PS A Comparison of Geological CO_2 Storage Resource Calculation Methodologies to Evaluate Parameter Sensitivity and Reduce Uncertainty: Case Study of the St. Peter Sandstone (Ordovician) in the Illinois and Michigan Basins*

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Abstract

In the Illinois and Michigan Basins, the St. Peter Sandstone (Ordovician) occurs at depths from surface outcrop to in excess of 11,000 ft (3.35 km), and ranges in thickness from 0 ft to more than 1,100 ft (335 m). Although the formation pinches out onto the Kankakee, Findlay, and Cincinnati Arches, extensive portions of the St. Peter occurs at depths greater than 2,600 ft (800 m) where CO_2 can exist in a dense, supercritical fluid phase. Thus, the St. Peter is considered a potentially significant CO_2 storage resource in both the Illinois and Michigan Basins where it occurs as isolated successions. In this study, a series of storage resource estimates were developed using the results of reservoir characterization analysis in conjunction with the methodology outlined in the DOE-NETL Carbon Sequestration Atlas III. The purpose of this paper is to analyze how variation in CO_2 storage resource estimates depends on the specific methods used for determining effective reservoir porosity, CO_2 density, and storage efficiency factors in the volumetric equation.

Considering all methods, storage resource estimates range from 2.6 Gt to 46.3 Gt in the two basins. We found that variability in CO_2 density throughout the reservoir domain had only minor influence on resource estimates. Calculations using gross isopach values and average formation porosity tended to overestimate storage resource relative to estimates based on porosity functions derived from core data and well logs. This result is due to an apparent diagenetic reduction in porosity commensurate with the depth of burial.

Improved reservoir characterization using well logs and core data to determine net porosity in control wells resulted in reduced uncertainty in net-to-gross reservoir area and porosity. Porosity cutoff values (i.e., minimum porosity for consideration as an effective sequestration reservoir) were established using a core-based permeability-to-porosity transform. Net porosity was then determined in each of the control wells and these data were gridded to determine total reservoir porosity in the study area. Using this net porosity method, estimates of storage resource were between 24 percent (Michigan Basin) to 150 percent (Illinois Basin) of the storage resource estimate obtained by the gross isopach and depth-dependent porosity method.

Although results are highly sensitive to the method used for calculating effective porosity, storage resource estimates appear most sensitive to storage efficiency factors. Minimizing the uncertainty in net-to-gross area and porosity justifies the use of larger storage efficiency factors (e.g., 24.0% versus 5.4% at the 90% probability range for clastics), in which case resource estimates equal or exceed all other methods and exhibit a more geologically realistic spatial distribution.

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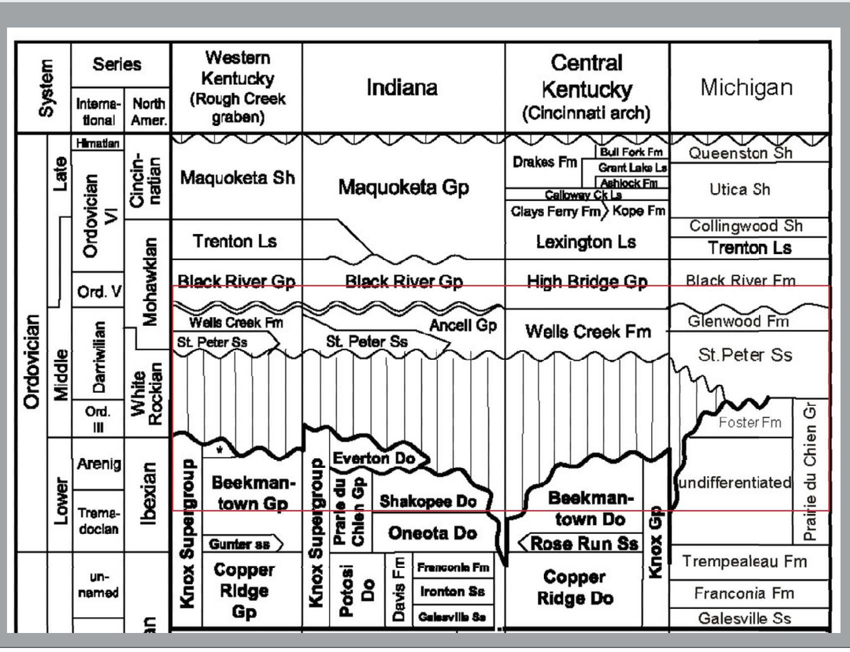
1. Abstract

The St. Peter Sandstone (Ordovician) occurs at depths from surface outcrop to in excess of 3.35 km and ranges in thickness from 0 to more than 335 m in the Illinois and Michigan Basins. The formation pinches out onto adjacent arches, but occurs at depths greater than 800 m over extensive areas in both basins. CO2 storage resource estimates (SRE) were developed using the results of reservoir characterization analysis and methodology outlined in the DOE-NETL Carbon Sequestration Atlas III. Along with refined storage resource estimates for the St. Peter Sandstone this paper also attempts to demonstrate how variation in CO2 storage resource estimates depends on the specific methods used for determining effective reservoir porosity, CO2 density, and storage efficiency factors (SEF) in the volumetric equation. The SEF is by far the most significant influence on SRE.

