[PS]Lithostratigraphic Division of the Mount Simon Sandstone (Cambrian) along the Cincinnati Arch: Implications for Reduction of Uncertainty in Estimations of Geologic Sequestration Storage Capacity*

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Abstract

The Mount Simon Sandstone (Cambrian) in the Midwest region has significant potential to serve as a reservoir for geologic Carbon Capture, Utilization and Storage (CCUS). Despite numerous recent studies of the Mount Simon, petrophysical heterogeneities controlled by the changes in lithologic and diagenetic character of these rocks remain poorly understood. The process of reducing uncertainty in the storage capacity of this reservoir is challenging. The Carbon Sequestration Atlas of the United States and Canada defines the storage "efficiency factor" as the proportion of the accessible pore volume that could conceptually be occupied by the injected carbon dioxide. Values of efficiency factors used in regional reservoir characterization studies are typically 1-4 percent based on Monte Carlo simulations. To employ higher efficiency factor values, uncertainties associated with the three geologic parameters must be reduced. These include: (1) actual versus approximate area to be occupied by the CO_2 plume, (2) net versus gross reservoir thickness, and (3) effective versus total porosity. To accomplish this, gamma-ray logs were interpreted in the Cincinnati Arch region to define three lithostratigraphic subunits within the Mount Simon Sandstone: (1) an upper unit that has relatively high gamma-ray values, owing to the admixture of argillaceous material; (2) a middle unit defined by relatively lower gamma-ray values that result from a cleaner quartzose sandstone; and (3) a lowermost unit defined by gamma-ray values that, in general, progressively increase with depth toward the base of the formation. This downward increase is due to the increased non-quartz fraction in the formation as the top of the Precambrian basement complex is approached. To reduce uncertainties associated with the vertical distribution of reservoir facies, storage capacities for all three units were calculated using the standard Department of Energy methodology, using values from geophysical porosity logs. A minimum porosity of 7 percent was imposed as a threshold for this assessment. Results from 14 wells in the study area show a linear relationship between calculated capacities for the entire Mount Simon Sandstone and its lower unit. The relationship established when comparing these two variables ($R^2 = 0.97$) can be used to help reduce uncertainties associated with the net-to-total area ($E_{An/At}$), net-to-gross thickness ($E_{hh/hg}$), and effective-to-total porosity ($E_{\varphi\varepsilon/\varphi tot}$) components in the efficiency factor. Although this methodology reports enhanced

efficiency factor values for the Mount Simon Sandstone in the study area, more detailed assessments of the vertical distribution of porosity and permeability will further reduce uncertainties and will allow the use of even higher values of the efficiency factor at specific localities.

Lithostratigraphic Division of the Mount Simon Sandstone (Cambrian) along the Cincinnati Arch:
Implications for Reduction of Uncertainty in Estimations of Geologic Sequestration Storage Capacity.

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ABSTRACT

The Mount Simon Sandstone (Cambrian) in the Midwest region has significant potential to serve as a reservoir for geologic Carbon Capture, Utilization and Storage (CCUS). Despite numerous recent studies of the Mount Simon, petrophysical heterogeneities controlled by the changes in lithologic and diagenetic character of these rocks remain poorly understood. The process of reducing uncertainty in the storage capacity of this reservoir is challenging. The Carbon Sequestration Atlas of the United States and Canada defines the storage "efficiency factor" as the proportion of the accessible pore volume that could conceptually be occupied by the injected carbon dioxide. Values of efficiency factors used in regional reservoir characterization studies are typically 1-4 percent based on Monte Carlo simulations. To employ higher efficiency factor values, uncertainties associated with the three geologic parameters must be reduced. These include: (1) actual versus approximate area to be occupied by the CO_2 plume, (2) net versus gross reservoir thickness, and (3) effective versus total porosity. To accomplish this, gamma-ray logs were interpreted in the Cincinnati Arch region to define three lithostratigraphic subunits within the Mount Simon Sandstone: (1) an upper unit that has relatively high gamma-ray values, owing to the admixture of argillaceous material; (2) a middle unit defined by relatively lower gamma-ray values that result from a cleaner quartzose sandstone; and (3) a lowermost unit defined by gamma-ray values that, in general, progressively increase with depth toward the base of the formation. This downward increase is due to the increased non-quartz fraction in the formation as the top of the Precambrian basement complex is approached. To reduce uncertainties associated with the vertical distribution of reservoir facies, storage capacities for all three units were calculated using the standard Department of Energy methodology, using values from geophysical porosity logs. A minimum porosity of 7 percent was imposed as a threshold for this assessment. Results from 55 wells in the study area show a linear relationship between calculated capacities for the entire Mount Simon Sandstone and its Middle and Lower unit. The relationship established when comparing these two variables ($R^2 = 0.97$) can be used to help reduce uncertainties associated with the net-to-total area (E_{A_n/A_t}), net-to-gross thickness (E_{h_n/h_g}), and effective-to-total porosity ($E_{\phi_e/\phi_{tot}}$) components in the efficiency factor. Although this methodology reports enhanced efficiency factor values for the Mount Simon Sandstone in the study area, more detailed assessments of the vertical distribution of porosity and permeability will further reduce uncertainties and will allow the use of even higher values of the efficiency factor at specific localities.

