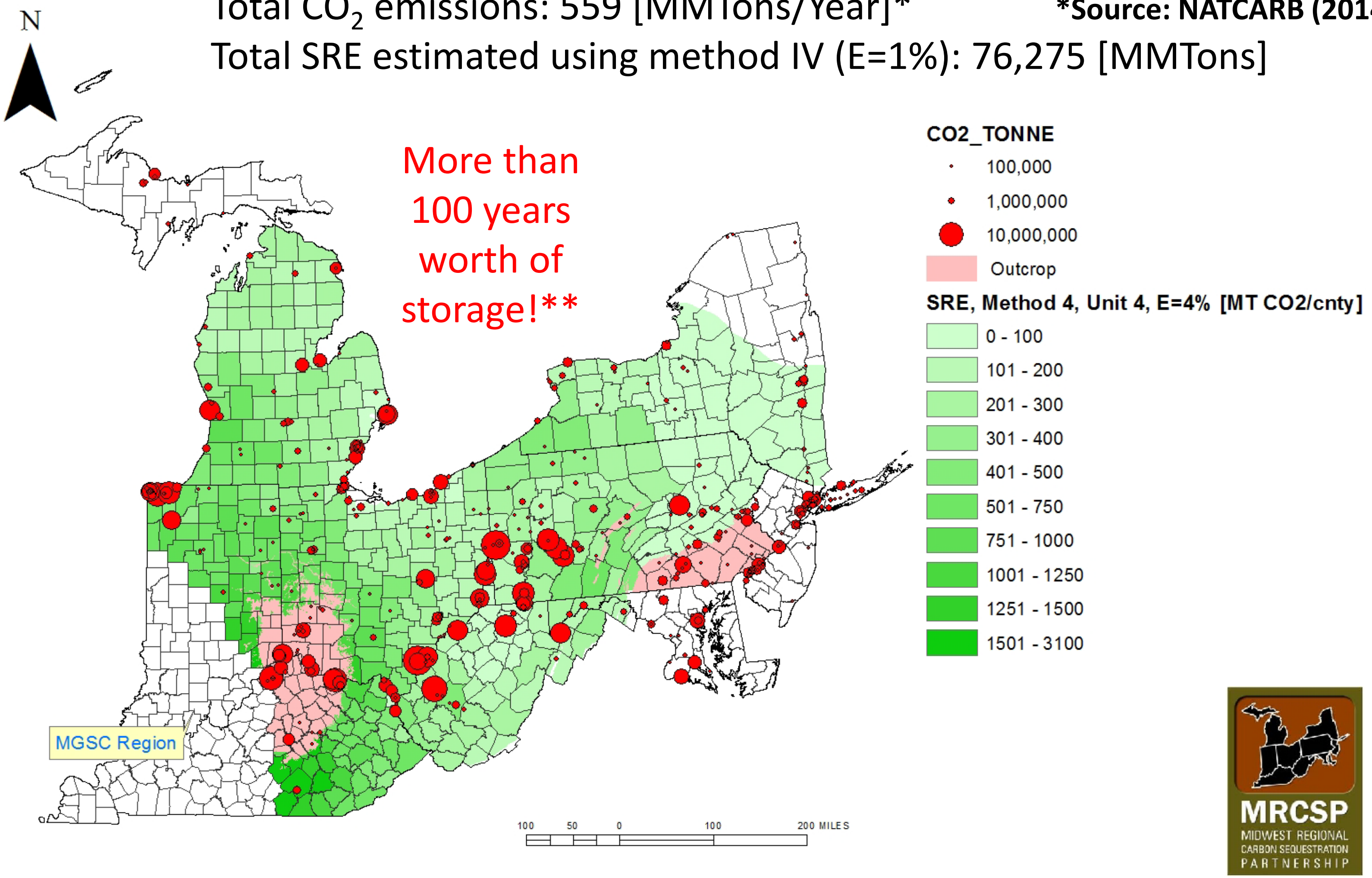
*In method II, we averaged values of porosity when more of one well per county had core analysis.

How do these SREs compare with Emissions from Point Sources?