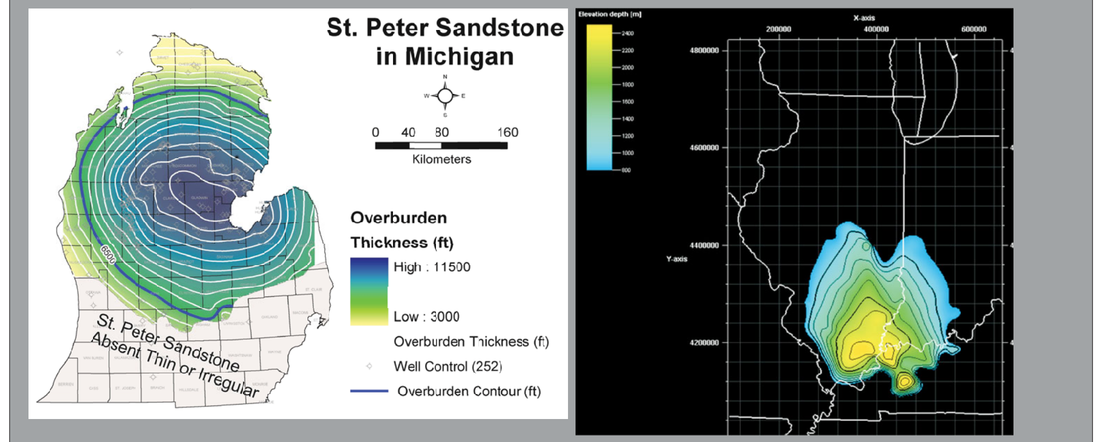
Considering all methods, SRE range from 3.4 billion metric tons (Gt) to almost 80 Gt in the two basins. Variability in CO2 density throughout the reservoir domain has only minor influence on SRE. Calculations using gross isopach values and average formation porosity overestimated storage resource relative to estimates based on porosity functions derived from core data and well logs. This approach should reduce uncertainty and is justified because diagenetic reduction in porosity is commensurate with depth of burial in both basins.

Improved reservoir characterization using core data and well logs to determine net porosity in control wells justifies reduced uncertainty in net-to-gross reservoir area, porosity and effective to total porosity. Porosity cutoff values (i.e., minimum porosity for consideration as an effective sequestration reservoir, 5 md) were established using core-based permeability-to-porosity transforms. Net porosity was then determined in each of the control wells and these data were gridded to determine total reservoir porosity in the study area. Using this net porosity method, SRE were between 34% (Michigan Basin) to 72% (Illinois Basin) of the SRE obtained by the gross isopach and depth-dependent porosity method using the same SEF although these SEF are not appropriate for the net porosity method since uncertainty in gross to net area, porosity, and effective to total porosity each approach 1.

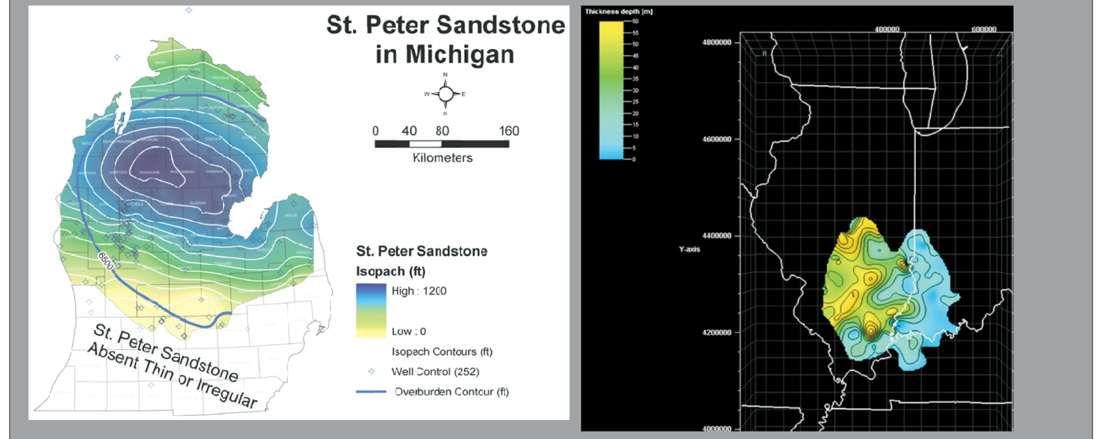
Although results are highly sensitive to the method used for calculating effective porosity, SRE are, by far, most sensitive to SEF. Minimizing the uncertainty in net-to-gross area, porosity and effective versus total porosity justifies the use of larger storage efficiency factors (e.g., 24.0% versus 5.4% at the 90% probability range for clastics), in which case resource estimates exceed all other methods (by ~135%) and exhibit a more geologically realistic spatial distribution.

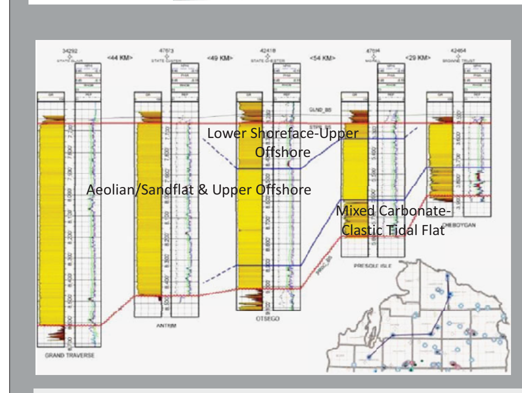


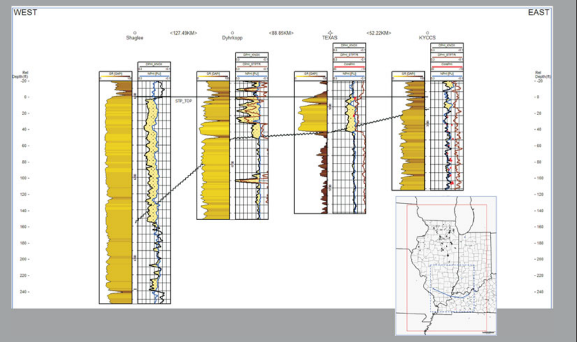
2a. St. Peter Sst Overburden Thickness Maps



2b. St. Peter Sst Isopach Maps







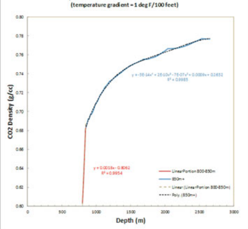
Overburden and Isopach thickness maps on the St Peter Sandstone in the Michigan and Illinois Basins clipped to where reservoir target burial depth exceeds 800 m. Regional stratigraphic thickness and sedimentary facies trends and depth of burial-related diagenesis, are the first order controls on reservoir quality and the spatial distribution of geological carbon storage capacity.