STUDY AREA: MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (MRCSP)

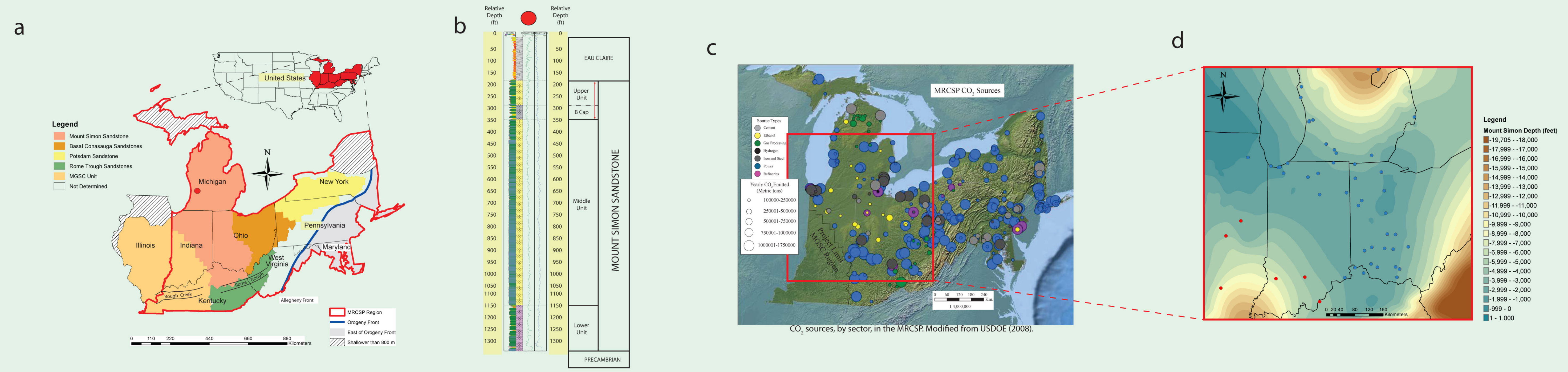

Figure 1: a) Map of Midwest Geological Sequestration Consortium (MGSC) and Midwest Regional Carbon Sequestration Partnership (MRCSP), b) representative well in Michigan with geophysical logs indicating the three-part subdivision of the Mount Simon Sandstone, c) CO_2 point sources location in the MRCSP region, and d) map indicating the wells used in this study.

SUBDIVISION OF THE MOUNT SIMON SANDSTONE

Becker (1978) identified a shale zone in northwestern Indiana, also called the "B Cap," which ranges between 10 and 60 feet in thickness. Based on both geophysical logs (gamma-ray) and lithologic strip logs of well cuttings from the sample library of the Indiana Geological Survey, we have delineated this unit throughout northern Indiana.