Total CO_2 emissions: 559 [MMTons/Year]*

Total SRE estimated using method IV (E=1%): 76,275 [MMTons]

***Source: NATCARB (2014)**

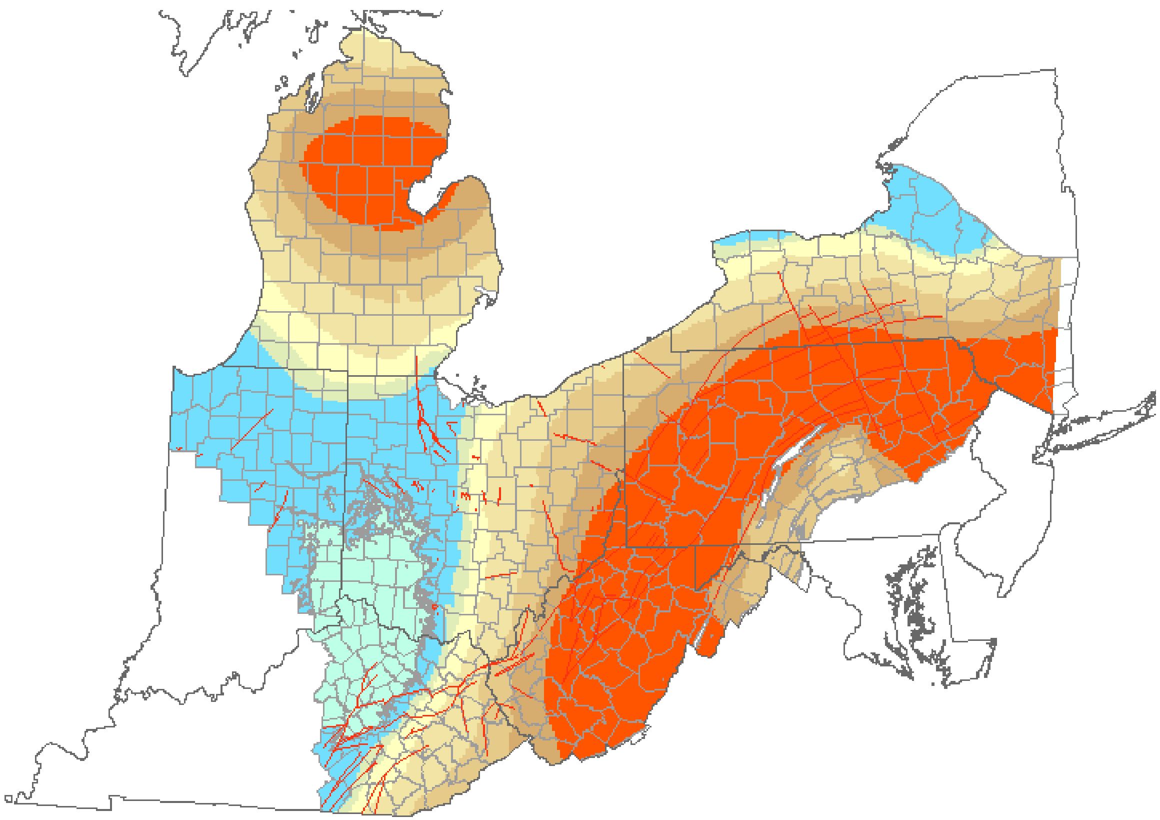


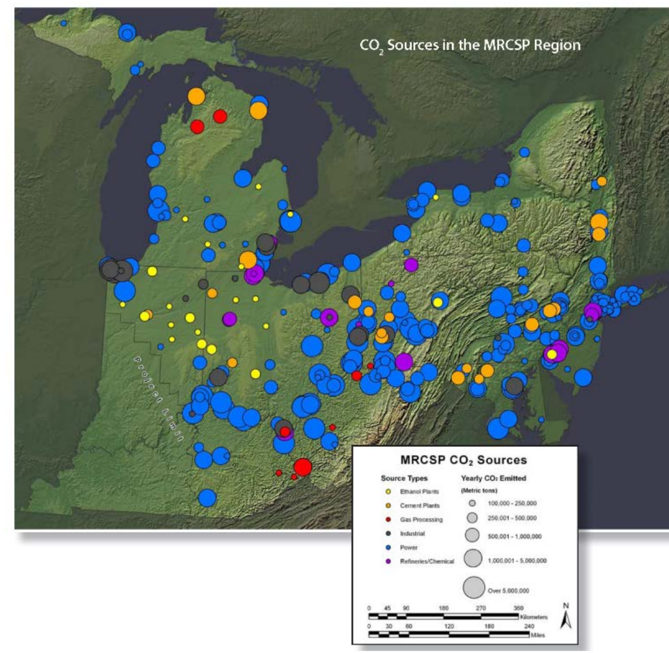
** Further screening is necessary, such as min/max depth considerations, distance to source (pipeline), etc.