Note in both basins that the isopach patterns are shifted to the north and west relative to the basin structural center. This relationship is, in part, interpreted to represent sandy sediment source terrains located to the (modern) northwest in both basins. Facies relationships shown in log cross sections support this interpretation in the Michigan basin but are less clear in the Illinois basin.

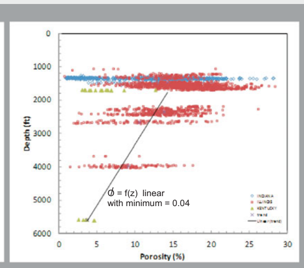
3. Storage Resource Estimation:

$G_{CO2} = A_t\, h_g\, Ø_{tot}\, rho\, E_{saline}$

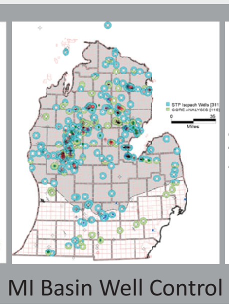
CO_2 Storage Resource Estimates (SRE) were calculated using procedures described in DOE-NETL Atlas III (see formula above) using total area (A_t), gross formation thickness (h_g) total porosity ($Ø_{tot}$), CO_2 density (rho), and a storage efficiency factor for saline reservoirs(E_{saline}). SRE were insensitive to the use of a constant CO_2 rho versus depth dependent rho. The E used for these calculations, for p_{10}, p_{50} and p_{90}, are 0.51%, 2% and 5.4% respectively (Atlas III). A porosity-depth relationship was established in each basin and used in place of average porosity values due to observed depth-dependent decrease in porosity.



