Regional Reservoir Characterization and CO_2 Storage Resource Estimate (SRE) in a Geologically Complex, Deep Saline Formation, Middle Ordovician St. Peter Sandstone (STPR), Michigan Basin, USA*

David A. Barnes[1] and Stephen Zdan[2]

Search and Discovery Article #80572 (2016)**
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See similar article Search and Discovery Article #80278 (2013)

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Abstract

The Middle Ordovician St. Peter Sandstone is widespread in the Midwest, USA. The formation is an important aquifer, gas storage reservoir, and source of proppant sand with typically friable and super-mature mineralogy/texture in shallowly buried occurrences. In the Michigan Basin, the formation ranges in thickness from a stratigraphic pinchout to more than 335m in thickness and occurs at depths of burial of greater than 800m to in excess of 3.35 km throughout much of the Lower Peninsula of Michigan. The St. Peter has been the subject of hydrocarbon exploration/production activity in the basin since the early 1980's. As a result, substantial modern subsurface geological data is available including conventional core and core analysis data from nearly 100 wells and modern, down-hole logs from complete formation penetrations in over 250 wells. CO_2 storage resource estimates (SRE) were developed as part of US DOE-NETL sponsored (ARRA) project led by the Illinois State Geological Survey (ISGS) focusing on the regional site characterization of high-potential geologic storage formations in the Michigan and Illinois basins. The St. Peter is an important, deep saline CO_2 storage target in Michigan with SRE of between 3.0 to 50.1 GT of CO_2 based on various SRE methodologies and a range of confidence intervals. We present the results of high resolution reservoir characterization studies using an extensive subsurface data set to determine a more reliable SRE, compared to more simplistic approaches, in a geologically complex, deep saline reservoir. Sedimentary facies, petrographic and petrologic analysis, including special core analysis studies were used to characterize and quantify reservoir petrophysical properties in the formation throughout the basin. Regional stratigraphic thickness, 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. Sedimentary facies variations typically template complex diagenetic modification of primary textures, mineralogy and reservoir quality and these factors have a substantial influence on regional variation in storage resource potential. Application of high resolution reservoir characterization methodology justifies significantly reduced uncertainty in net-to-gross reservoir area, porosity and effective to total porosity estimates and increased storage efficiency factors (SEF) used in SRE calculations.

References Cited

DOE-NETL, 2015, Carbon Storage Atlas, 5th ed.: U.S. Department of Energy, 114 p. https://www.netl.doe.gov/File%20Library/Research/Coal/carbon-storage/atlasv/ATLAS-V-2015.pdf. Website accessed December 2016.

Peck, W.D., T.P. Bailey, G. Liu, R.C.L. Klenner, C.D. Gorecki, S.C. Ayash, E.N. Steadman, and J.A. Harju, 2014, Model Development of the Aquistore CO_2 Storage Project: Energy Procedia, v. 63, p. 3723-3734. doi:10.1016/j.egypro.2014.11.401

Regional Reservoir Characterization & CO_2 Storage Resource Estimate (SRE) in a Geologically Complex, Deep Saline Formation

Middle Ordovician St. Peter Sandstone (STPR) Michigan Basin, USA

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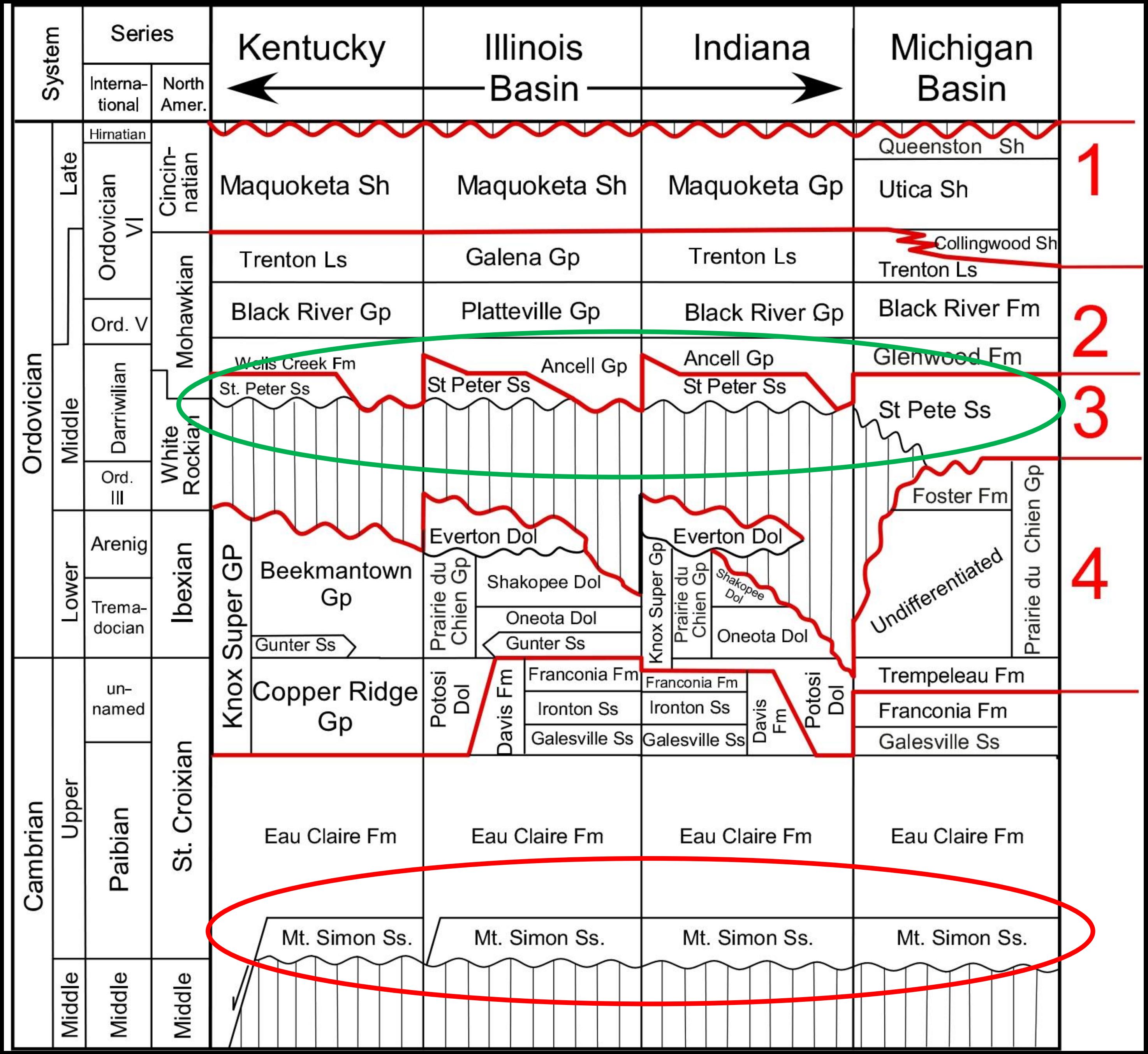
Cambro-Ordovician Strata in the Illinois and Michigan Basins

OBJECTIVE:

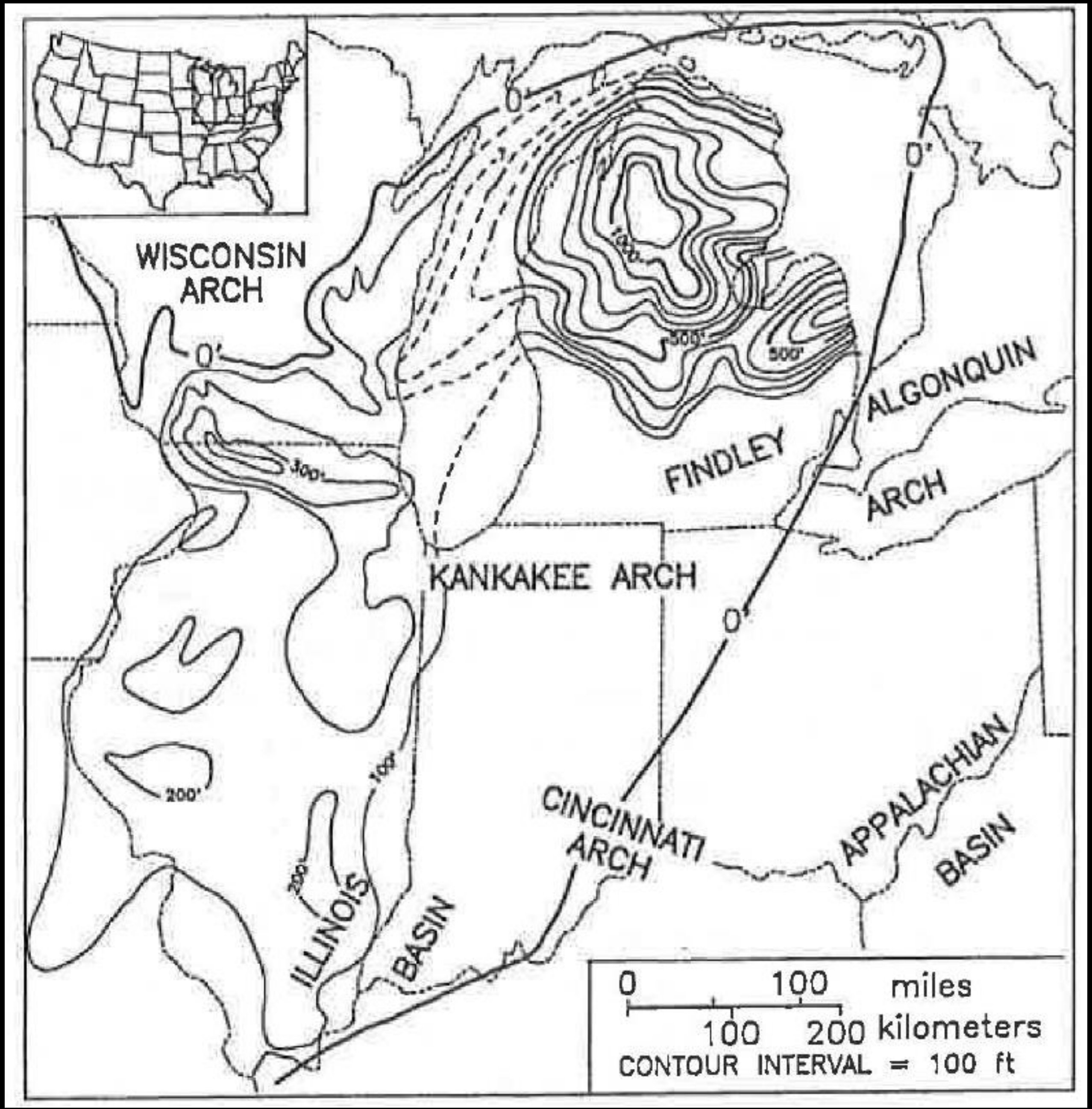
- Establish an alternative sequestration target to the Mount Simon Ss where MNSM is thin/absent or non-reservoir

- Interval #3: Prospective GCS reservoirs in the St. Peter Ss



St. Peter Sandstone in the Midwest

- The middle Ordovician St. Peter Sandstone is widespread in the Midwest, USA
- An important gas storage reservoir, aquifer, and source of proppant sand
- Typically friable and super-mature mineralogy/texture in shallowly buried occurrences



Geological Carbon Storage Resource Estimate (SRE)

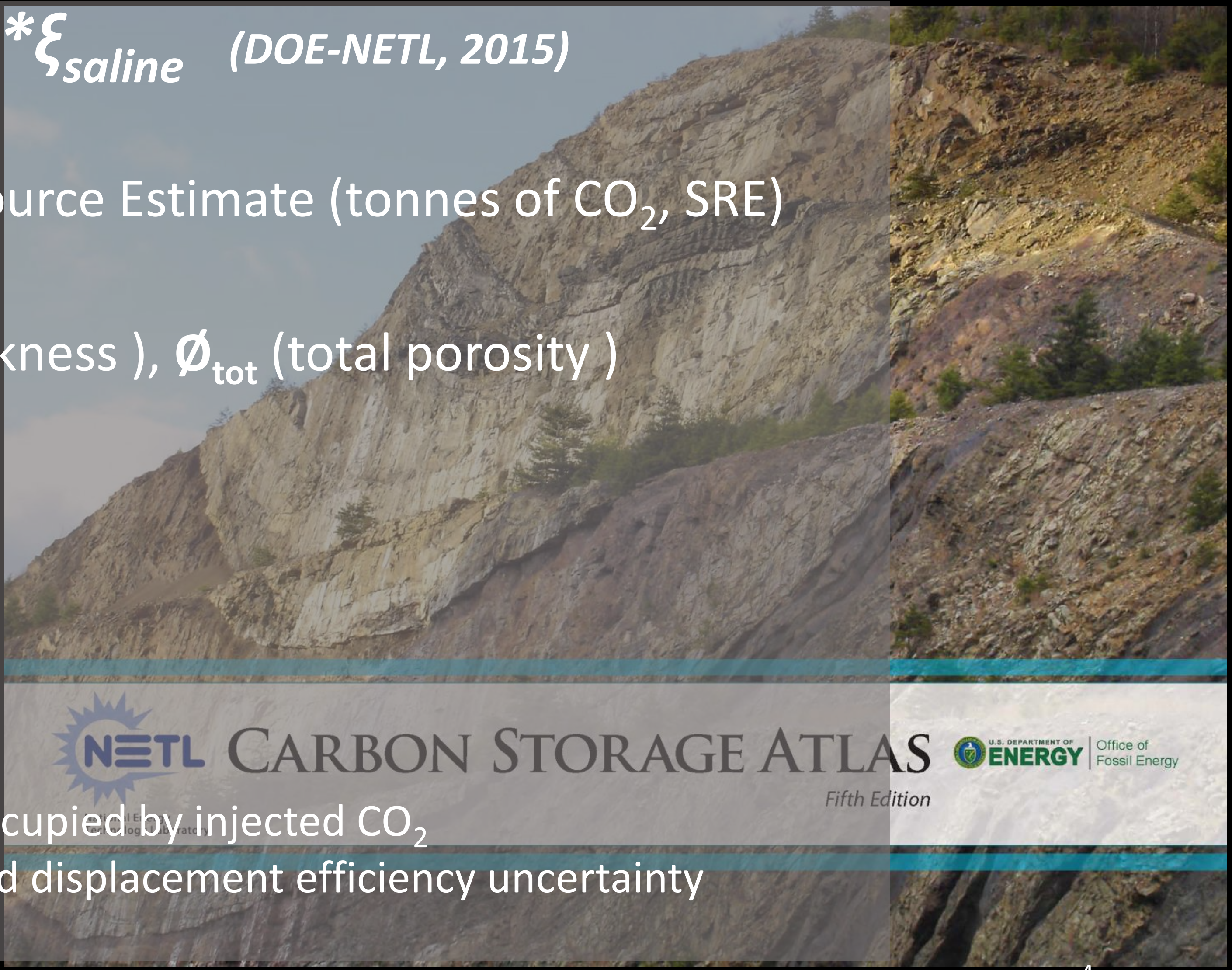
$$GCO_2 = A_t * h_g * Ø_{tot} * \rho * \xi_{saline}$$ *(DOE-NETL, 2015)*

- **GCO_2** = Geological Carbon Storage Resource Estimate (tonnes of CO_2, SRE)

- **A_t** (total area), **h_g** (gross formation thickness), **$Ø_{tot}$** (total porosity)
  - Estimated total bulk volume of pore space

- **ρ** (CO_2 density)
  - converts reservoir volume of CO_2 to mass.