B-CAP AND UPPER UNIT

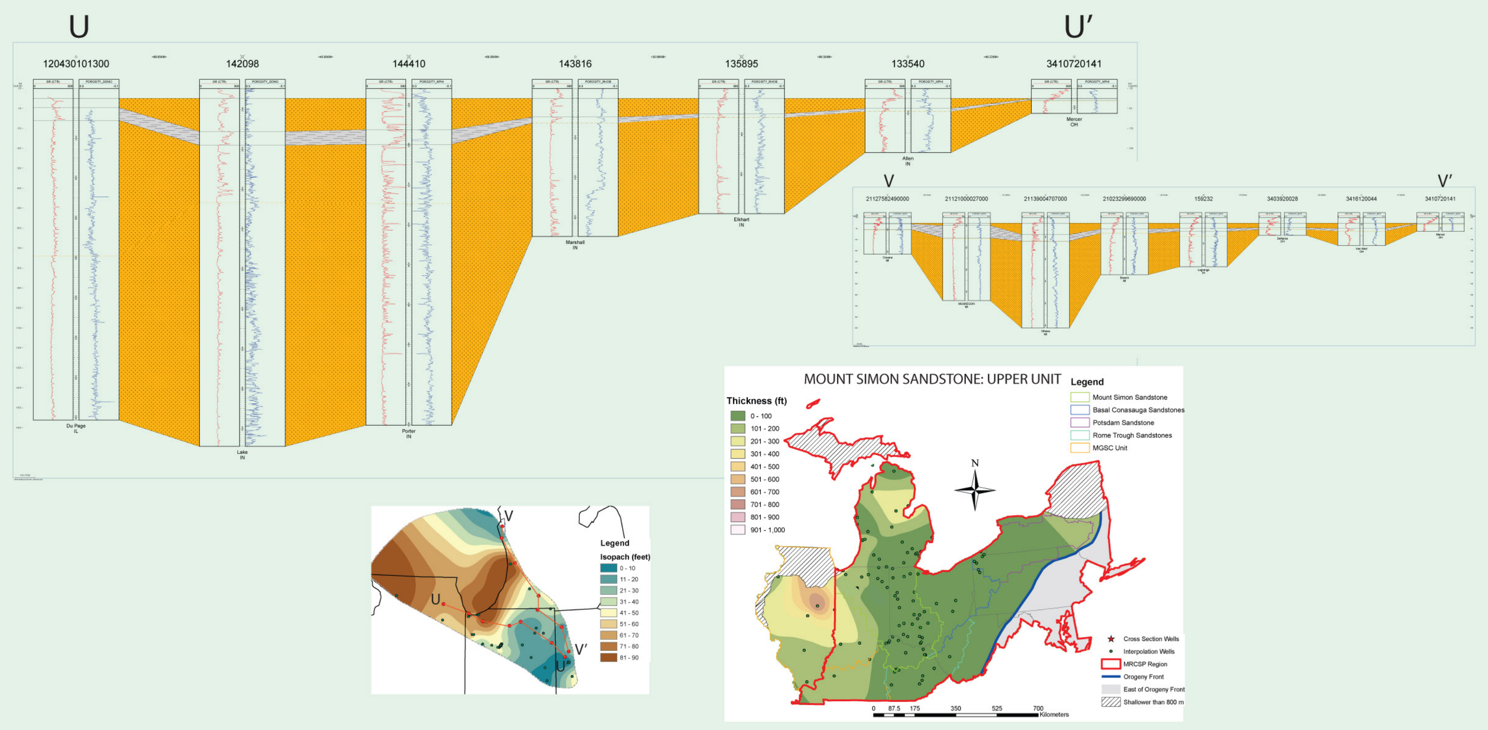

Figure 2: Cross section in northern Indiana of the Upper Unit, revealing the presence of an argillaceous interval, also known as the "B Cap" (Becker, 1978).