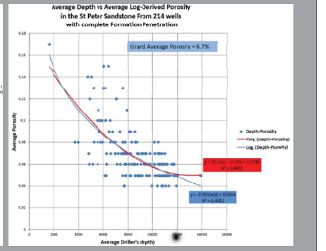
IL Basin CO_2 rho-Depth



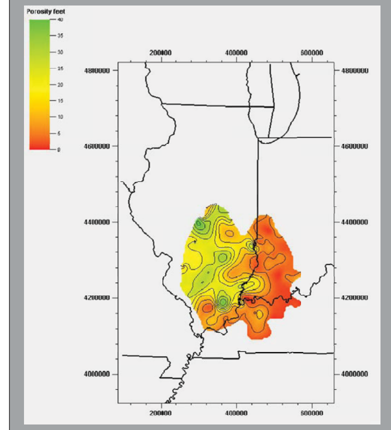
IL Basin Porosity-Depth



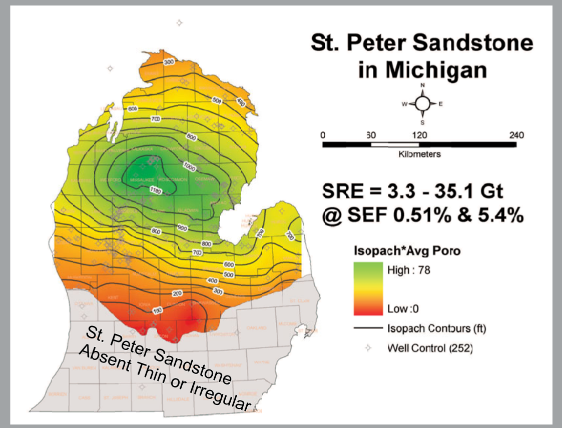
MI Basin Well Control



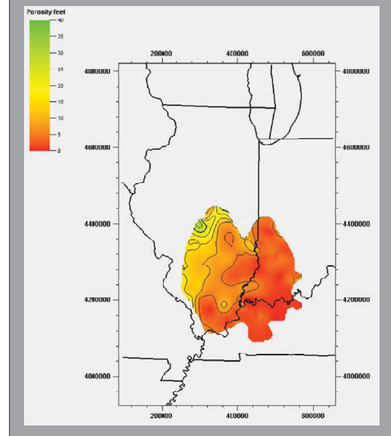
MI Basin Porosity-Depth



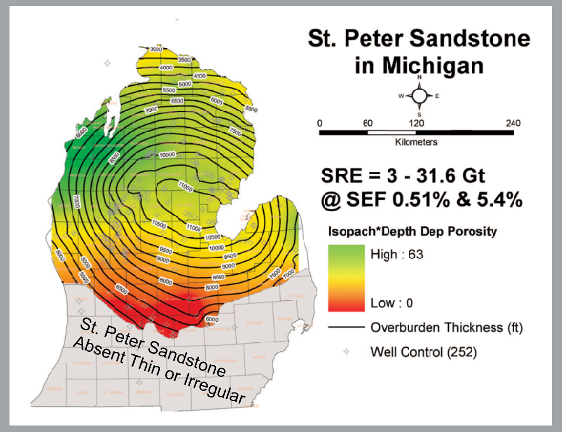
Basin SRE: Average Porosity-Isopach



MI Basin SRE: Average Porosity-Isopach



MI Basin SRE: Depth Dependent Porosity-Isopach

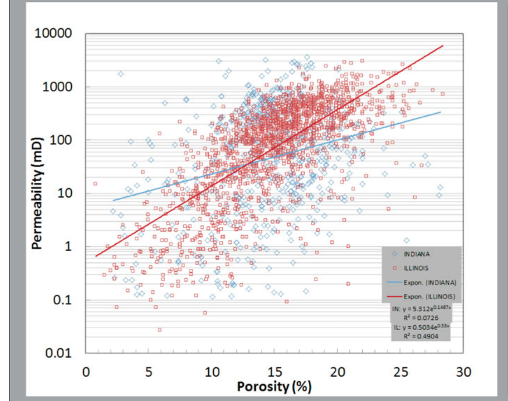


MI Basin SRE: Depth Dependent Porosity-Isopach

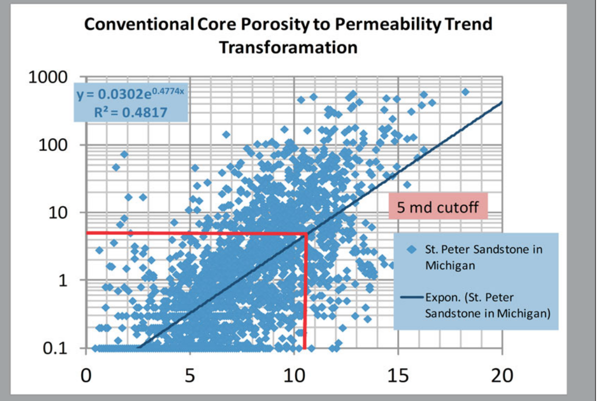
4. Storage Resource Estimation:

Reducing Uncertainty Through Log Analysis

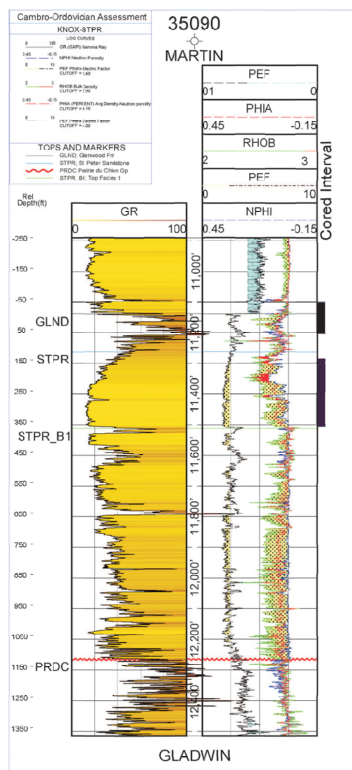
An alternate approach to SRE was undertaken using core analysis data and porosity logs. A porosity to permeability transform equation was used to establish a net porosity cutoff in the St. Peter Sandstone in each basin; 5 md at 7% porosity in the Illinois basin and 5 md at 10% porosity in the Michigan basin. This log cutoff (along with a minimum GR log filter) was used to calculate net porosity in control wells. These values were then gridded and summed to calculate total porosity in each basin. Enhanced geological log analysis procedures justify the use of a displacement storage efficiency factor only, which is 7.4%, 14%, and 26 % for p10, p50, and p90, respectively (Atlas III).



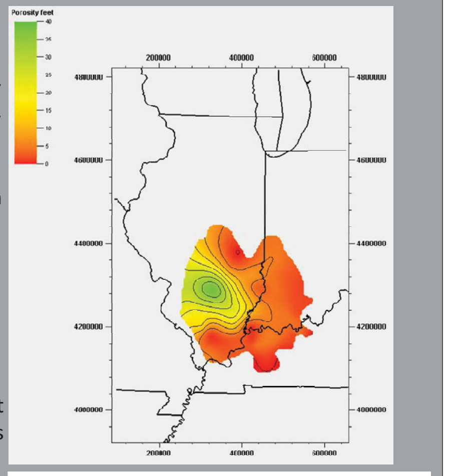
IL Basin Porosity to permeability transform from core analysis; 5 md at 7% porosity



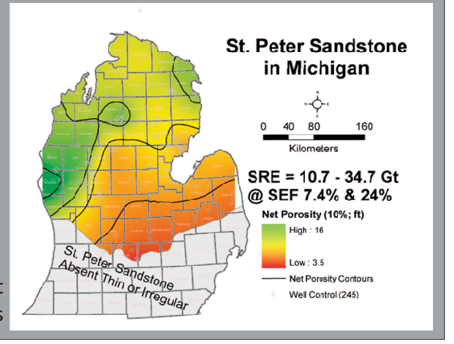
MI Basin porosity to permeability transform from core analysis; 5 md at 10% porosity



Type subsurface log from the central Michigan basin. Geological log/net porosity analysis using a 10% porosity log cutoff from the MI Basin as conducted from almost 250 wells (as shown in well control map in panel #3). Cored interval is indicated.