- **ξ_{saline}** (*Storage Efficiency Factor*)
  - estimated fraction of total pore volume occupied by injected CO_2
  - includes CO_2 sequestration (geological) and displacement efficiency uncertainty



Geological Carbon Storage Resource Estimate (SRE)

- ξ_{saline} (Storage Efficiency Factor, SEF)

SEF is highly variable dependent on data control & methodology

Net Area Only

Lithology	P10	P50	P90
Clastics	1.62%	4.41%	9.53%
Dolomite	2.03%	4.96%	9.11%
Limestone	1.26%	3.38%	6.91%

Net Area and Net Thickness

Lithology	P10	P50	P90
Clastics	5.17%	9.88%	17.24%
Dolomite	9.32%	12.71%	16.93%
Limestone	7.18%	10.43%	14.74%

Net Area, Net Thickness, and Net porosity

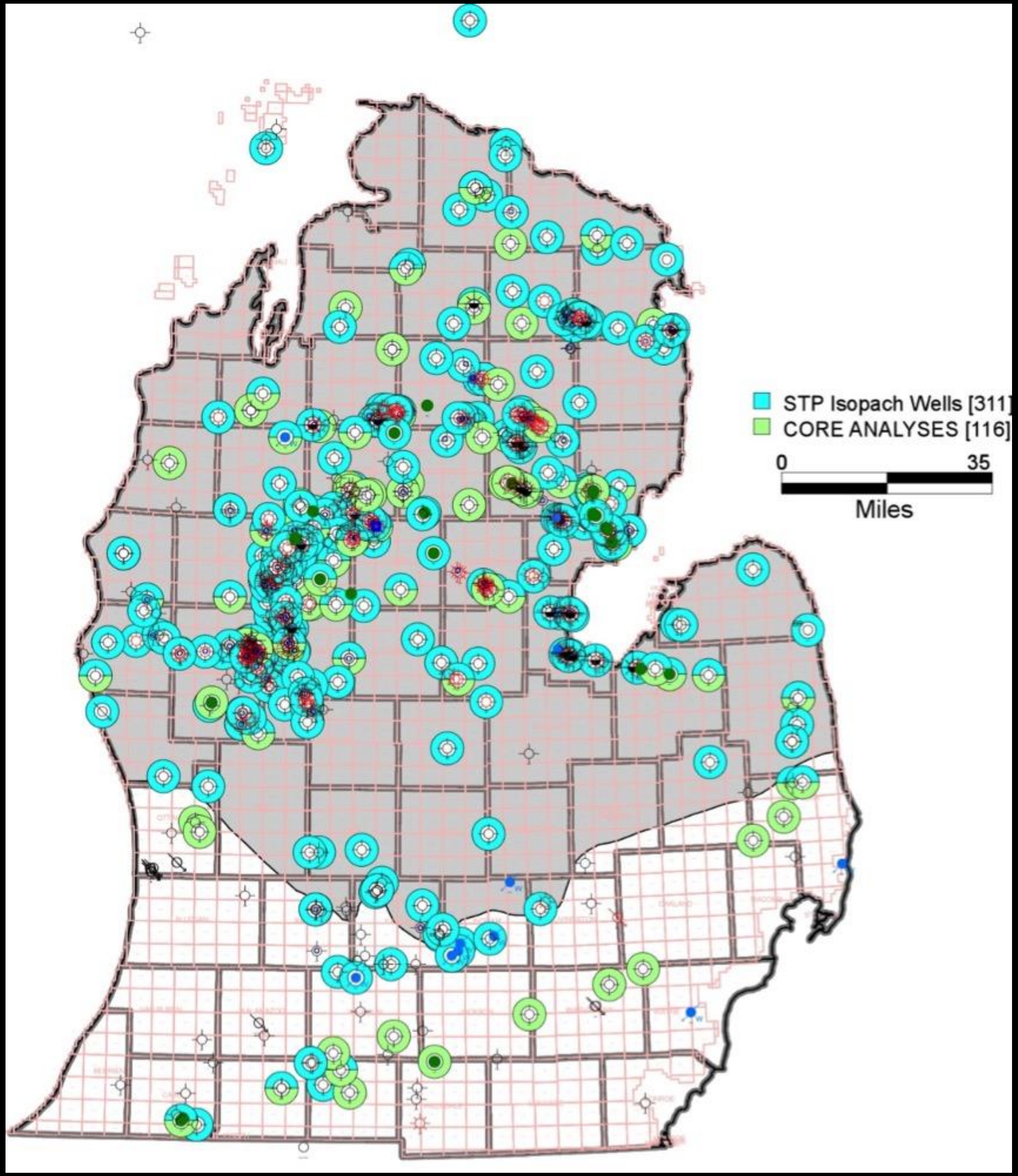
Lithology	P10	P50	P90
Clastics	7.4%	14%	24%
Dolomite	16%	21%	26%
Limestone	10%	15%	21%

Source of image: Peck et al., 2014. GHGT---12 Energy Procedia

St. Peter Sandstone in the Michigan Basin

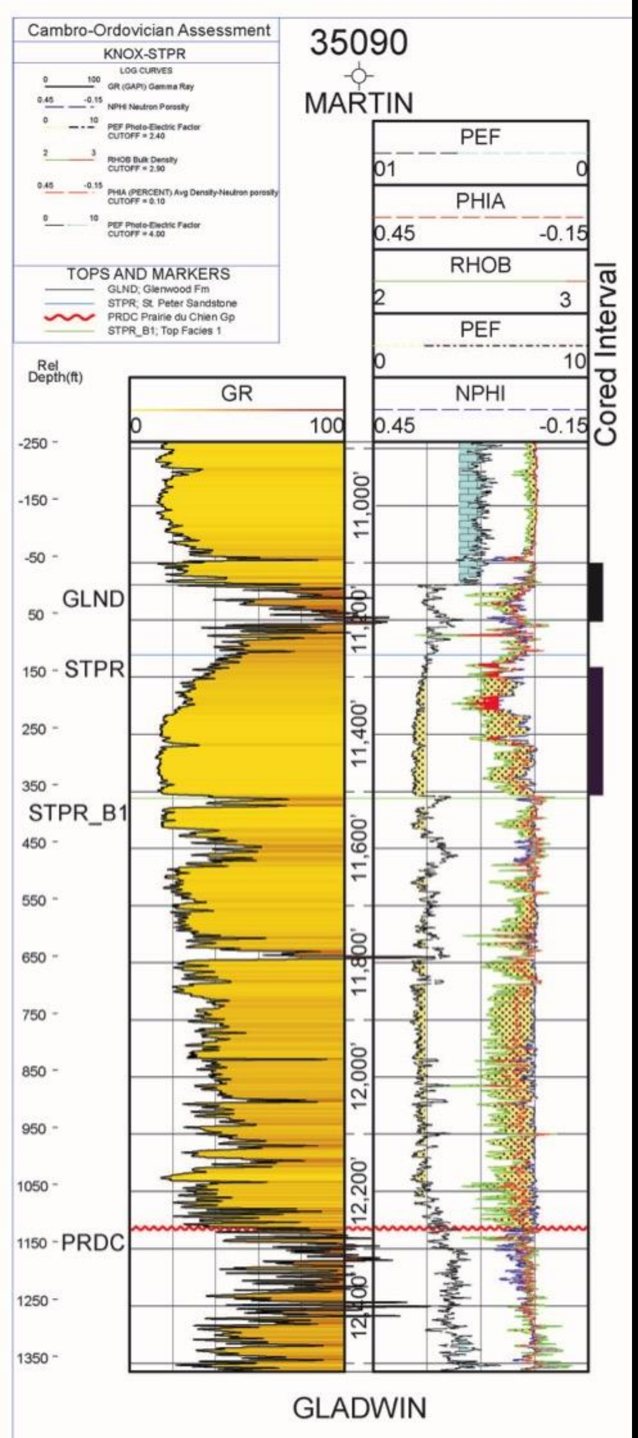
- Significant hydrocarbon exploration/ production target since the early 1980's

- Substantial modern subsurface data:
  - Conventional core and core analysis data from **<u>~100 wells</u>**
  - Modern, down-hole wire-line logs from complete formation penetrations **<u>> 250 wells</u>**

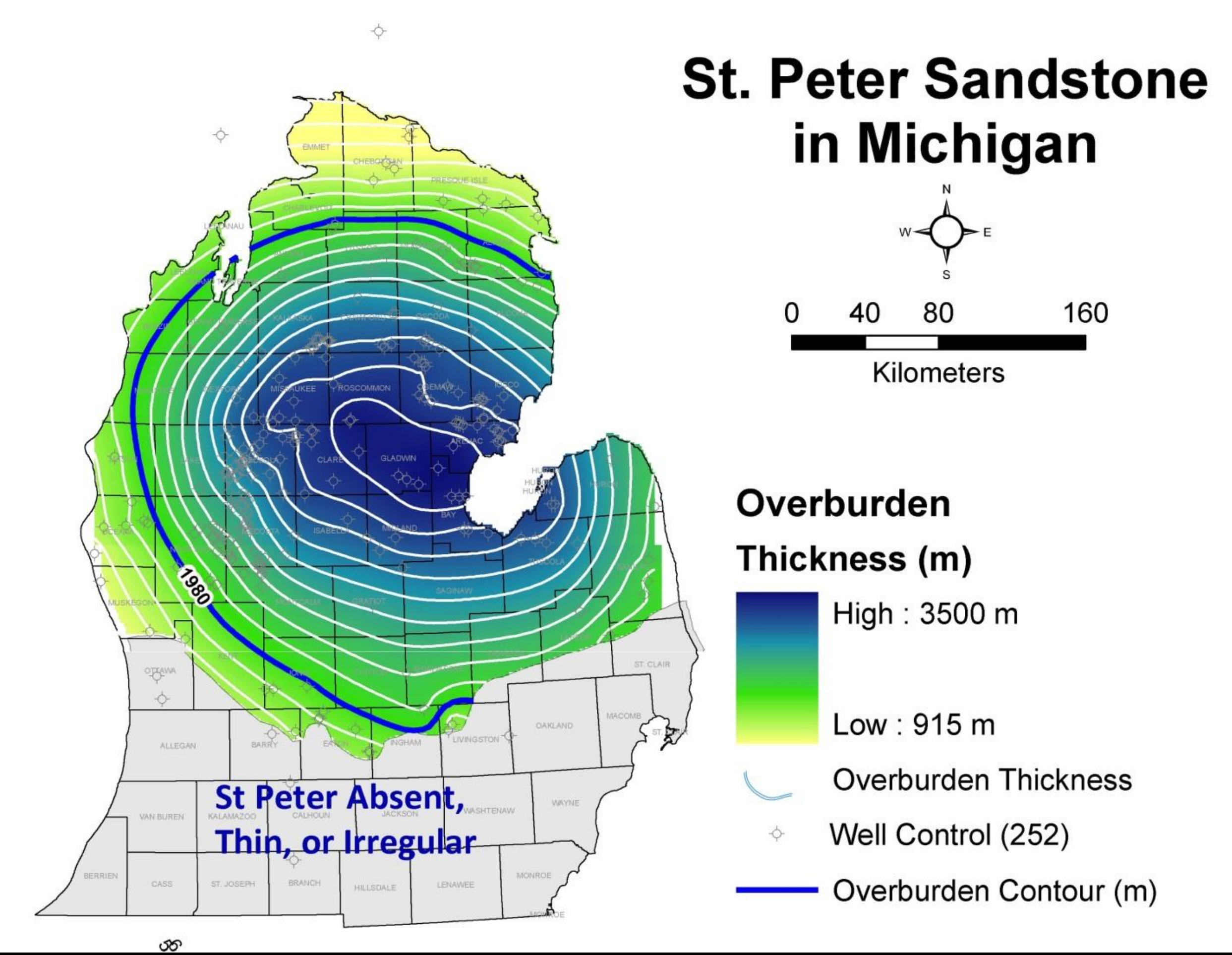


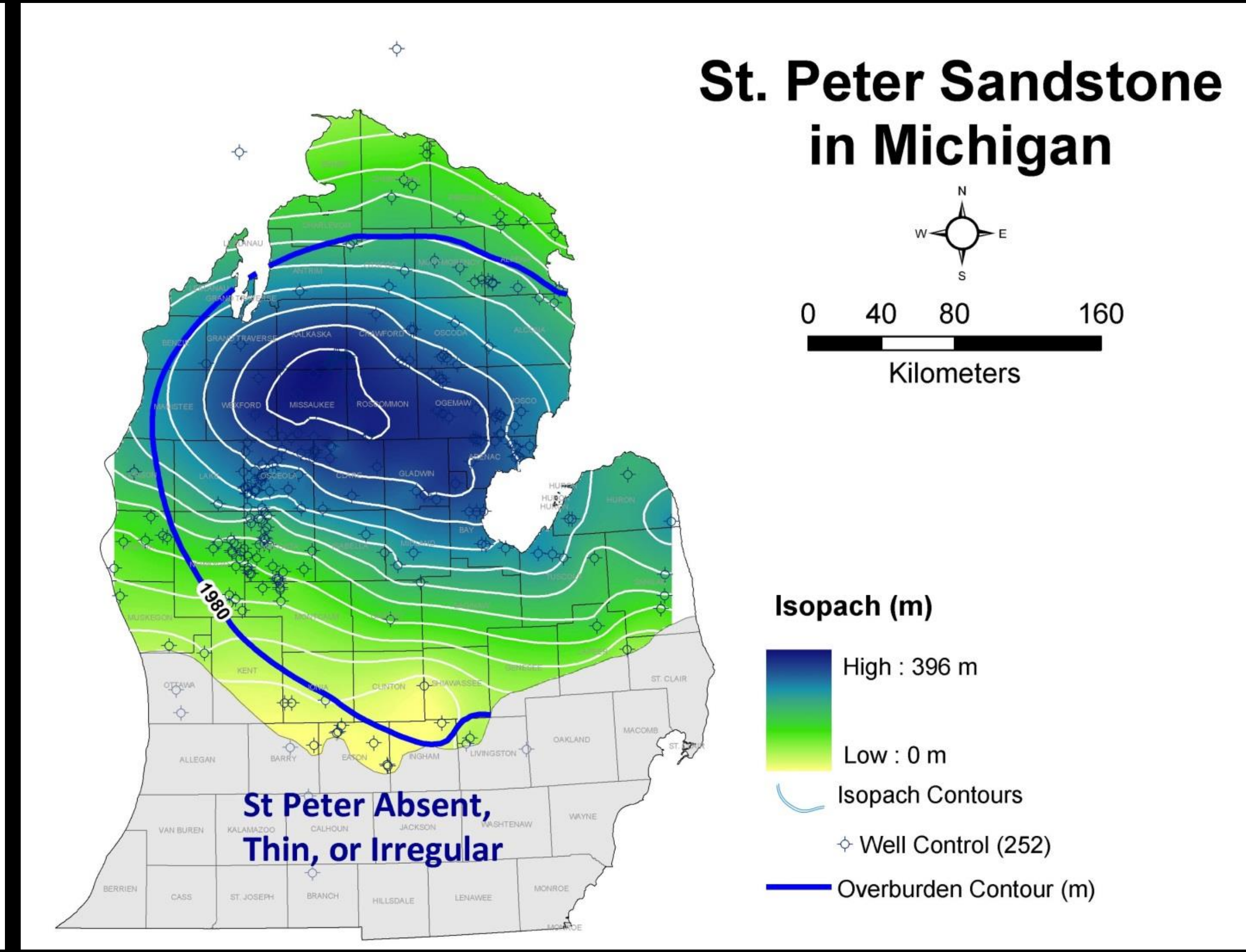
Wire-line Log Displays:
Type Log from the St. Peter Sandstone Michigan Basin; Hunt Martin, Gladwin Co.