MIDDLE UNIT

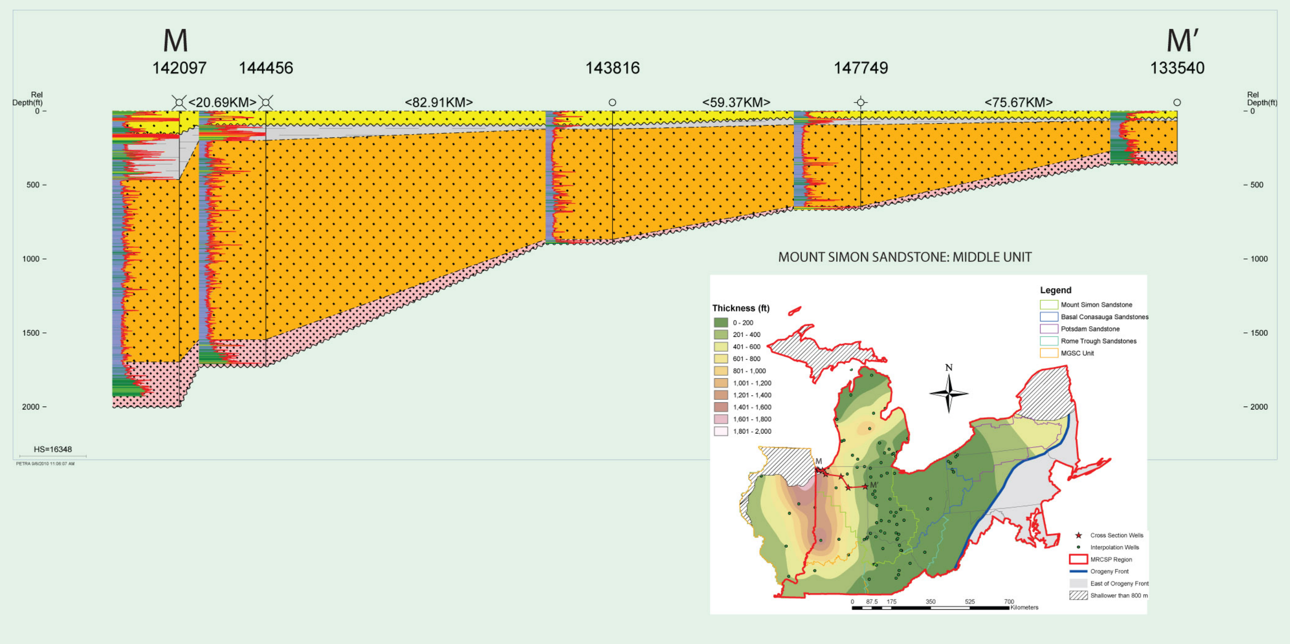

Figure 3: Cross section in northern Indiana of the Middle Unit. The gamma-ray log here and in another locations throughout the region suggests homogeneity.

LOWER UNIT

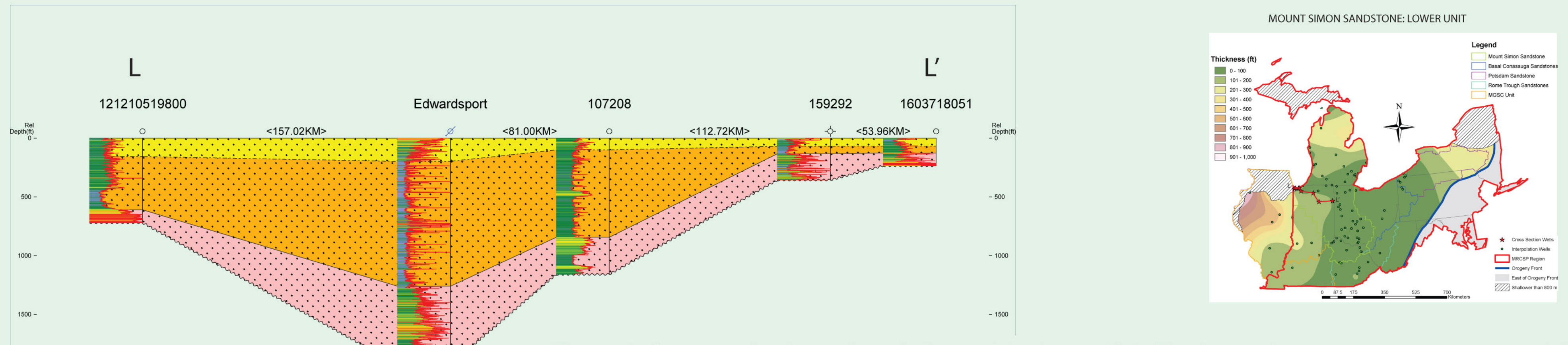

Figure 4: Cross section in northern Indiana of the Lower Unit. The increasing gamma ray count toward the log bottom, suggests increasing amounts of nonquartz materials.

GENERALIZED CROSS SECTIONS

Well ID# 144456
Porter County, Indiana

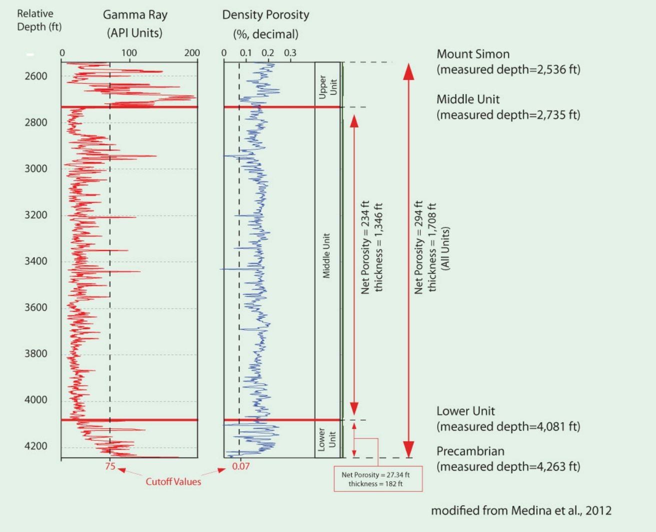

Figure 5:
A preliminary subdivision using geophysical logs (principally gamma-ray) is the first step toward constraining the formation interval that should be assessed for carbon sequestration. The middle unit displays gamma-ray and porosity signatures that suggest it is the most homogeneous unit with the largest percentage of quartz sand.