IL Basin SRE: Gridded Net Porosity from Log Analysis



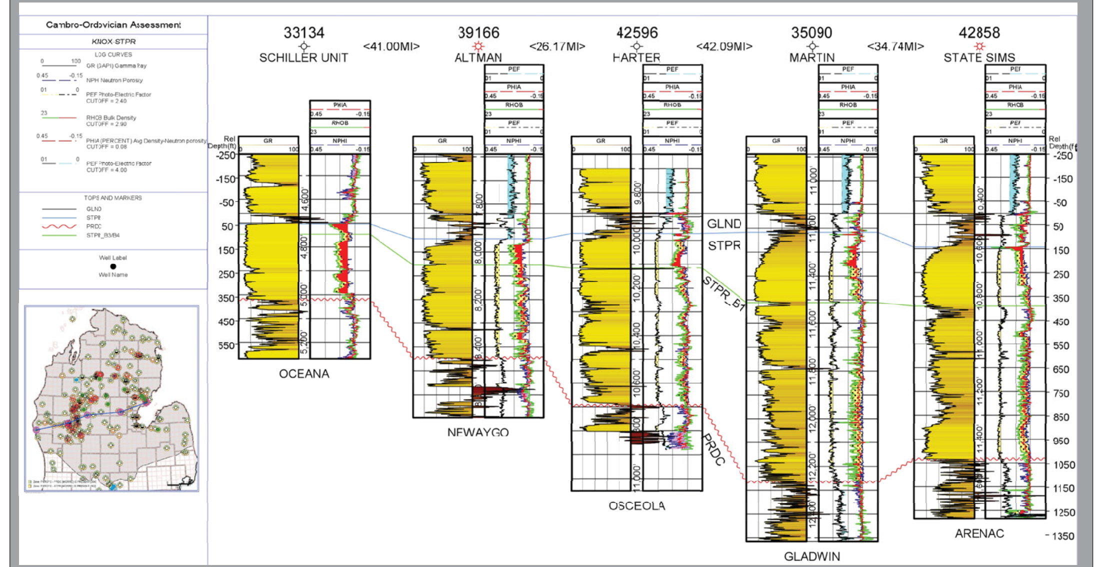
MI Basin SRE: Gridded Net Porosity from Log Analysis

2.

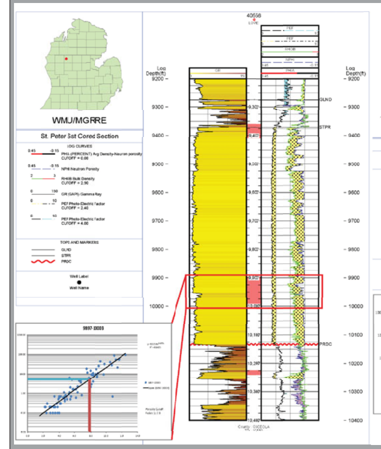
A Comparison of Geological CO2 Storage Resource Calculation Methodologies to Evaluate Parameter Sensitivity and Reduce Uncertainty: Case study of the St. Peter Sandstone (Ordovician) in the Illinois and Michigan Basins

5. Storage Resource Estimation: Reducing Uncertainty Through Geological Characterization and Log Analysis

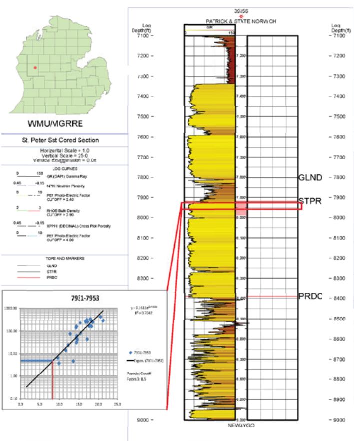
Nearly 100 conventional cores, hundreds of thin sections, over 250 modern well logs, and previous work were used to establish important geological controls on reservoir quality in the St. Peter Sandstone in the Michigan basin. Reservoir facies were identified in porosity logs through core to log calibration of sedimentary facies, petrologic/diagenetic and petrophysical properties. Special core analysis (MICP, CO2/brine relative permeability, CT scans) were also undertaken to further provide quantitative reservoir characterization of reservoir facies



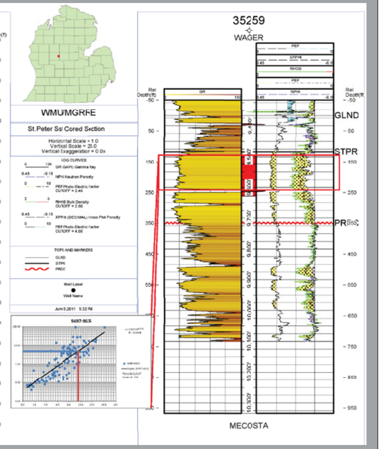
West to east MI Basin stratigraphic cross section showing internal reservoir facies subdivisions. Facies 1 predominates in the lower St. Peter (STPR_B1); Facies 3 & 4 occur in the upper St. Peter and are discriminated using a GR log filter (Facies 4 has > K-feldspar and illite cement producing higher GR log response).



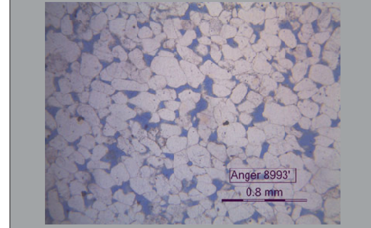
Facies 1 Poro-Perm transform:
5 md = 7.6% cutoff porosity



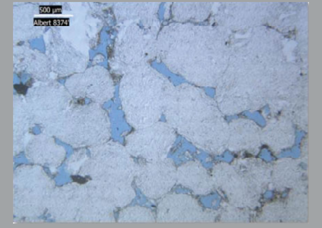
Facies 3 Poro-Perm transform
5 md = 8.5% cutoff porosity



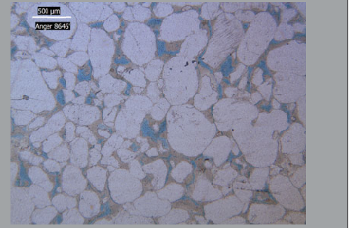
Facies 4 Poro-Perm transform
5 md = 10.5% cutoff porosity