- GR (GAMMA RAY)
- PEF (Photoelectric Effect)
- NPHI (Neutron Porosity)
- RHOB (Bulk Density)
- PHIA (derived log: Average NPHI/RHOB)

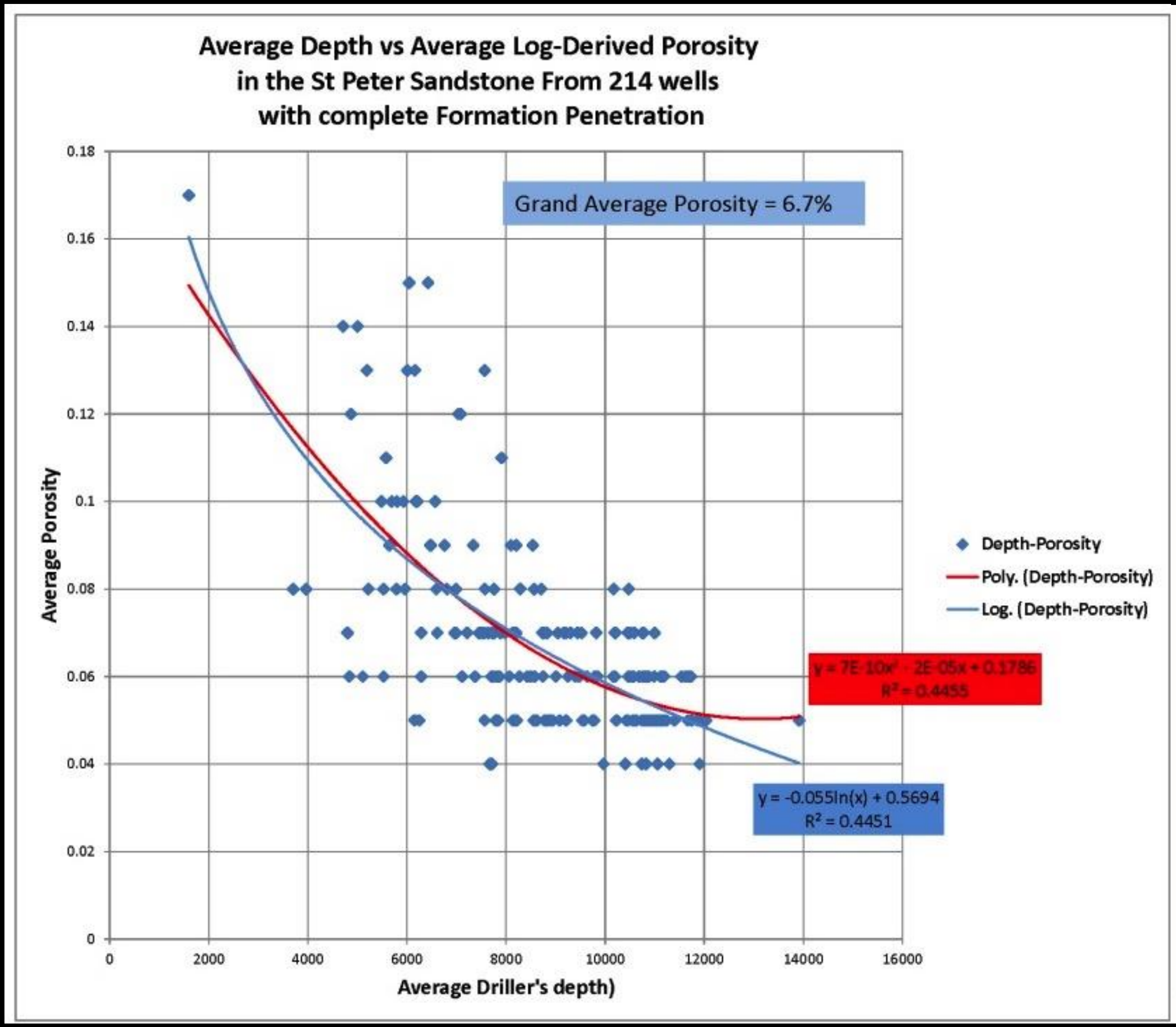


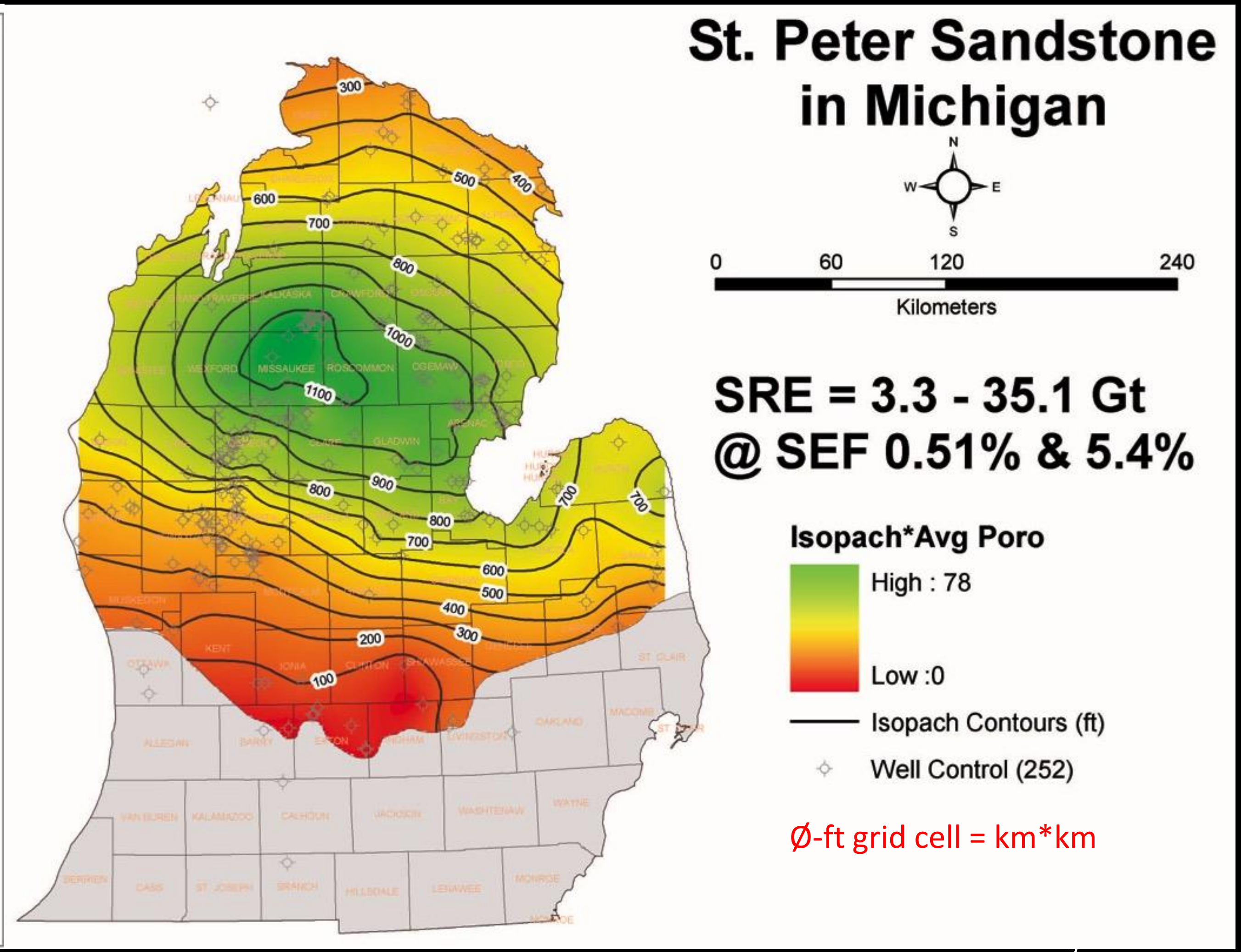
Structure (Overburden) and Isopach Maps; St. Peter Sandstone in Lower Michigan



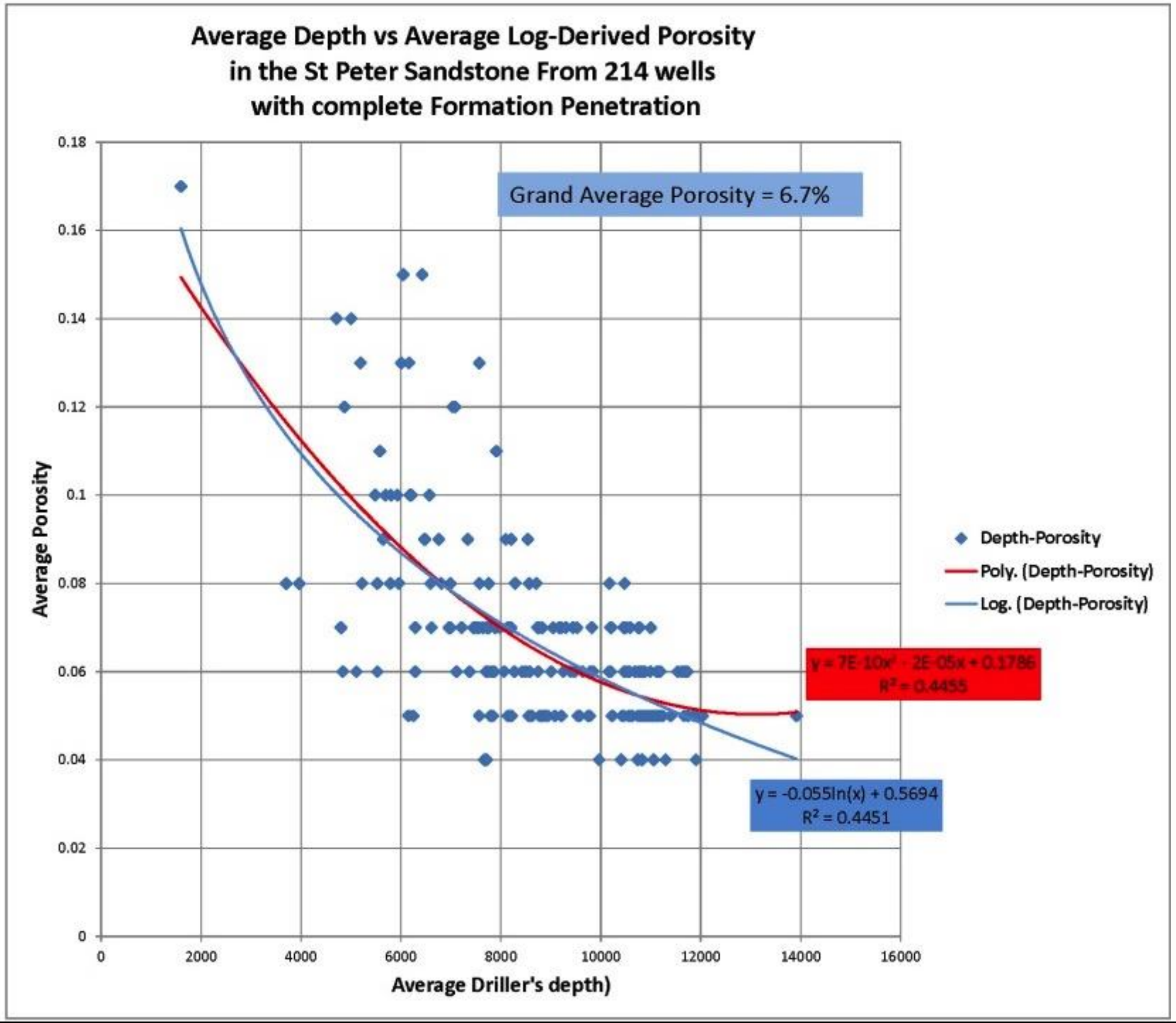


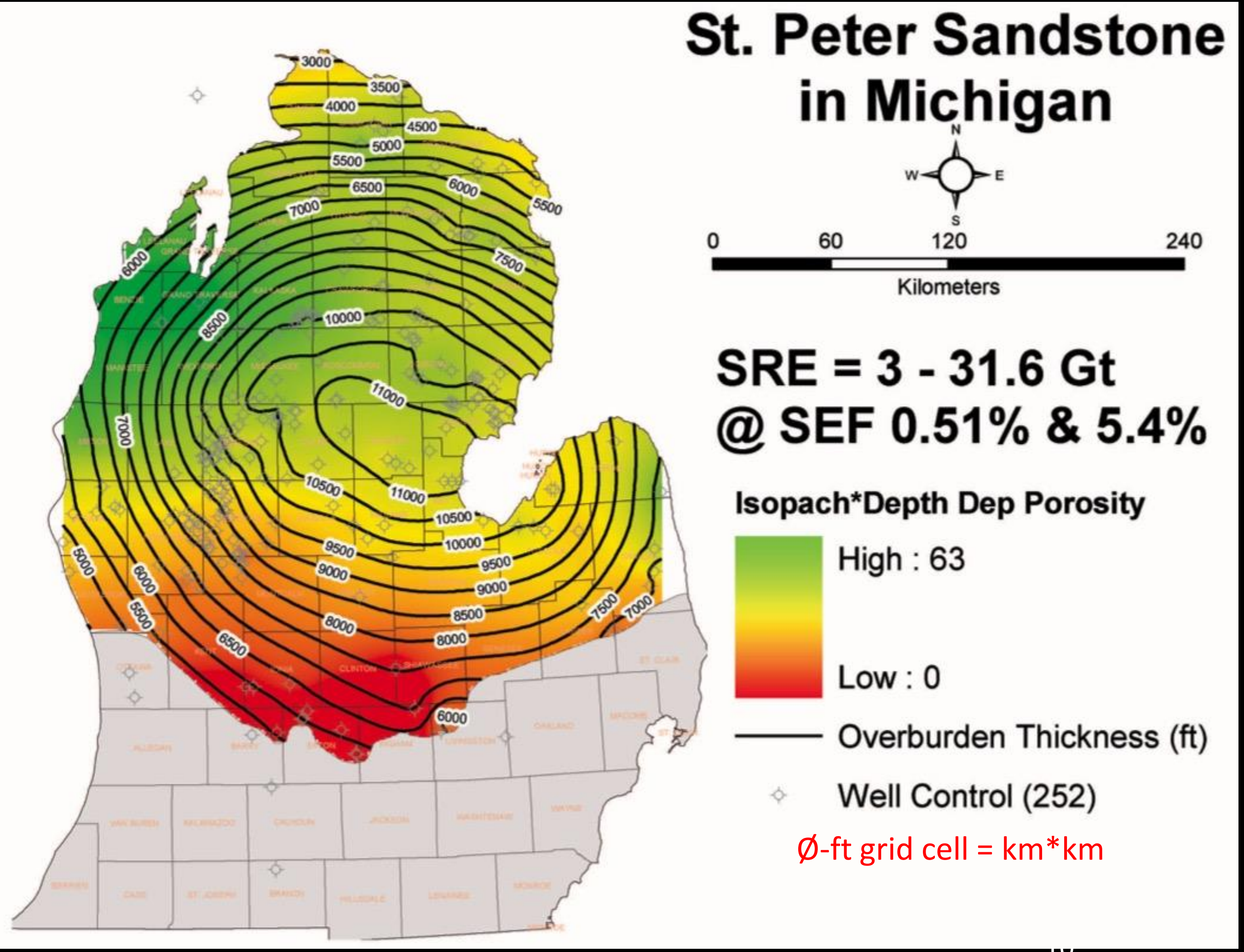
Method 1: SRE *($GCO_2 = A_t * h_g * Ø_{tot} * \rho * \xi_{saline}$)* with Limited Data; Gross Area, Gross Thickness, & Average Porosity