Reservoir Characterization: Isopach and Structure (Unit 4: Knox Supergroup and Equivalents)

But…

…Portions of the region do not meet the basic criteria (i.e. too shallow). A second analysis excluding those areas resulted in SRE for unit 4 (Know and equivalents) using method IV is:





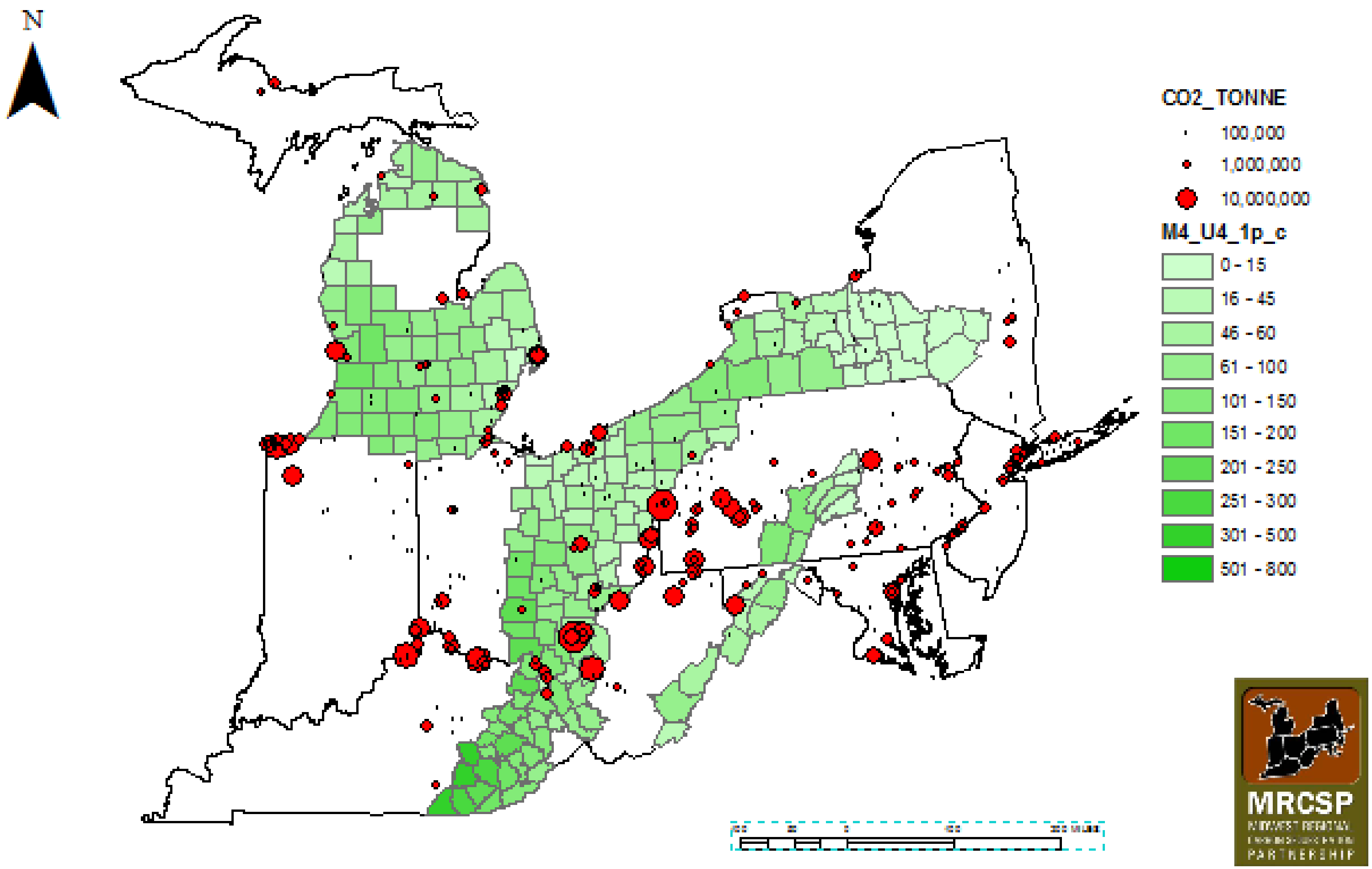
Shallower than 2,500 ft.

Deeper than 10,000 ft.

Reservoir Characterization: Isopach and Structure (Unit 4: Knox Supergroup and Equivalents)

Total CO_2 emissions: 559 [MMTons/Year]* ***Source: NATCARB (2014)**

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



Conclusions [1/2]

- SRE in the MRCSP region suggest that, there is sufficient storage capacity in the carbonate reservoirs of the Cambrian-Ordovician to deploy CCUS 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) or average porosity from wireline logs (Method 3) results in overestimation of SRE.
- Regional scale SREs could possibly benefit from the use of efficiency factors that incorporate increased accuracy in factors (A, h, Ø). These "intermediate" efficiency factors will increase to reflect the decrease in uncertainty (e.g. Peck et al, 2014).

Conclusions [2/2]

- These estimates do not include local factors that should be included in site-scale analysis (i.e., details of the local geology).
- Future work should incorporate dynamic aspects of reservoir performance during and after injection.
- 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. This is a good time, for example, to start considering the Variable Grid Method (VGM) introduced by NETL.

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Thank you!

Questions?

MRCSP MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP

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