Facies 1 photomicrograph; 11.1% & 60 md
Minor quartz cement & cement dissolution



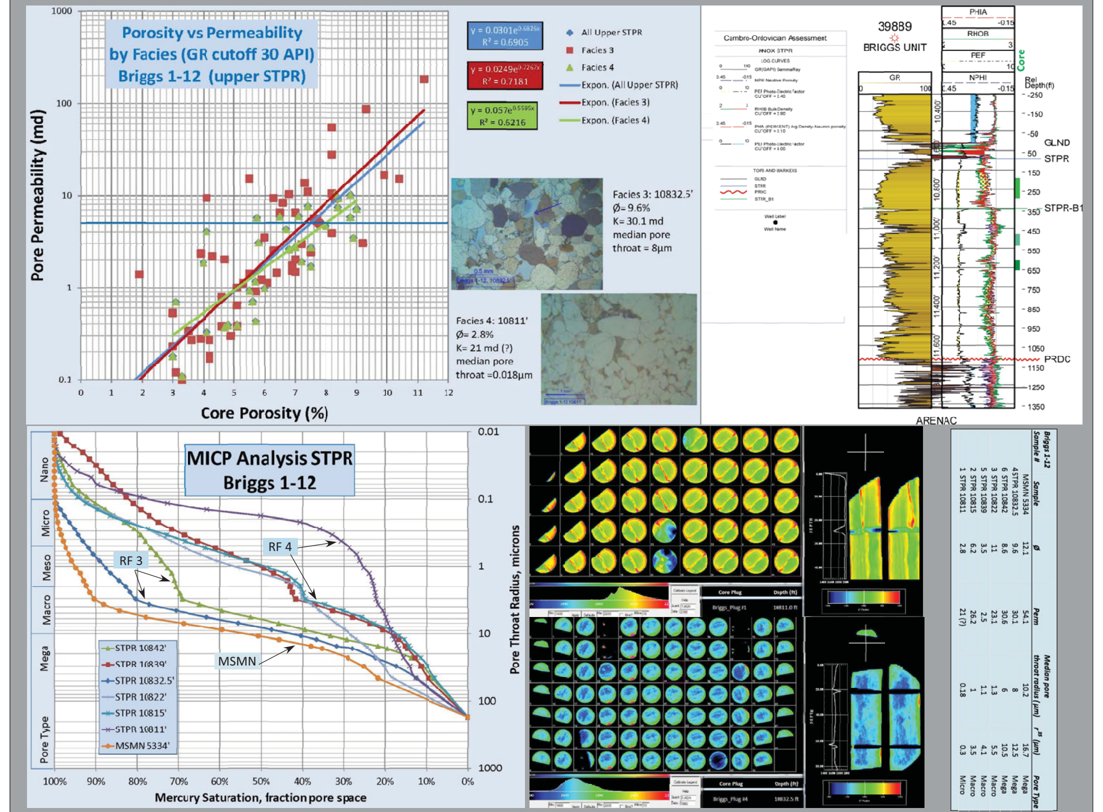
Facies 3 photomicrograph; 12.1% & 282 md
Cement dissolution and oversized pores



Facies 4 photomicrograph; 11% & 11.6 md
Authigenic clay cement

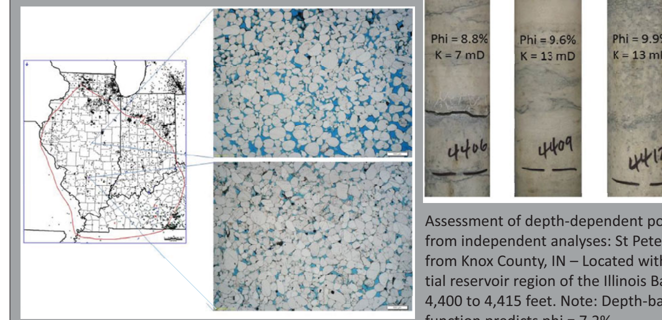
5 (cont.). Storage Resource Estimation: Reducing Uncertainty Using Special Core Analysis

Michigan Basin

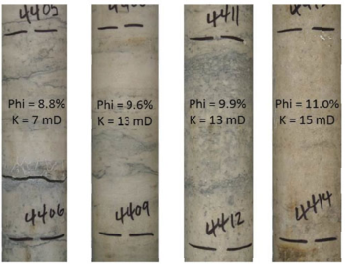


Special core analysis and core to log calibration from the Brigss Unit1-12, Arenac Co., MI (top right, interpreted FD-CNL log display). Top-left chart is a semi-log plot of core porosity vs permeability sorted by gamma-ray log (> and < than 30 API) response showing trend lines by reservoir facies (RF 3 & RF 4), in the top STPR (above STPR-B1 pick in the log).
Lower left plot is mercury injection capillary pressure measurements of RF 3 & 4 (orange curve is a sample of excellent quality Mount Simon Sandstone from Ottawa Co., Michigan, for comparison). CT core plug scans (right center) represent end member examples of RF 3 & 4 (CT scan and relative permeability studies by Shameem Siddiqui and Ottman A. Algadi, Texas Tech Un., Lubbock, TX)

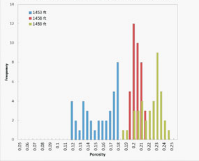
Illinois Basin

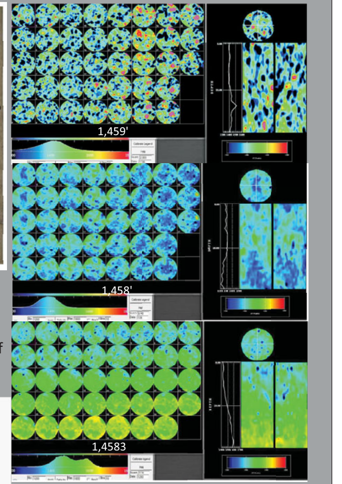


Photomicrographs of St Peter Ss core from the Illinois Basin illustrating diagenetic affects on porosity. Top: CCS#1 well in Decatur, IL; depth = 3,450 ft; porosity = 19.6%. Bottom Johnson #1 well in Marion County, IL; depth = 5,249 ft; porosity = 11.6%.