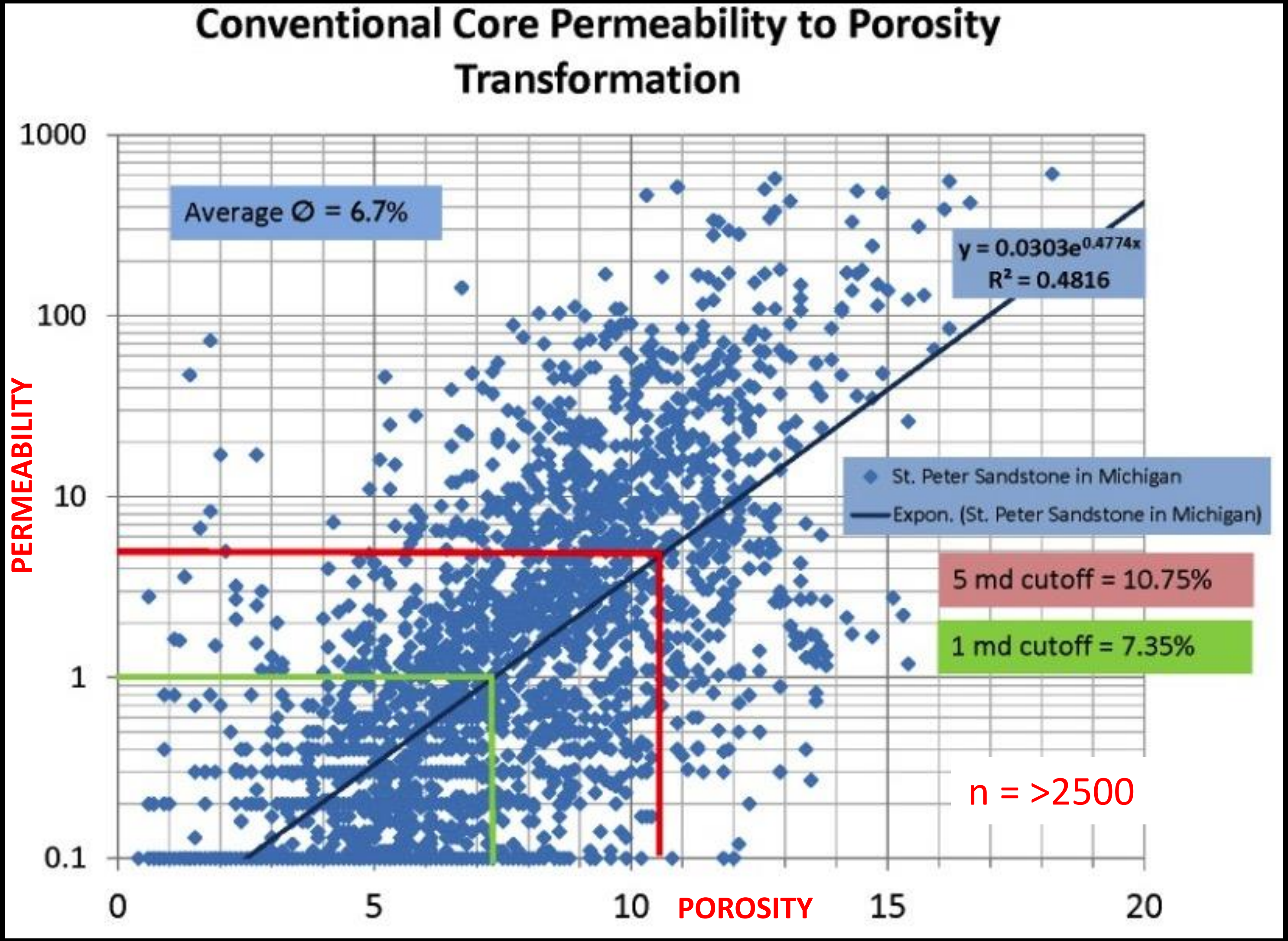


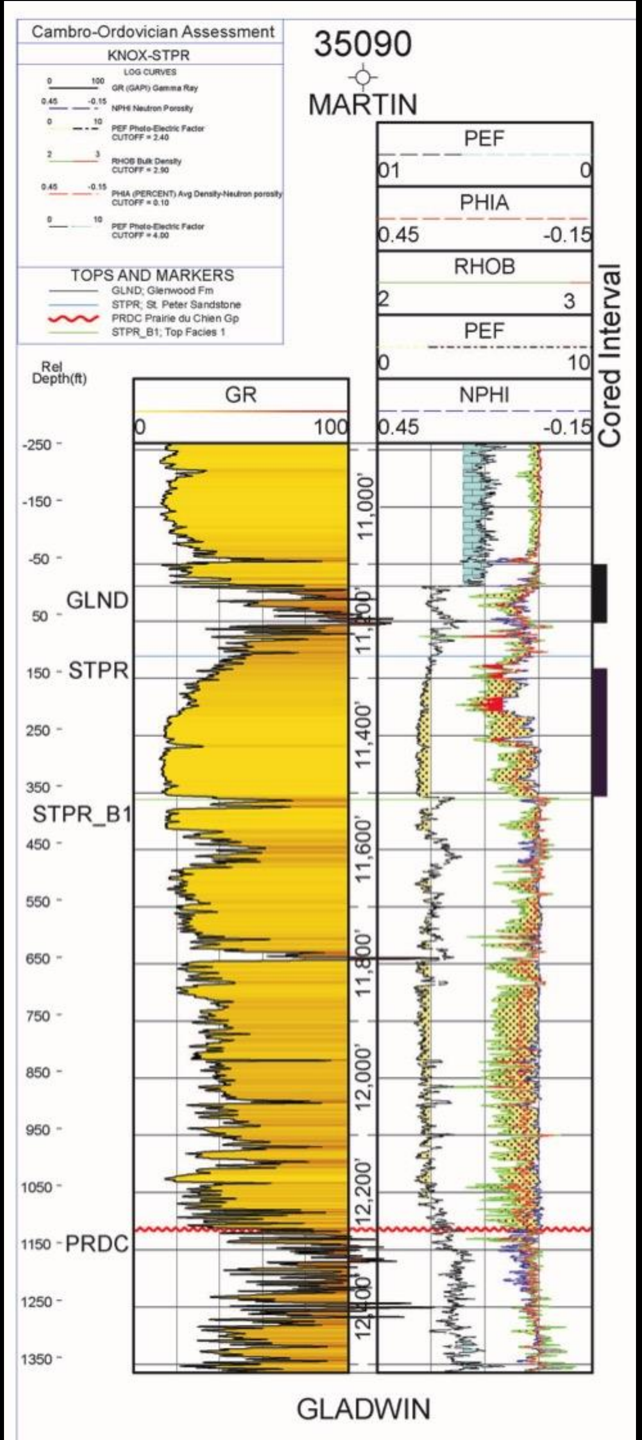
Method 2: SRE *($GCO_2 = A_t * h_g * \O_{tot} * \rho * \xi_{saline}$)* with Limited Data; Gross Area, Gross Thickness, & Depth Dependent Porosity



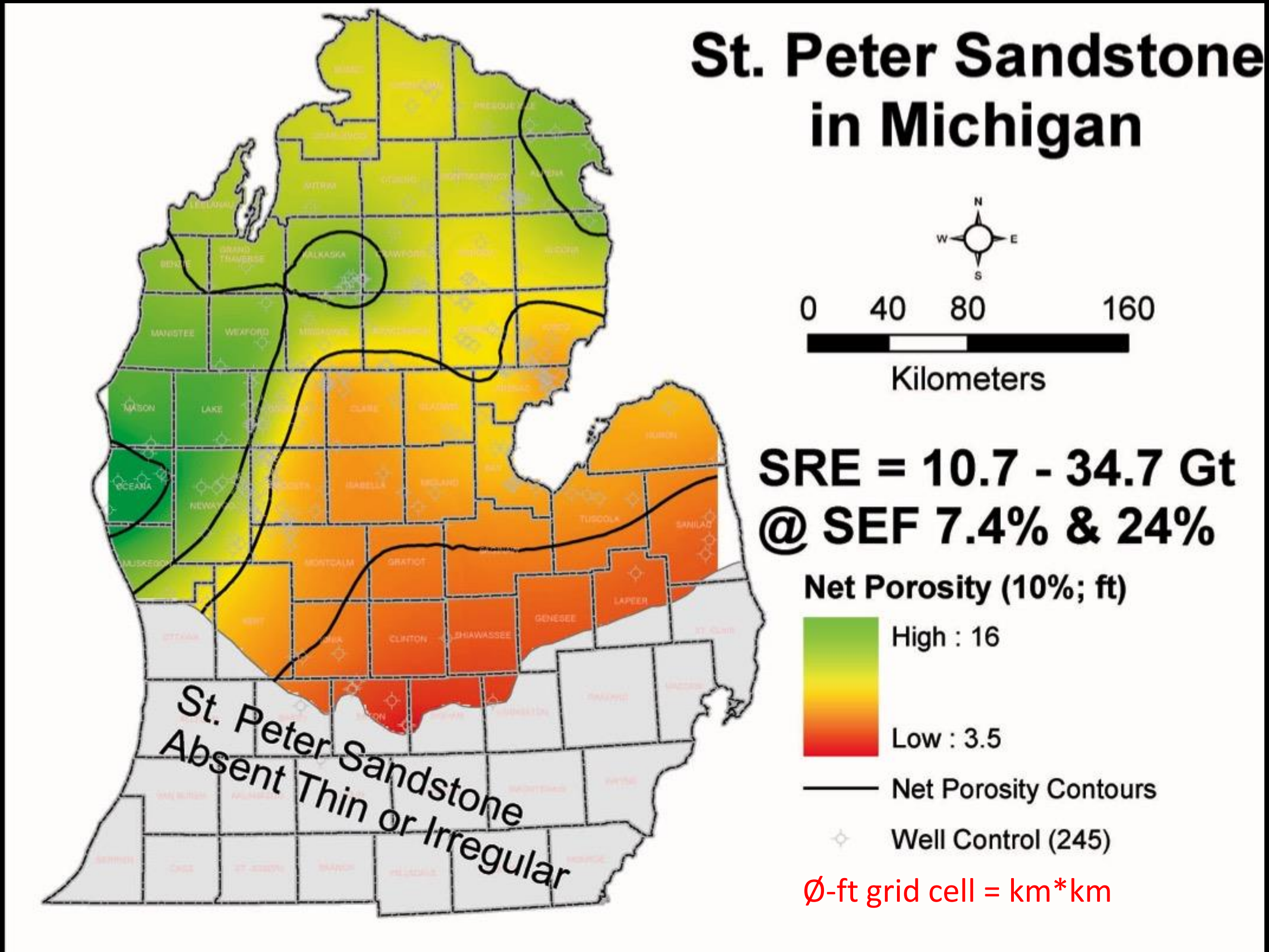


Method 3: SRE $(GCO_2 = A_t * h_g * Ø_{tot} * \rho * \xi_{saline})$ with Additional Data; Core-derived Net Porosity and Log Analysis

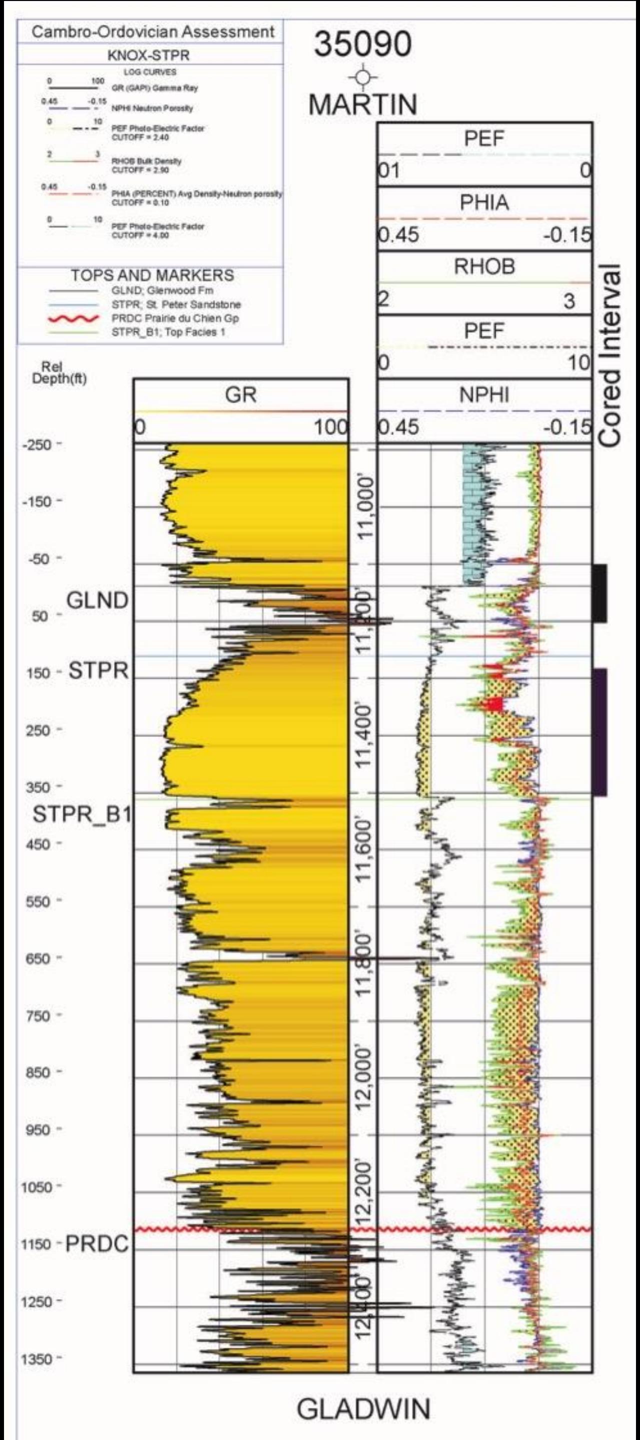




Method 3: SRE $(GCO_2 = A_t * h_g * Ø_{tot} * \rho * \xi_{saline})$ with Additional Data; Core-derived Net Porosity, Area and Thickness Using Gridded Net Porosity from Log Analysis