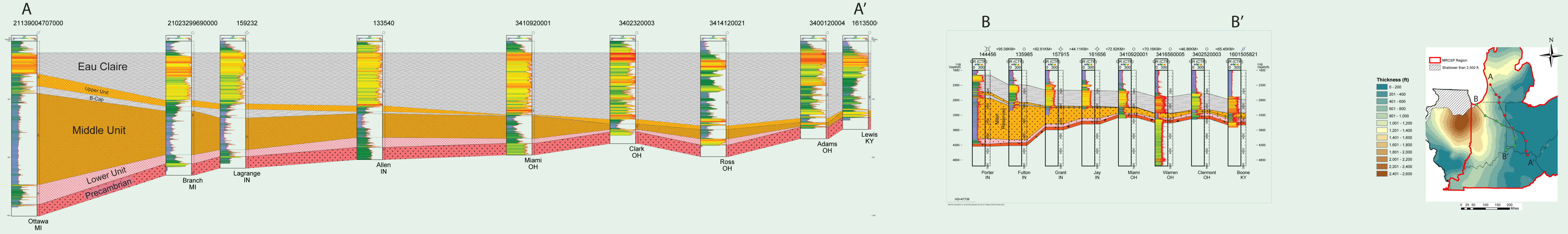

Figure 6: NW-SE cross sections indicating the proposed three-part subdivision within the Mount Simon Sandstone. Interpolation of well data was used to construct isopach maps for the Lower Unit, the Middle Unit, and the Upper Unit (Figures 2-4).

This poster can be downloaded from the author's webpage:

This work is funded by the DOE and is part of the regional carbon sequestration assessment being conducted by the Midwest Regional Carbon Sequestration Partnership (MRCSP).

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STANDARD DOE STORAGE CAPACITY (SC) CALCULATION METHOD

The Department of Energy (DOE) defines the carbon dioxide storage capacity estimates as the geologic storage potential when current economic and regulatory considerations are included.

The Efficiency Factor (E_{saline}) reflects the fraction of the total pore volume that will be occupied by the injected CO_2

(Gorecki et al., 2009; DOE/NETL Atlas, 2010)

$$G_{CO_2} = A_t * h_g * \phi_{tot} * \rho * E_{saline}$$

Mass; Total Area; Gross Thickness; Total Porosity; Density; Efficiency Factor

Parameter	Units [a]	Description
G_{CO_2}	M	Mass estimate of saline formation CO_2 storage resource.
A_t	L^2	Geographical area that defines the basin or region being assessed for CO_2 storage.
h_g	L	Gross thickness of saline formations for which CO_2 storage is assessed within the basin or region defined by A.
ϕ_{tot}	L^3/L^3	Total porosity in volume defined by the net thickness.
ρ	M/L^3	Density of CO_2 evaluated at pressure and temperature that represents storage conditions anticipated for a specific geologic unit averaged over h_g and A_t.
E_{saline}	L^3/L^3	CO_2 storage efficiency factor that reflects a fraction of the total pore volume that is filled by CO_2.

[a] L is length; M is mass.

Goodman et al., 2011

ENHANCED STORAGE CAPACITY CALCULATION METHOD

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

Table 1: Parameters for Saline Formation Efficiency

Term	Symbol	P_{10}/P_{90} Values by Lithology: Clastics	Dolomite	Limestone	Description
Geologic terms used to define the entire basin or region pore volume					
Net-to-Total Area	$E_{An/At}$	0.2/0.8	0.2/0.8	0.2/0.8	Fraction of total basin or region area with a suitable formation.
Net-to-Gross Thickness	$E_{hn/hg}$	0.21/0.76*	0.17/0.68*	0.13/0.62*	Fraction of total geologic unit that meets minimum porosity and permeability requirements for injection.
Effective-to-Total Porosity	$E_{\phi e/\phi tot}$	0.64/0.77*	0.53/0.71*	0.64/0.75*	Fraction of total porosity that is effective, i.e., interconnected.
Displacement terms used to define the pore volume immediately surrounding a single well CO_2 injector					
Volumetric Displacement Efficiency	E_v	0.16/0.39*	0.26/0.43*	0.33/0.57*	Combined fraction of immediate volume surrounding an injection well that can be contacted by CO_2 and fraction of net thickness that is contacted by CO_2 as a consequence of the density difference between CO_2 and in situ water.
Microscopic Displacement Efficiency	E_d	0.35/0.76*	0.57/0.64*	0.27/0.42*	Fraction of pore space unavailable due to immobile in situ fluids.

*Values from IEA (2009)

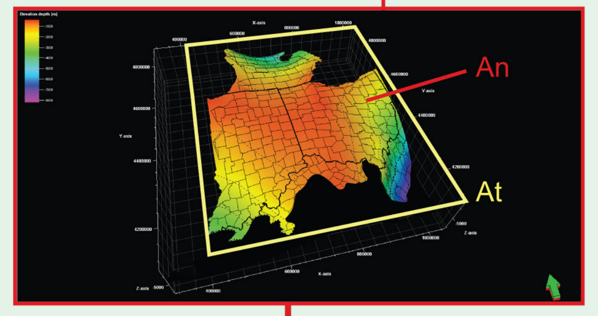

Figure 7: Map view of Total Area (At) and extent of storage formation, Net Area (An).