Assessment of depth-dependent porosity model from independent analyses: St Peter core samples from Knox County, IN – Located within the potential reservoir region of the Illinois Basin at depth of 4,400 to 4,415 feet. Note: Depth-based porosity function predicts phi = 7.2%

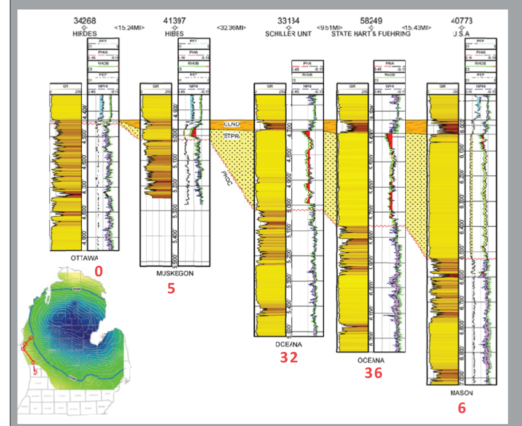


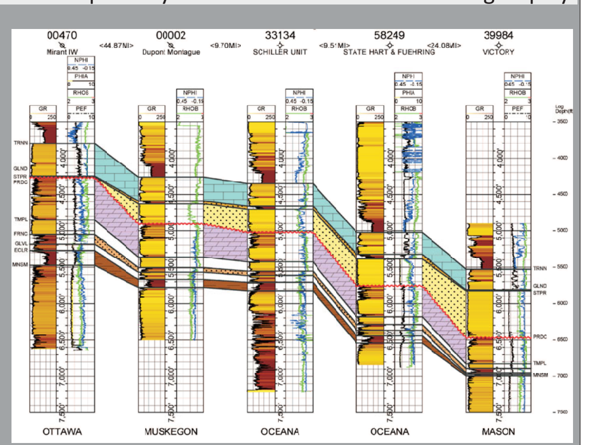


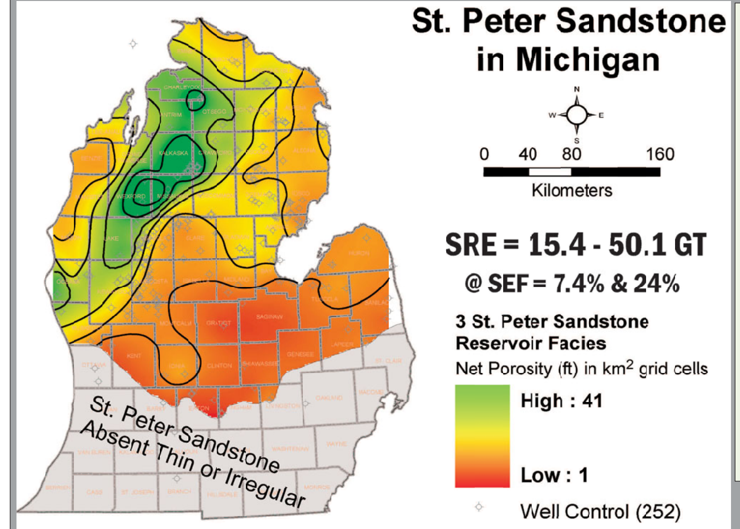
CT scan of St Peter Ss core samples from Starke County, IN (Well ID 159305)– Arches Province between the potential reservoir regions in the Illinois and Michigan Basins

6. Geological Controls on Reservoir Quality & Storage Capacity: Michigan Basin

Stratigraphic thickness, sedimentary depositional ithofacies, and depth of burial control reservoir quality in the St. Peter Sandstone in the Michigan basin. A structural cross section (right, see stratigraphic cross section, left, for section location map, in red on the inset overburden map) from south (left) to north (right) in western Lower Michigan from the St. Peter Sandstone pinch-out in the south (no storage capacity) to increased thickness in the St. Peter at relatively shallow burial depth to the north (best reservoir quality & good storage capacity), and finally to thick but deeply buried St. Peter furthest north with little reservoir quality/storage capacity due to extensive, depth of burial induced quartz overgrowth cementation. Note that the Mount Simon sandstone is a highly prospective sequestration target in southwestern Lower Michigan (southern-most log) while not prospective to the north, at greater burial depth, where the St. Peter Sandstone has substantial storage potential. Stratigraphic cross section (left) for the same wells shows porosity logs with a 10% cutoff (red fill) and resultant net porosity in red at the bottom of each log display.