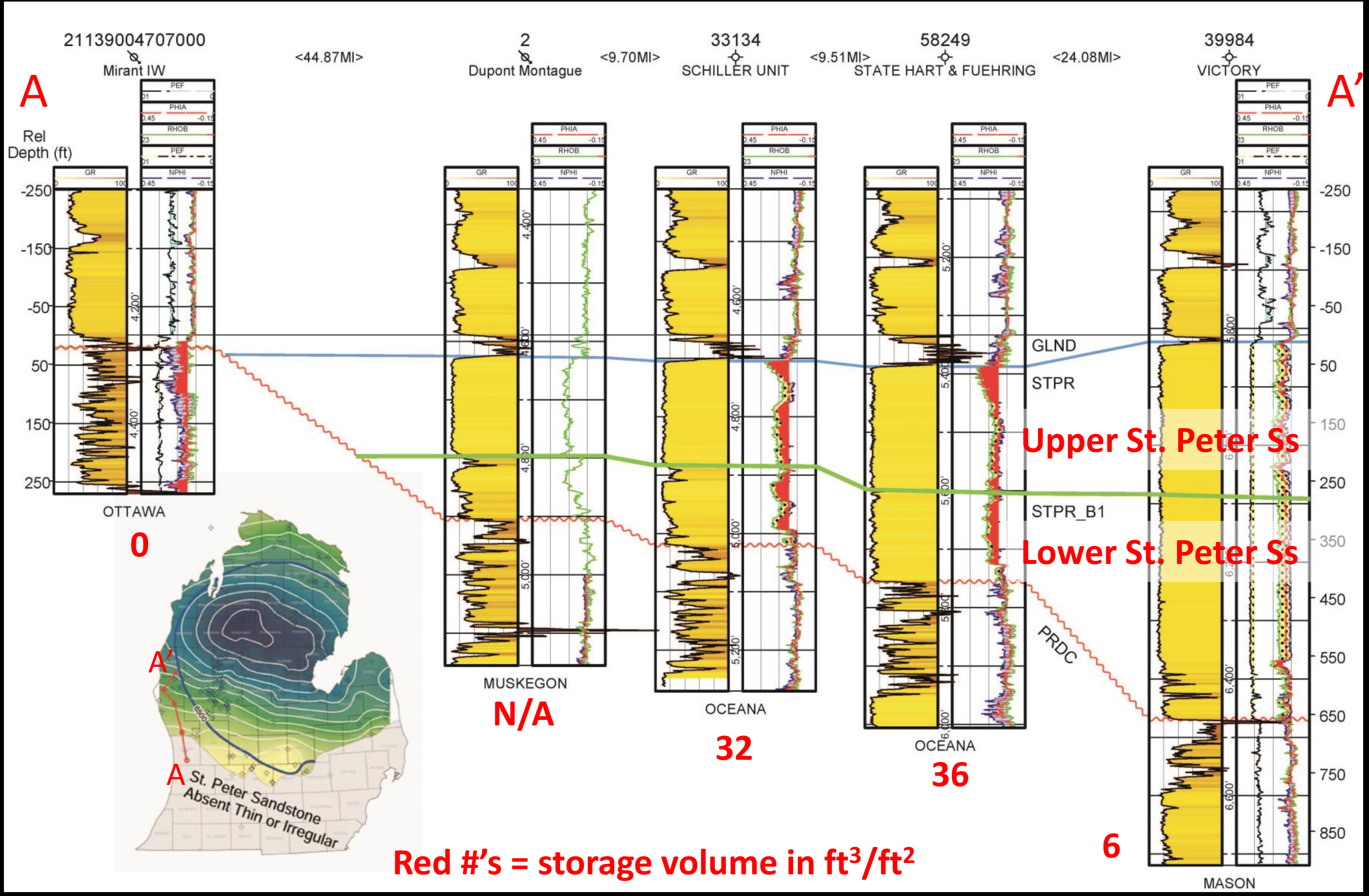


Ø-ft grid cell = km*km

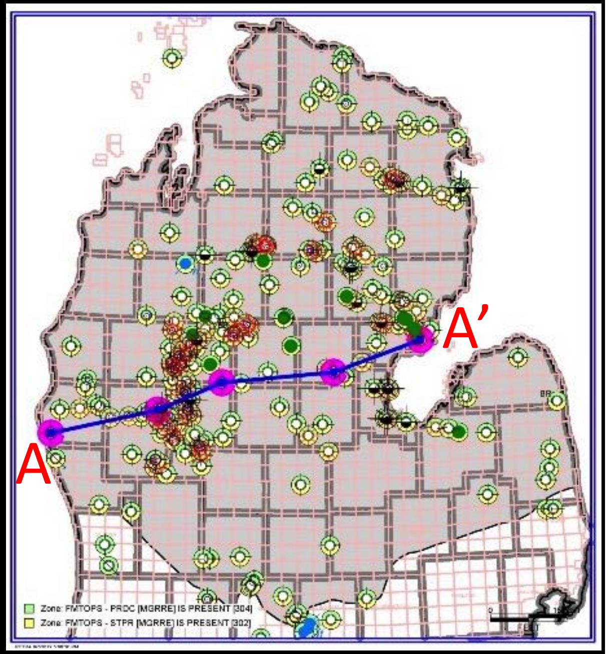


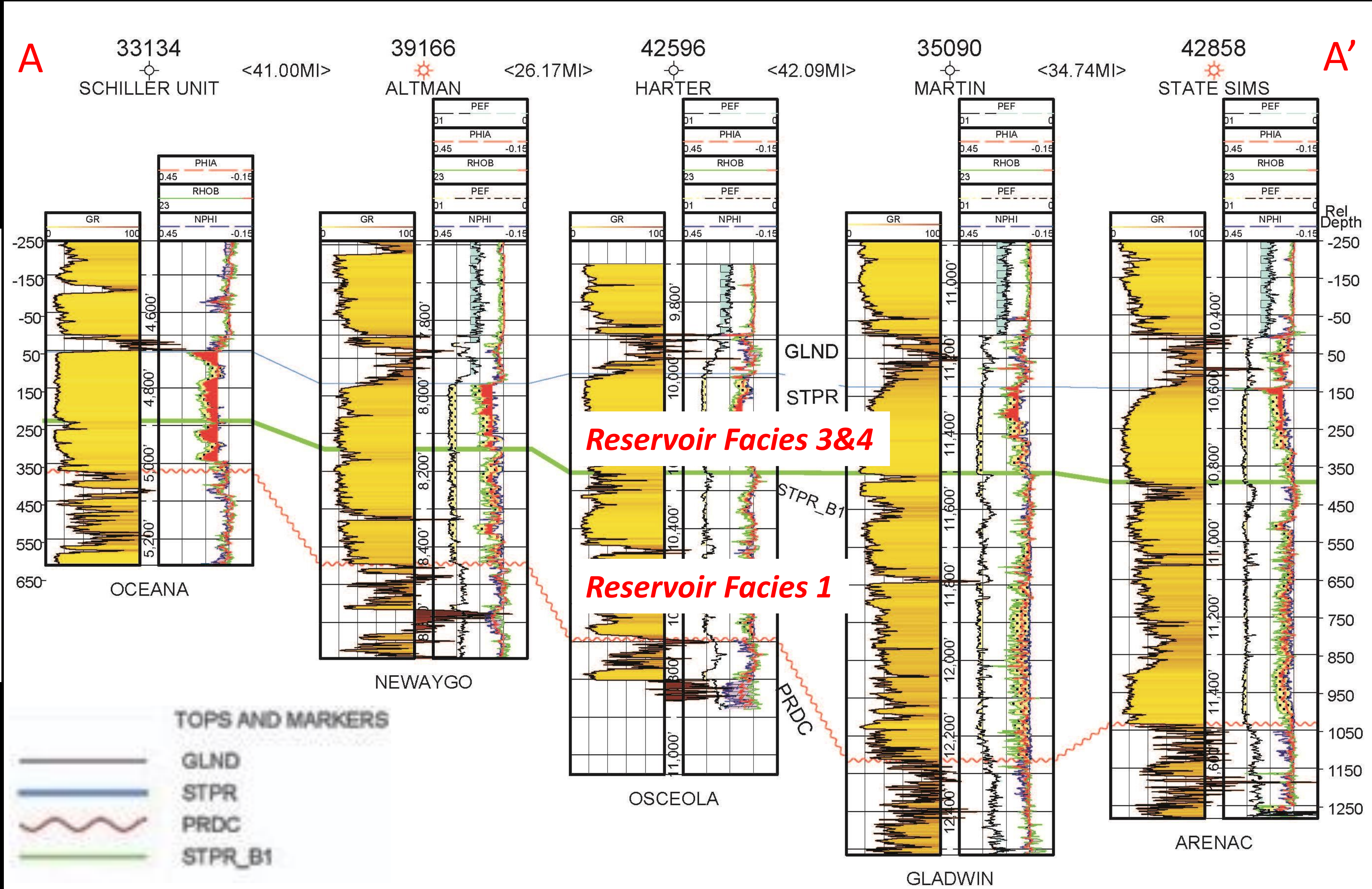
First Order Geological Controls on Reservoir Quality and the Spatial Distribution of CO_2 Storage Capacity

- Regional stratigraphic thickness
- Sedimentary facies trends
- Depth of burial-related diagenesis



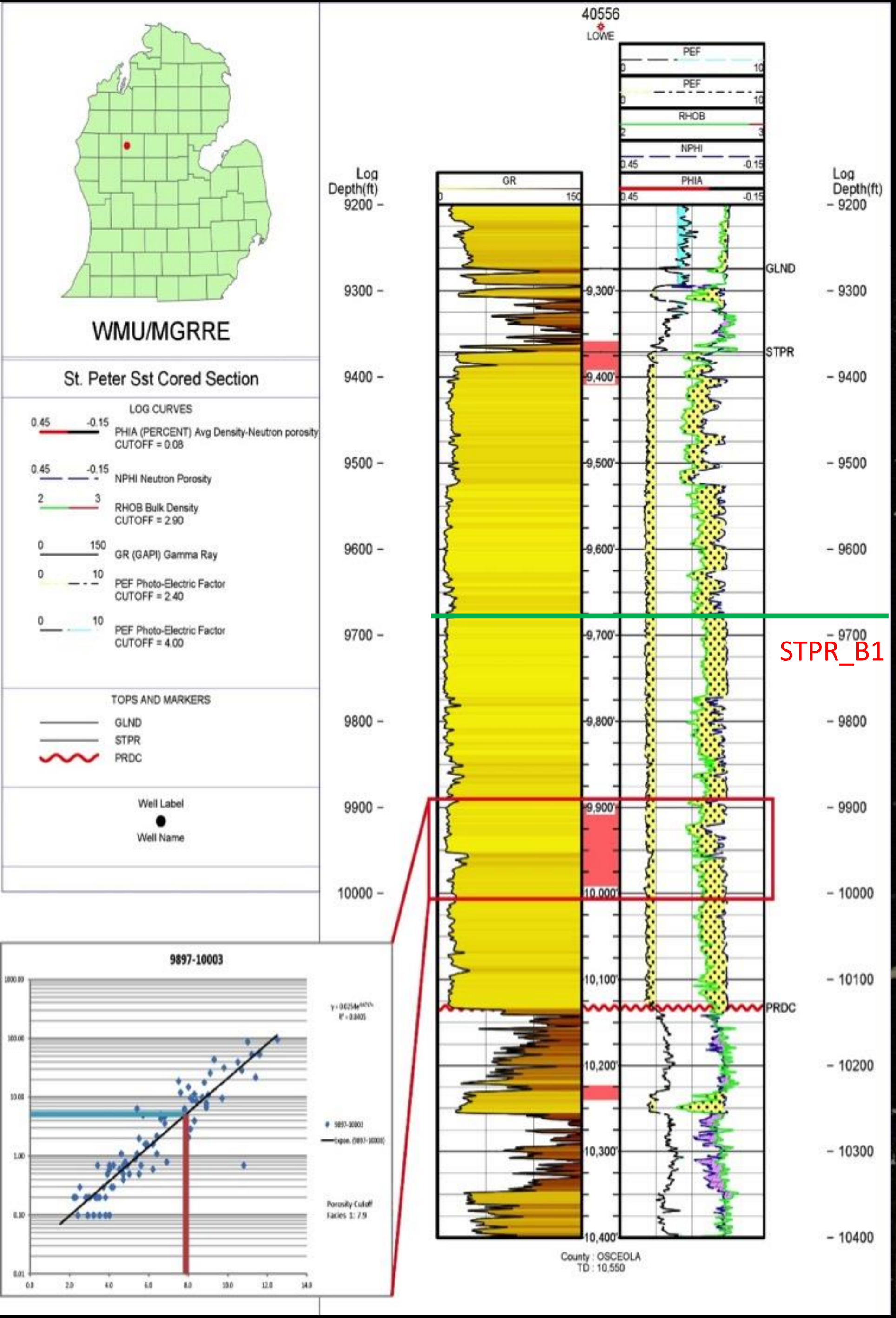
St. Peter Sandstone Regional Facies Variation