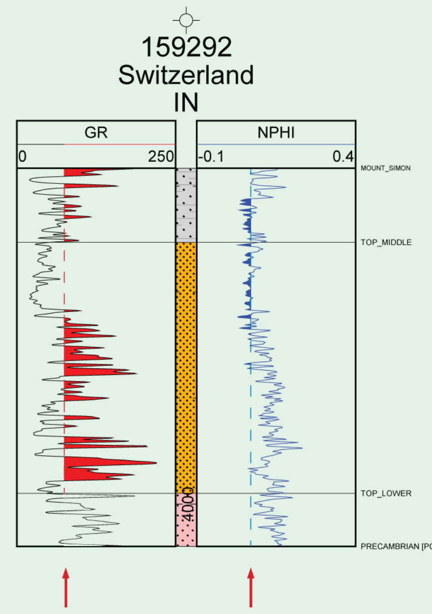

Figure 8: Gamma-Ray and NPHI log for Mount Simon Sandstone showing the complete (or gross) thickness of this unit (hg) and the portion considered as possible reservoir rock (hn). A gamma-ray cutoff of <75 API units and porosity of >7% were chosen as thresholds.

Table 2: Saline Formation Efficiency Factors for Geologic and Displacement Terms

Saline Formation Efficiency Factors for Geologic and Displacement Terms

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

Lithology	P_{10}	P_{50}	P_{90}
Clastics	0.51%	2.0%	5.4%
Dolomite	0.64%	2.2%	5.5%
Limestone	0.40%	1.5%	4.1%

Table 3: Saline Formation Efficiency Factors for Displacement Terms.

Saline Formation Efficiency Factors for Displacement Terms

$E_{saline}^{*} = E_v\, E_d$

Not Modified

Lithology	P_{10}	P_{50}	P_{90}
Clastics	7.4%	14%	24%
Dolomite	16%	21%	26%
Limestone	10%	15%	21%

*$E_{An/At}$, $E_{hn/hg}$, and $E_{\phi e/\phi tot}$ values are known directly

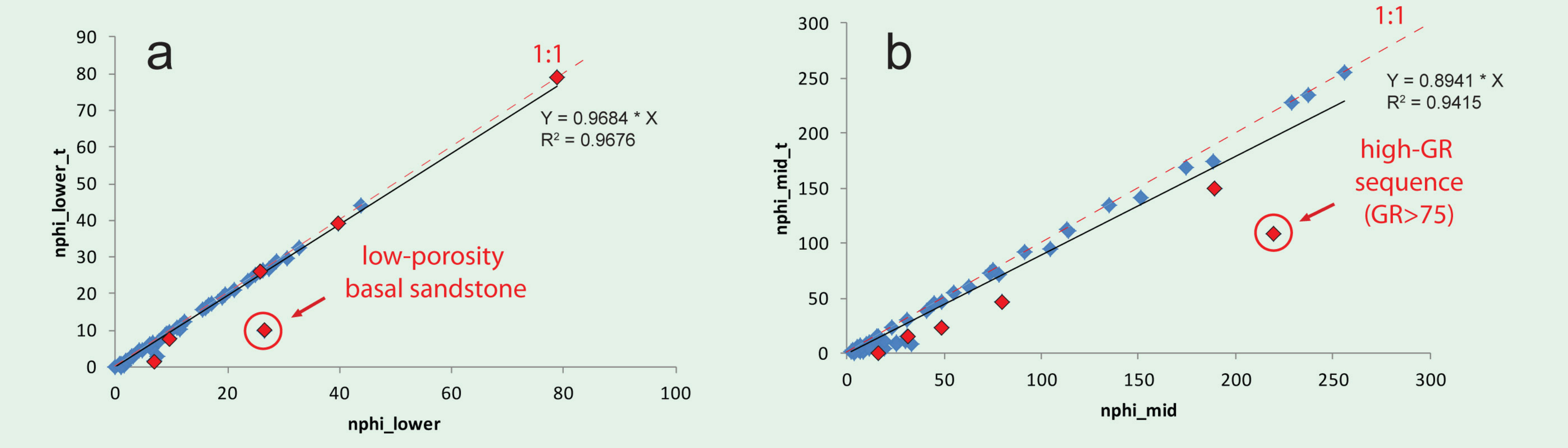

Figure 9: A 4% reduction of the net porosity feet is observed when applying only a porosity threshold in the Lower Unit (a). When applying both a porosity and a GR threshold in the Middle Unit, a 11% reduction in the net porosity footage is observed (b).