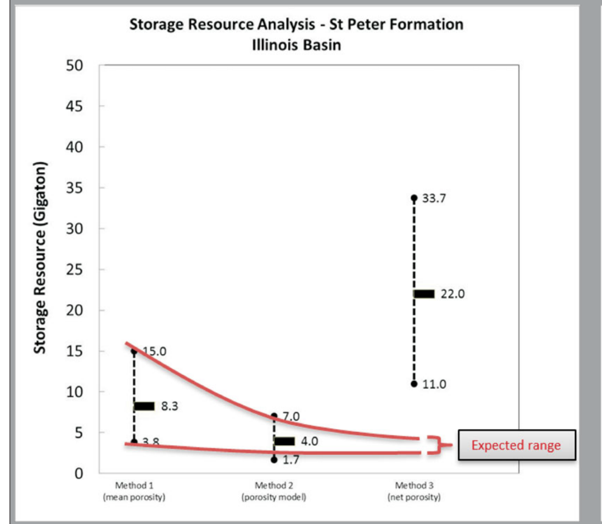


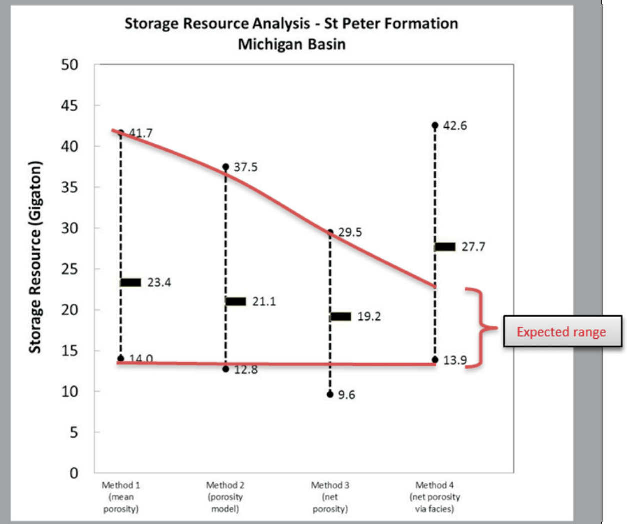
Porosity cutoff from transform sumary using core analysis(Ø & K) cross plots at 5 md permeability

Core Name	Well Label	Facies 1	Facies 3	Facies 4
Anger	41137		10	
Anger	41137	8.8		
Blair	34292		9	10.3
State Garfield	43570			11.4
State Garfield	43570			10.9
Gernaat	35781		8.4	
Harter	42596	6.9		
Hunt-Martin	35090	6	7	11.2
Lowe	40556	7.9		10.2
Patrick	39856		8.8	11
Robinson	35482		9	9.9
State Summerfield	42156			9.8
State Foster	42396	7.6		
State Garfield	45446	8.1		
Sundmacher	39433			13.6
Wager	35259			9.6
Briggs	39889		7.3	8
Avg. Porosity Cutoff:		**7.6**	**8.5**	**10.5**
Std. Deviation		**0.98**	**1.04**	**1.39**
Min		**6**	**7**	**8**
Max		**8.8**	**10**	**13.6**

The total porosity map constructed using Reservoir Facies porosity cutoffs (see adjacent table) in Michigan more closely agrees with geological relationships and suggests reduced uncertainty compared to previous maps. High resolution geological characterization and log analysis results in use of a displacement storage efficiency factor only, with enhanced confidence in SRE results.

7. Sensitivity and Uncertainty





In addition to evaluating potential new reservoirs for geologic sequestration in the Midwest a broader research objective of this project is to evaluate SRE uncertainty. Undertaking a series of increasingly sophisticated characterization analyses is expected to reduce uncertainty in SRE. The figure above summarizes our results from methods 1 (mean porosity and gross isopach), 2 (variable, depth-dependent porosity and gross isopach), 3 (net porosity characterization using cutoff value) and 4 (net porosity within multiple facies, MI Basin only). The red lines define a conceptual envelope in the range of uncertainty in SRE which is expected to decrease as the accuracy of our analysis increases. For both the Illinois and Michigan Basins we found that our most sophisticated analysis results were significantly larger than the prior estimates and lie outside of this conceptual expected range.

In order for our study to follow the Storage Efficiency Factor (SEF) methodology published in Atlas III it was necessary to modify the results from specific efficiency factors provided in Appendix B, Tables 7 and 8. Because we defined our reservoir area by mapping the 800 m overburden thickness, application of the published SEF values (0.51% and 5.4% for P10 and P90, respectively) in methods 1 and 2 would have effectively underestimated the actual SRE since the SEFs use a range of 0.2 to 0.8 in the net-to-total area term. To correct for this issue, we used more realistic estimates of the net-to-total area efficiency factor terms (0.85, 0.90, and 0.95 for the P10, P50, and P90 values, respectively) and implemented this by multiplying our initial SREs by factors of 4.25 (P10), 1.8 (P50), and 1.19 (P90), which is the ratio of efficiency factor terms (e.g., 0.85/0.20 = 4.25 for P10 value). Furthermore, directly applying the efficiency factors from Atlas III, Appendix B, Table 8 to our results for methods 3 and 4 would have effectively overestimated SRE since the SEF values assume that the geologic terms are known exactly (i.e., equal to 1) and uncertainty is accounted for only in the displacement terms. In reality there still exists some uncertainty in the geologic terms even though we have reduced the effective pore volume by our net porosity analysis. Thus for cases 3 and 4 we attempted to correct for this overestimation by multiplying our results by the more realistic geologic term factors of 0.85, 0.90, and 0.95 for the P10, P50, and P90 values, respectively.

The fact that our results still lie outside of the conceptual window of uncertainty shown in the figure above raises some important questions about the robustness of the current DOE methodology for SRE at regional scales. A significant impact comes from the uncertainty in our model of the bulk rock volumetrics, which changes significantly across the methods. Although the SRE methodology published in Atlas III uses probabilistic distributions to estimate uncertainty, it applies only as a fractional component of the total formational pore volume. The method does not account for uncertainty in the total bulk pore volume but only in the fraction of that particular volume (a single realization) that can ultimately be occupied by injected CO2. Thus by our analysis of the St Peter Sandstone, it seems that the methodology was not robust enough to truly capture the uncertainty that existed in SRE in the simpler models. It could also be argued that our St Peter results fall outside of the envelope because our regional data sets were insufficient to accurately characterize the reservoir net porosity, although this seems unlikely for the Michigan Basin with good well control and modern porosity logs. In any case, our study has pointed out a limitation of the current SRE methodology that may need further investigation if we are to be able to quantitatively demonstrate a reduction in uncertainty in SRE through more advanced reservoir characterization.