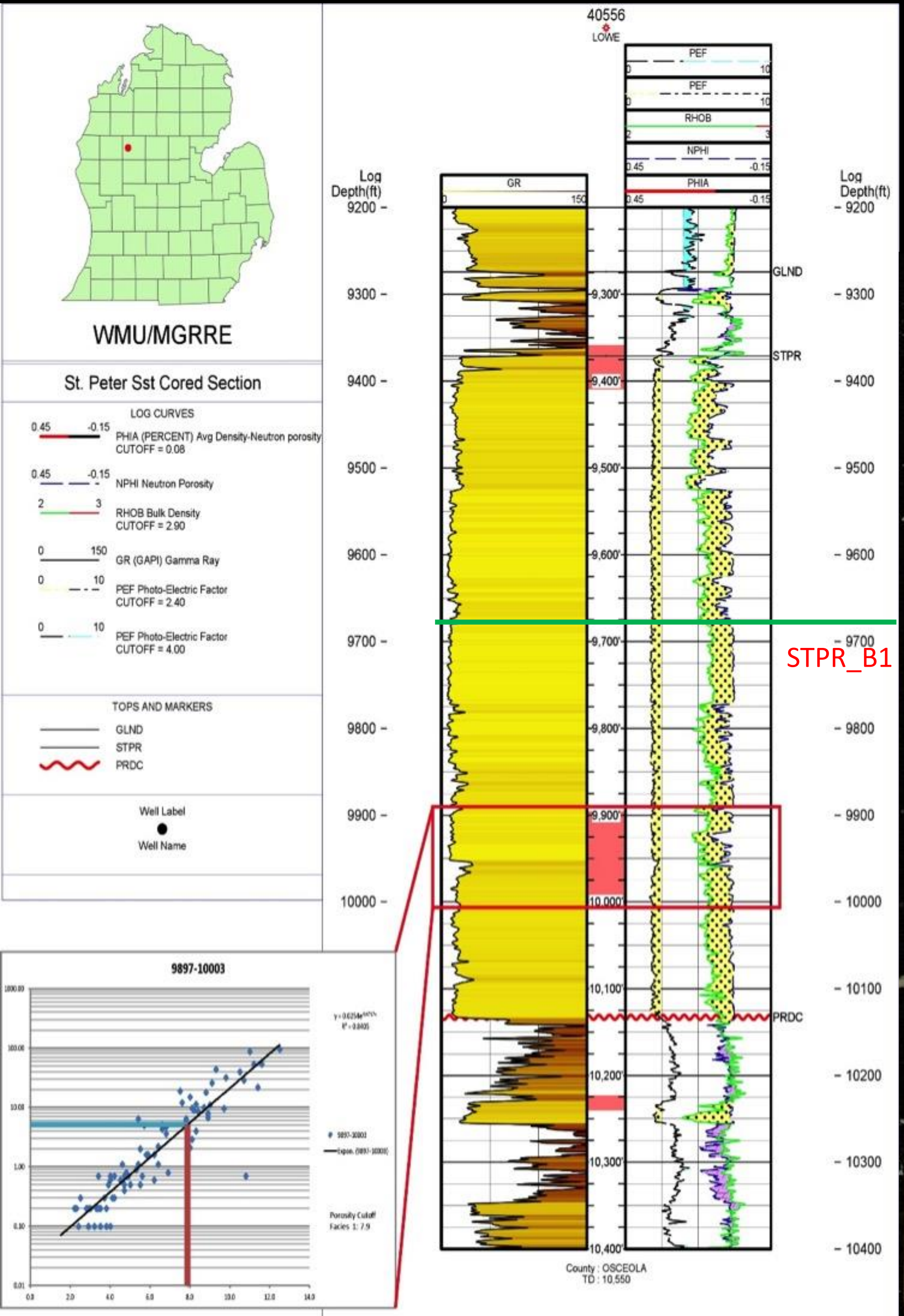


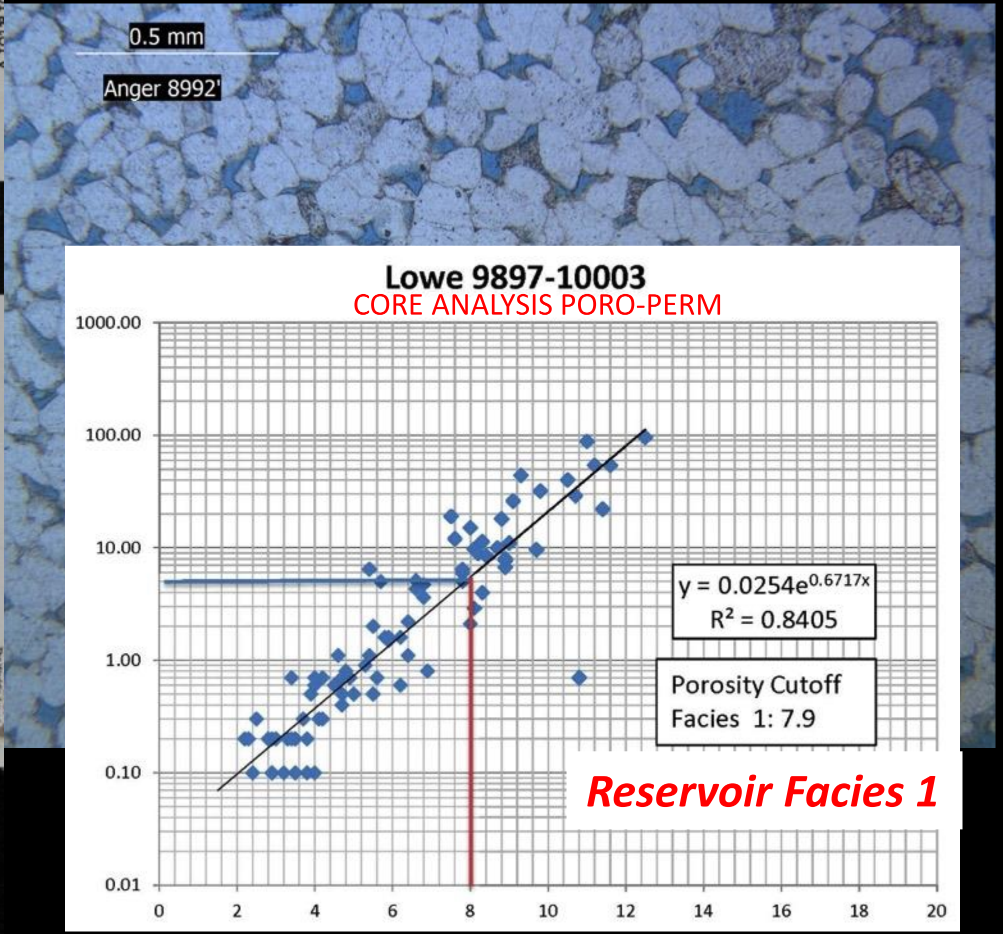
SRE *($GCO_2 = A_t*h_g*Ø_{tot}*\rho*\xi_{saline}$)* with Additional Data: Facies Controls on Reservoir Quality:

Lower St. Peter Ss



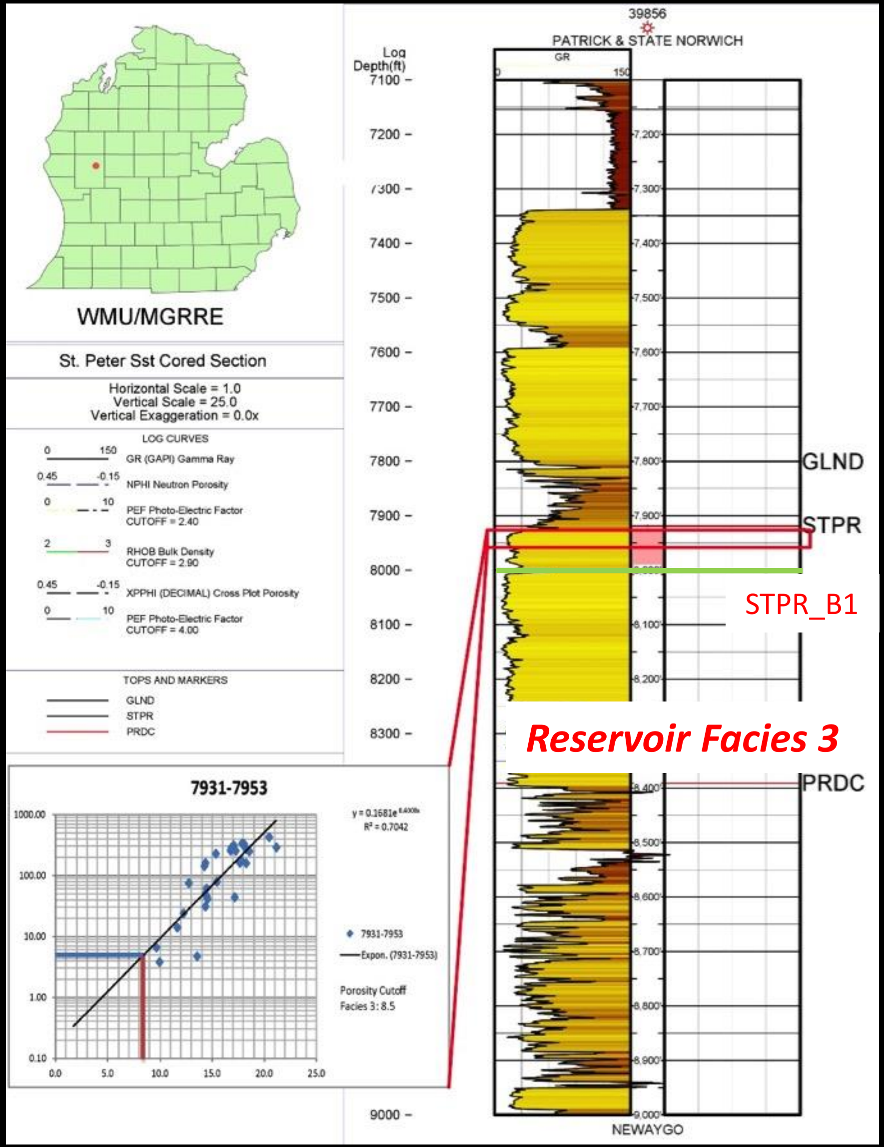
SRE *($GCO_2 = A_t * h_g * Ø_{tot} * \rho * \xi_{saline}$)* with Additional Data: Facies Controls on Reservoir Quality: *Lower St. Peter Ss*

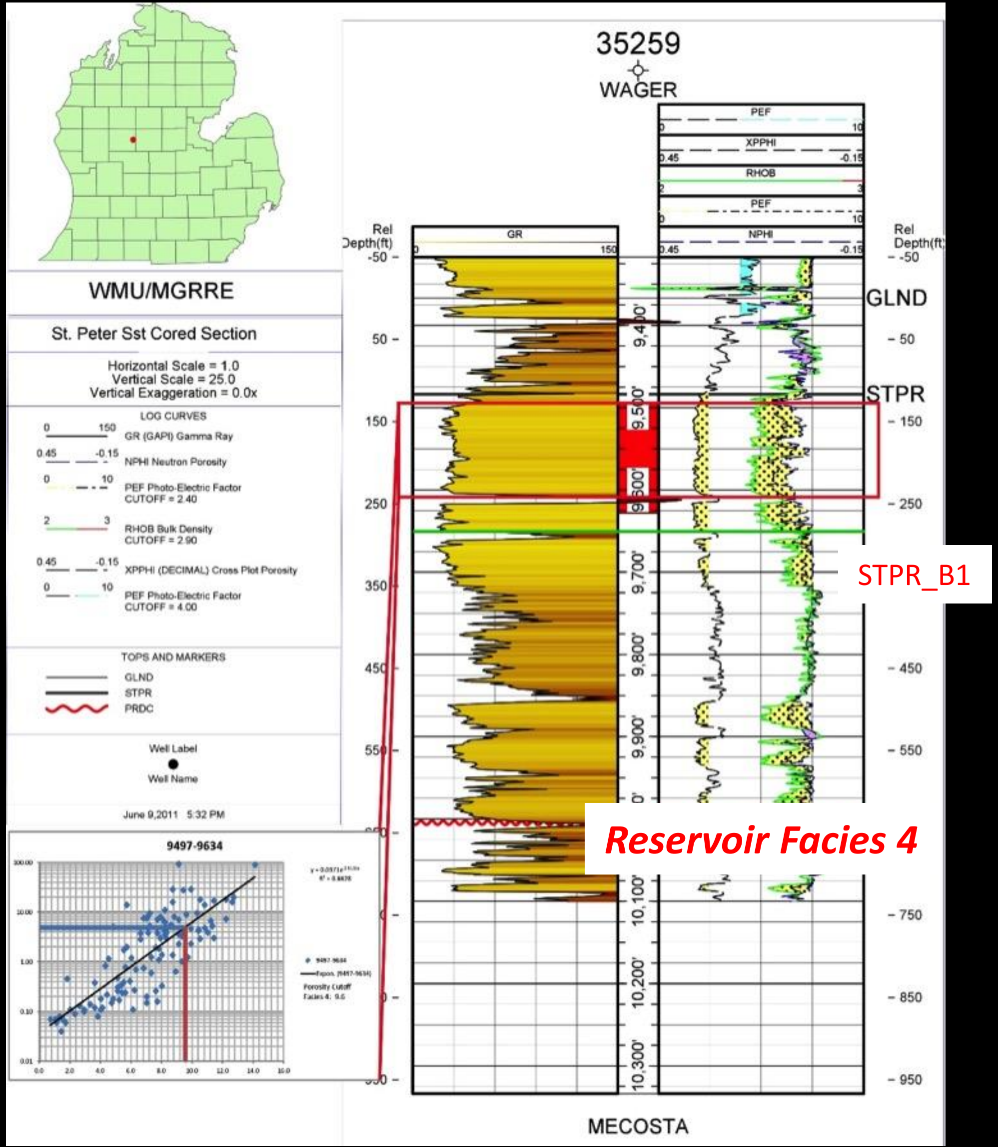




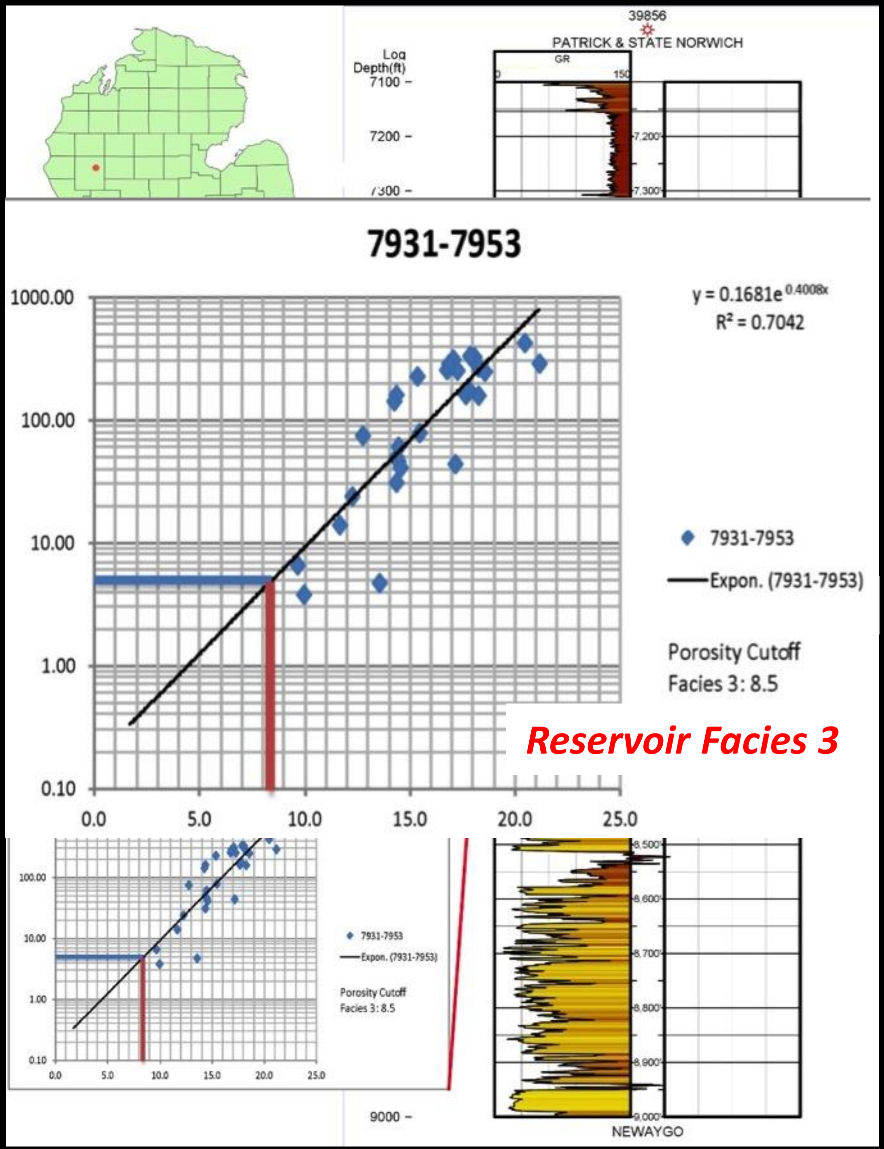
SRE $(GCO_2 = A_t * h_g * Ø_{tot} * \rho * \xi_{saline})$ with Additional Data:

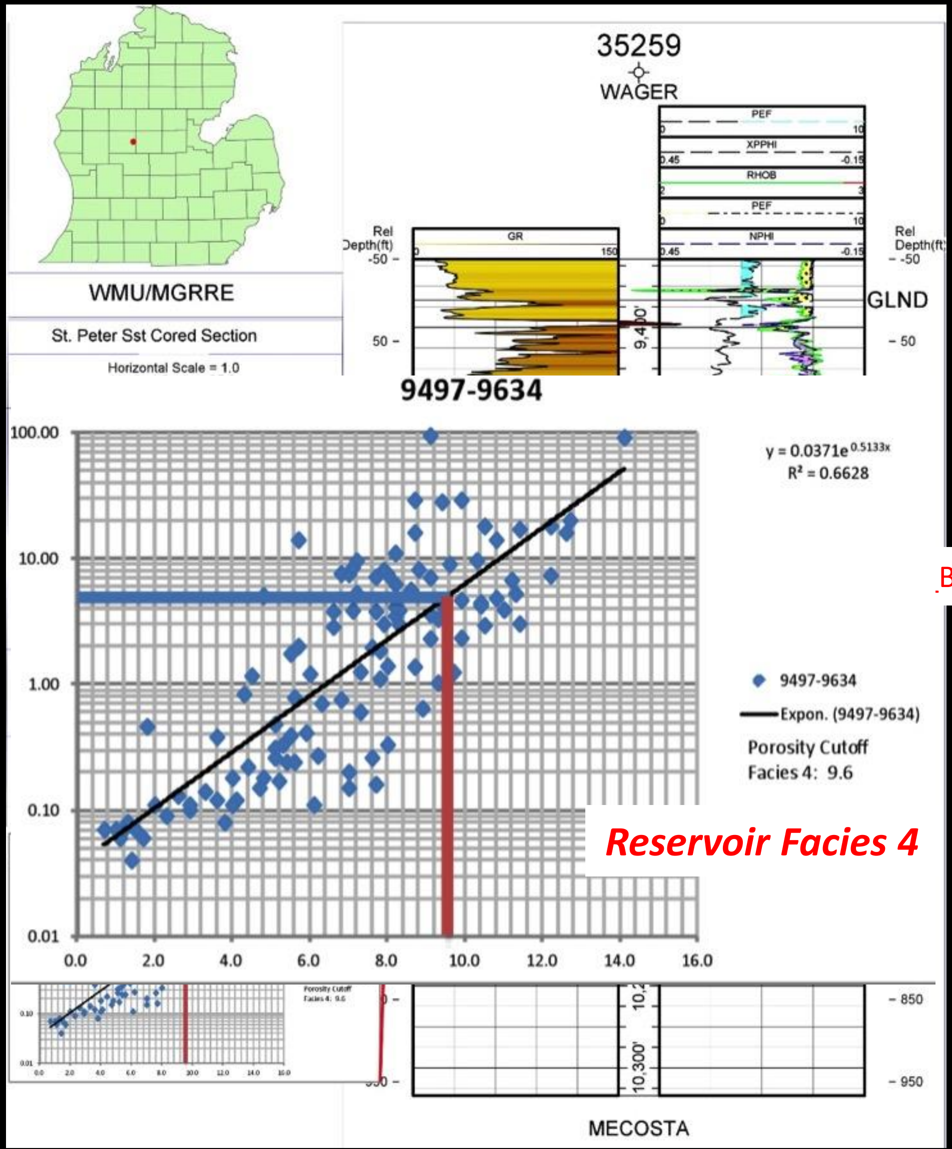
Facies Controls on Reservoir Quality: *Upper St. Peter Ss*





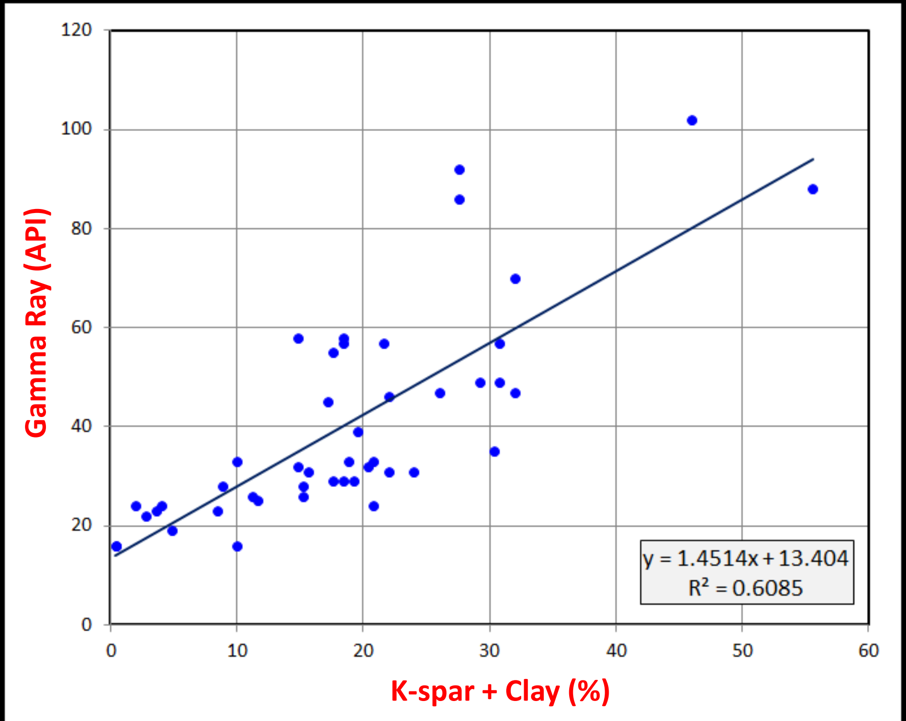
SRE *($GCO_2 = A_t*h_g*Ø_{tot}*\rho*\xi_{saline}$)* with Additional Data: Facies Controls on Reservoir Quality: *Upper St. Peter Ss*

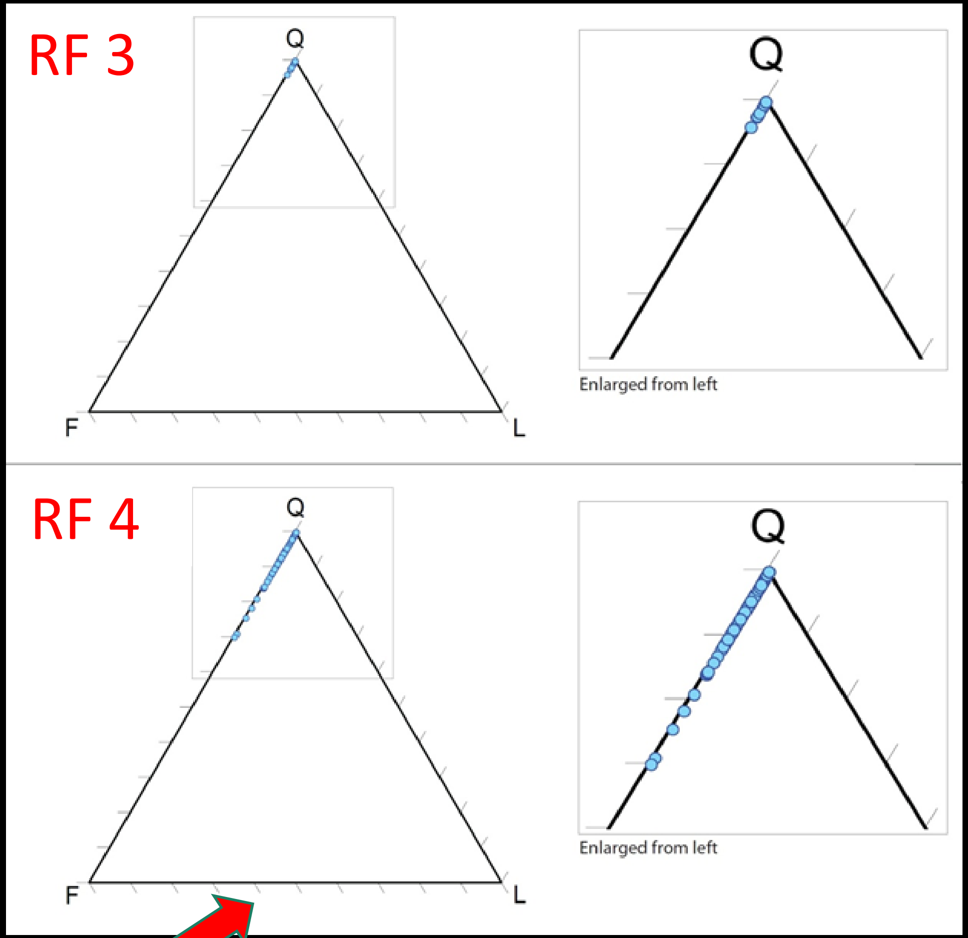




B1

SRE *($GCO_2 = A_t * h_g * Ø_{tot} * \rho * \xi_{saline}$)* with Additional Data: Petrologic Controls on Log Response; Reservoir Facies 3&4



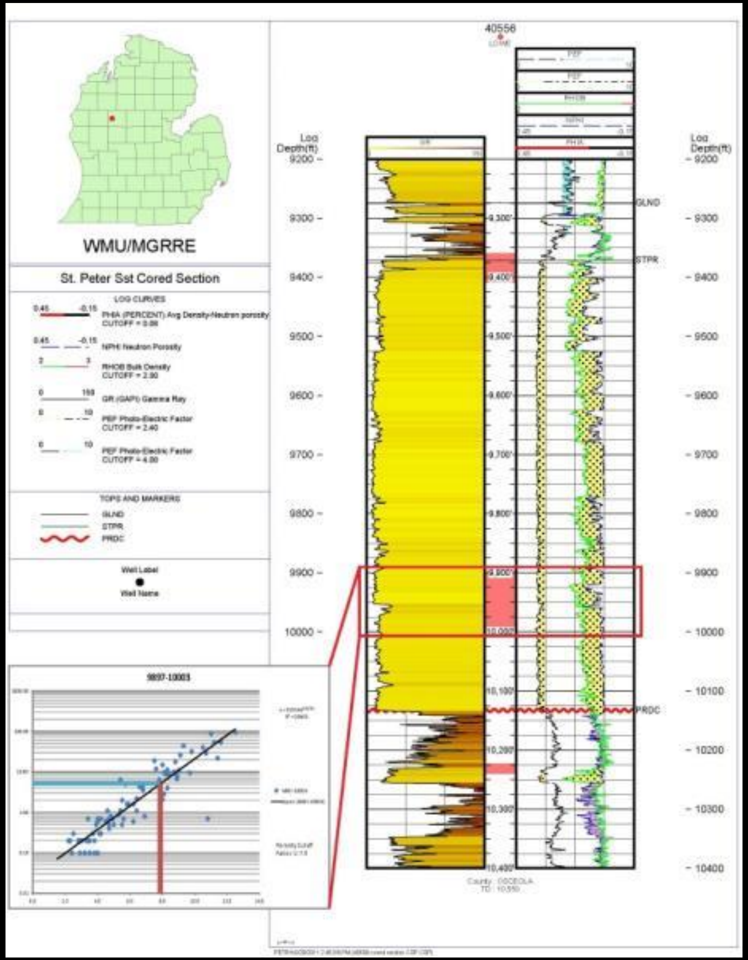


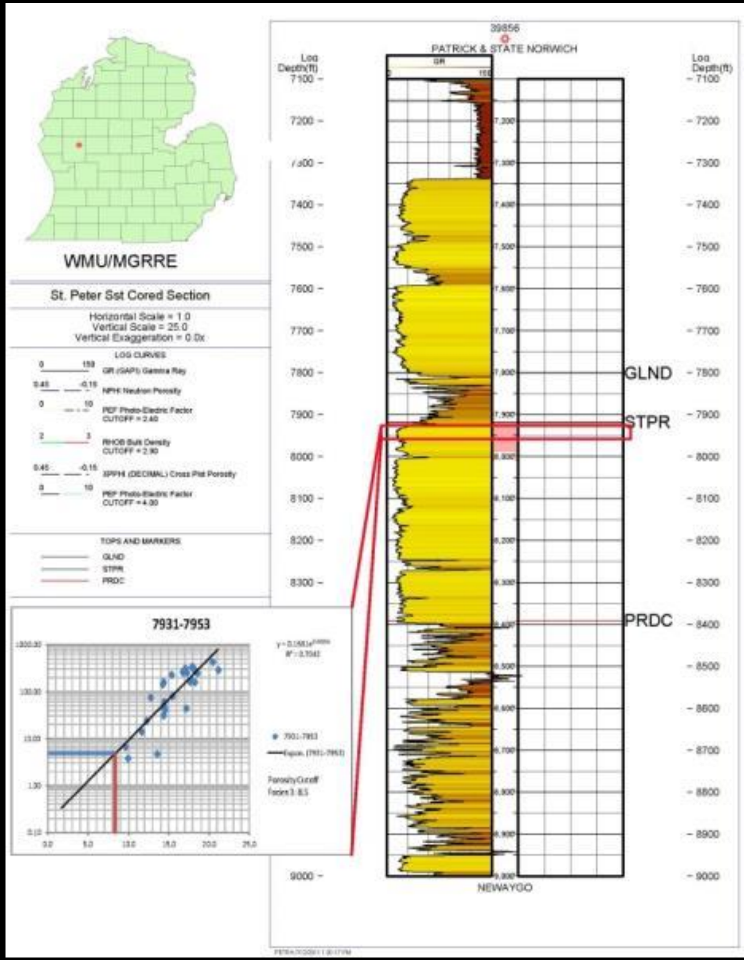
	Facies	Qtz	K-Feld	Dolo	Qtz-Og	Clay	Glauc	Collo	Pore	Cment total	Detrital	Minus Cement Porosity
Average	4	73.0	4.6	3.8	2.5	11.6	-	-	4.5	17.9	78.0	22.4
Stdv	4	8.1									8.0	8.0
Median	4	73.[illegible]									78.8	21.2
Average	3	84.8	0.9	0.0	4.5	5.4	-	-	4.4	9.9	86.0	14.3
Stdv	3	3.2	0.8	0.0	4.8	5.2	-	-	2.6	3.8	3.5	3.5
Median	3	84.6	0.2	0.0	3.6	3.8	-	-	4.2	9.4	85.0	15.0