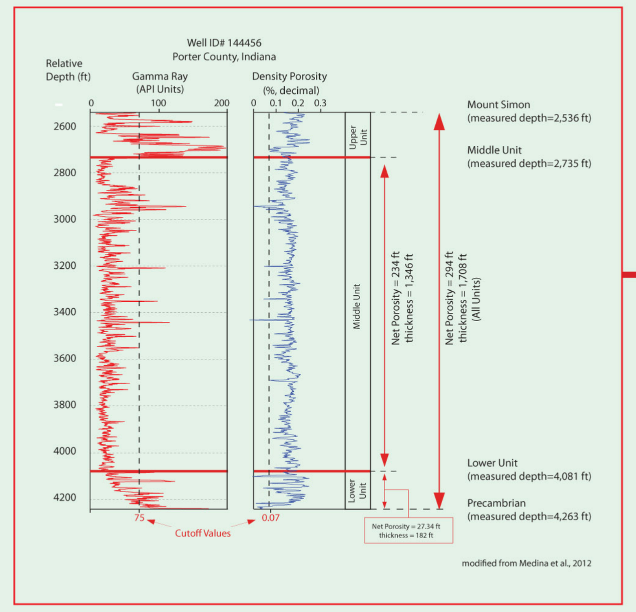

Figure 10: Porosity feet reduction due to the application of gamma ray and porosity threshold in the middle and lower units of the Mount Simon Sandstone. The log illustrates the high-gamma ray values for the lower unit. This explains why we applied only a porosity threshold of 7% to this unit.

EFFECTS OF LITHOSTRATIGRAPHIC DIVISION IN ENHANCING THE EFFICIENCY FACTOR

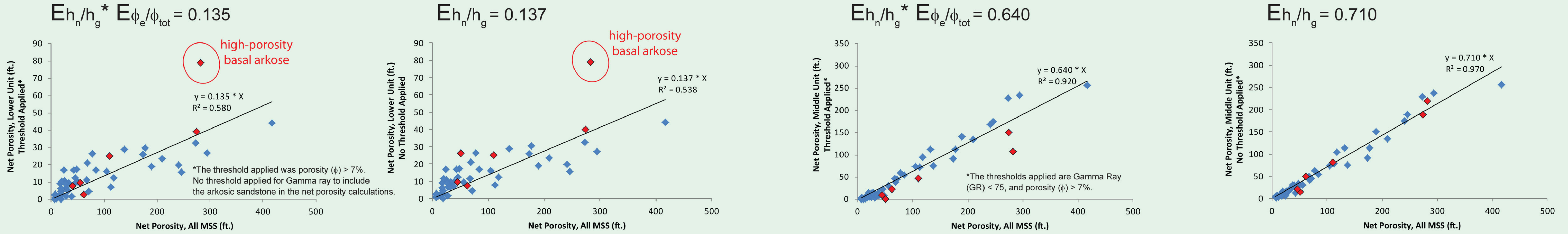

Figure 11: Net porosity reduction when considering only the moddle and lower units of the Mount Simon Sandstone. Values are compared with net porosity for the entire Mount Simon Sandstone.

Table 4: Estimation of **enhanced** efficiency factors when considering subdivision of Mount Simon Sandstone. *For simplicity, we considered the Lower Unit as the low confidence (P10) case, the Middle Unit as the middle confidence case (P50), and the entire Mount Simon Sandstone as the high-confidence case (P90).

$$E_{saline} = EA_n/A_t * Eh_h/h_g * E\phi_e/\phi_{tot} * E_v * E_d$$

	ATLAS			THIS STUDY			
Probability	E_{saline} (%)	$E_v * E_d$	$E_{An/At} * E_{hh/hg} * E_{\phi e/\phi tot}$	$E_{An/At} * E_{hh/hg} * E_{\phi e/\phi tot}$	$E_v * E_d$	E_{saline} (%)	Unit*
P10	0.005	0.074	0.069	0.135	0.074	0.010	Lower
P50	0.020	0.140	0.143	0.640	0.140	0.090	Middle
P90	0.054	0.240	0.225	0.850	0.240	0.204	All MS

Recalculated**

We kept this value (did not change)

Increased efficiency factor (and reduce uncertainty!)

** The assumption is that $E_{An/At}$ = 1

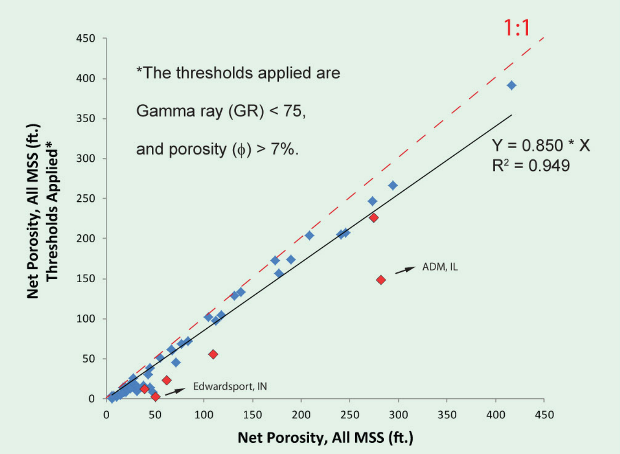

Figure 12: Net porosity reduction (85%) that accounts for the effective-to-total porosity ($E_{\phi e/\phi tot}$) term. The assumption is that $E_{An/At} = E_{hn/hg}$ = 1.

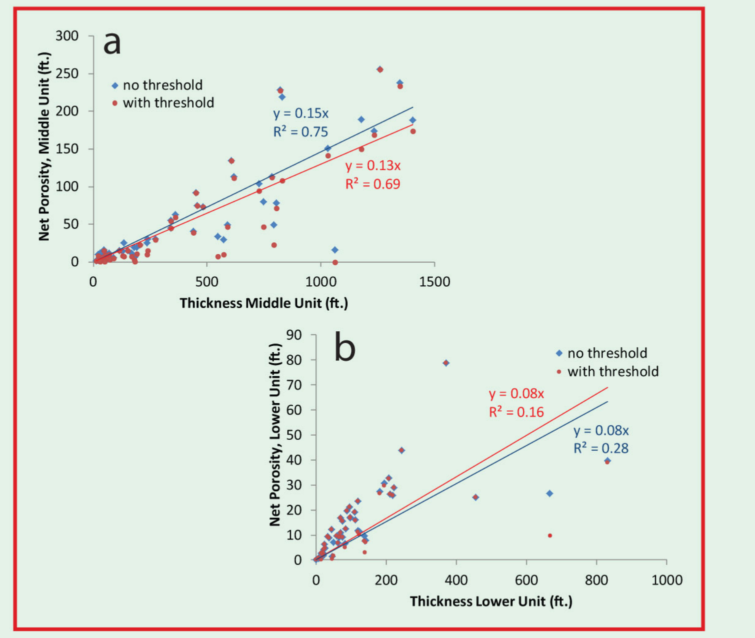

Figure 13: Net porosity vs. thickness of Middle Unit (a) and Lower Unit (b). Better predictability is observed in the Middle Unit.

CONCLUSIONS

1. Evidence from geophysical logs, core descriptions, and previously published work suggest that the Mount Simon Sandstone can be subdivided into three facies characterized by varying amounts of quartz silt, clay minerals, and feldspars.
2. In general, the uppermost subunit has a higher gamma-ray value (transitional zone from clean sandstone to argillaceous siltstone). The middle unit (thicker and likely to be the main CO_2 storage interval) has the lowest gamma-ray values, whereas the lowermost unit has a trend of increasing gamma-ray values with depth.This subdivision of the internal stratigraphy of the Mount Simon Sandstone will allow the identification of main reservoir flow units, which will result in a higher efficiency factor when calculating storage capacities at various localities. Consequently, the final estimate of storage capacity will be increased when decreasing uncertainty of the reservoir characterization process.
3. Previous calculations of storage capacity included the entire section of the Mount Simon Sandstone and used threshold values of 75 API and 7% for gamma-ray and porosity logs, respectively (Medina et al., 2010). The new approach, assessing the middle unit alone and without the threshold values, shows that the storage capacity for the middle unit is similar to the storage capacity previously estimated for the entire section (Medina et al., 2011).
4. Subdividing and characterizing the Mount Simon Sandstone also helps to reduce the uncertainties associated with the assumptions of reservoir properties, which will lead to more accurate conceptual flow models for this prospective storage reservoir. Storage capacity calculations cons brained by this subdivision of the Mount Simon Sandstone will allow us to work with higher values of efficiency factors and ultimately increase the estimates for storage capacity in the formation.
5. Higher values for efficiency factors are proposed when estimating the storage capacity of a specific sub-unit within the Moutn Simon Sandstone. However, the overall calculated storage capacity of the reservoir is lower due to the fact that only a portion of the reservoir is considered as effective reservoir. This method proposes a decrease in the uncertainty of reservoir characterization, and further studies are necessary to quantify this potential reduction in uncertainty.

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