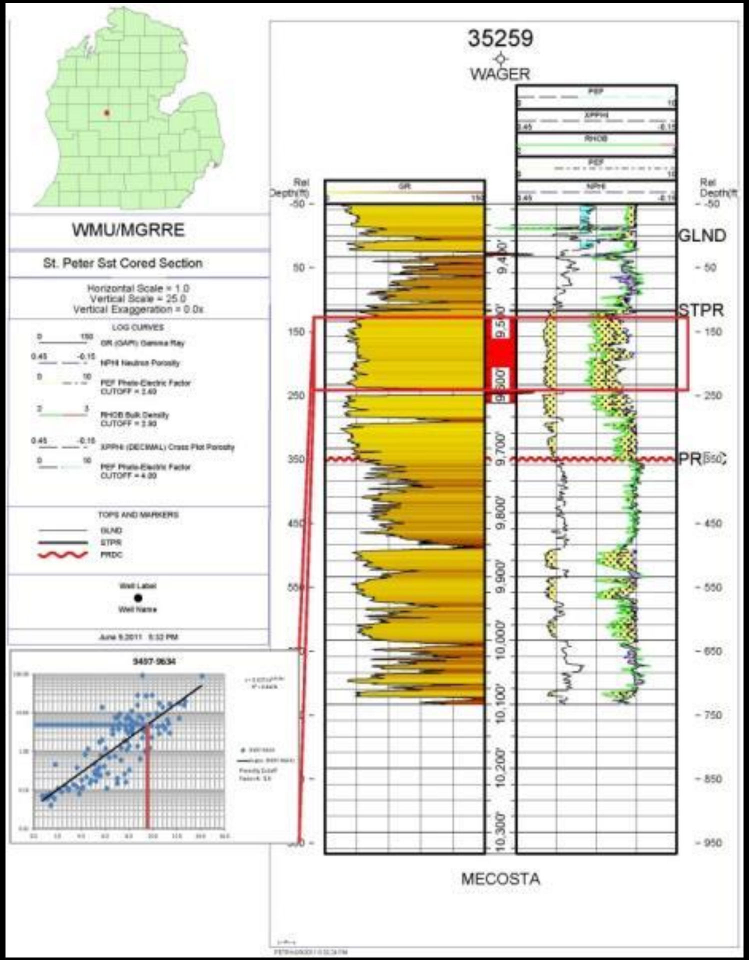
Petrographic Point Count

SRE *($GCO_2 = A_t*h_g*Ø_{tot}*\rho*\xi_{saline}$)* with Improved Knowledge:

Depositional Facies and Diagenetic Controls on Reservoir Quality

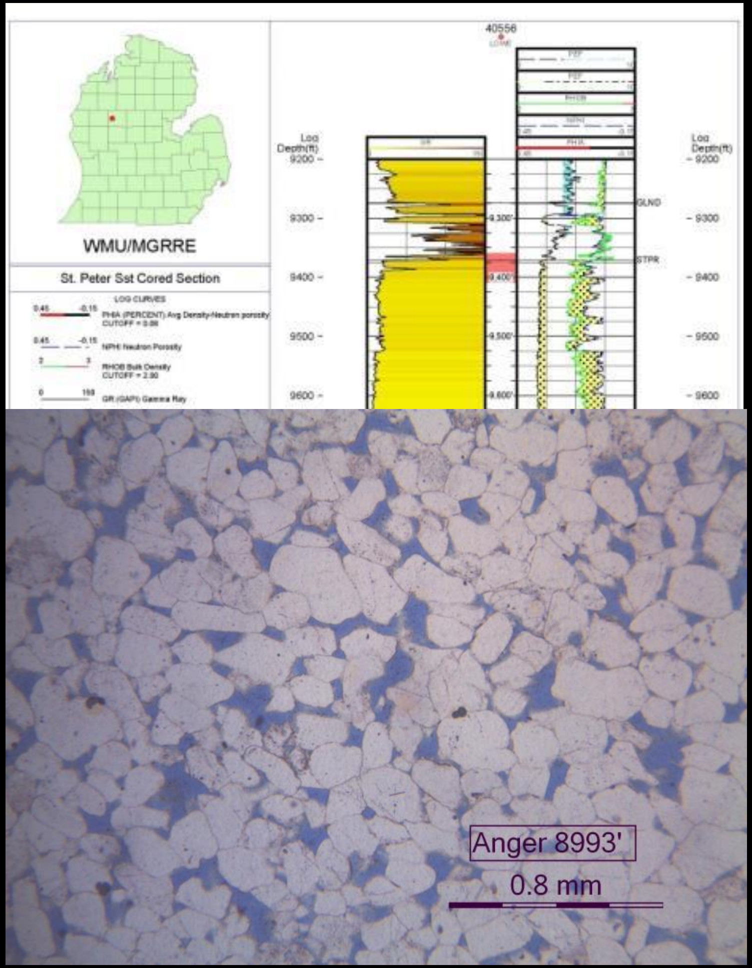




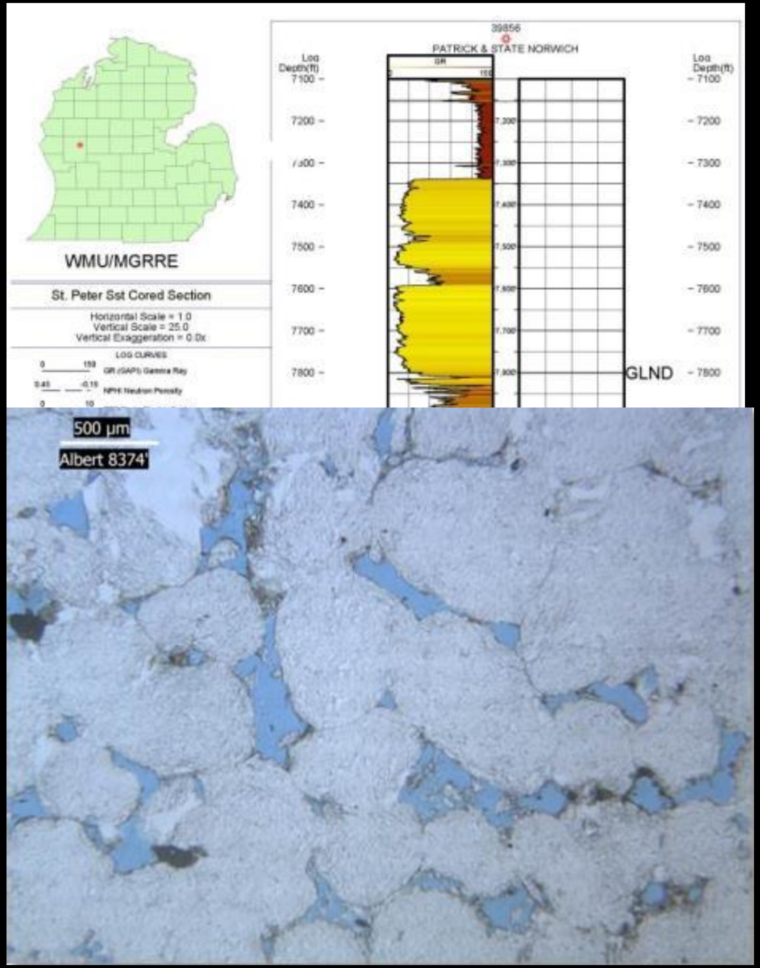


SRE $(GCO_2 = A_t * h_g * Ø_{tot} * \rho * \xi_{saline})$ with Improved Knowledge:

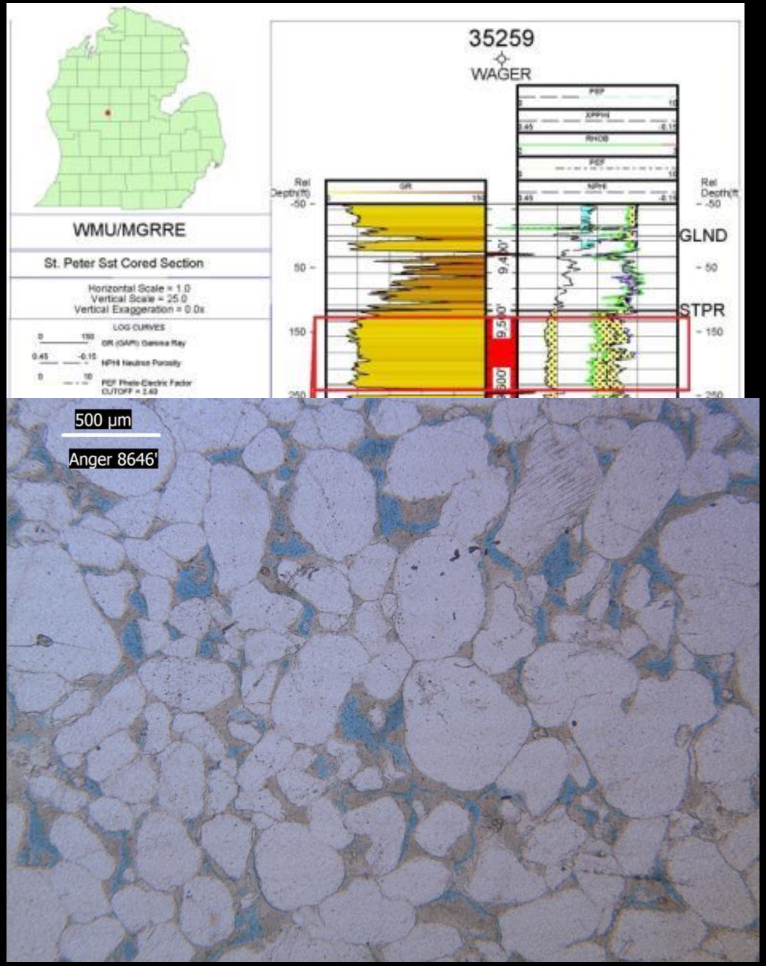
Depositional Facies and Diagenetic Controls on Reservoir Quality



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

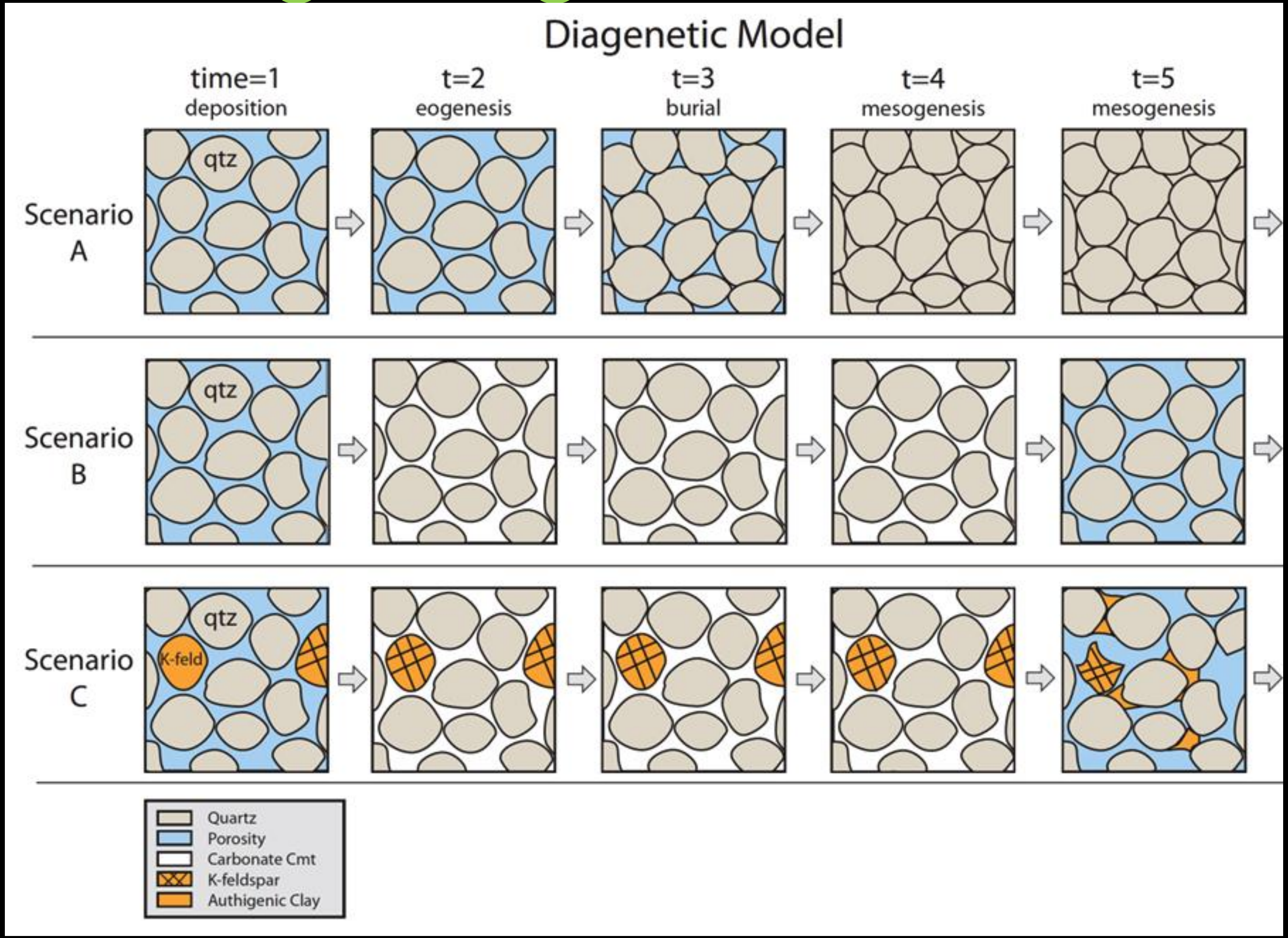


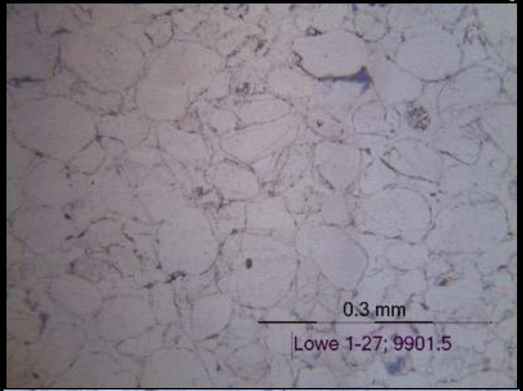
Reservoir Facies 3 Poro-Perm transform
5 md = 8.5% cutoff porosity

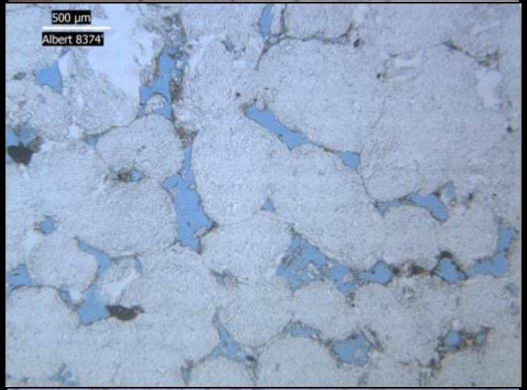


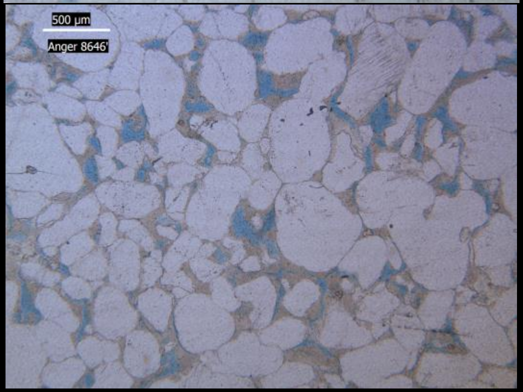
Reservoir Facies 4 Poro-Perm transform
5 md = 10.8% cutoff porosity

SRE $(GCO_2 = A_t*h_g*\O_{tot}*\rho*\xi_{saline})$ with Additional Data: Petrologic/Diagenetic Controls on Reservoir Quality

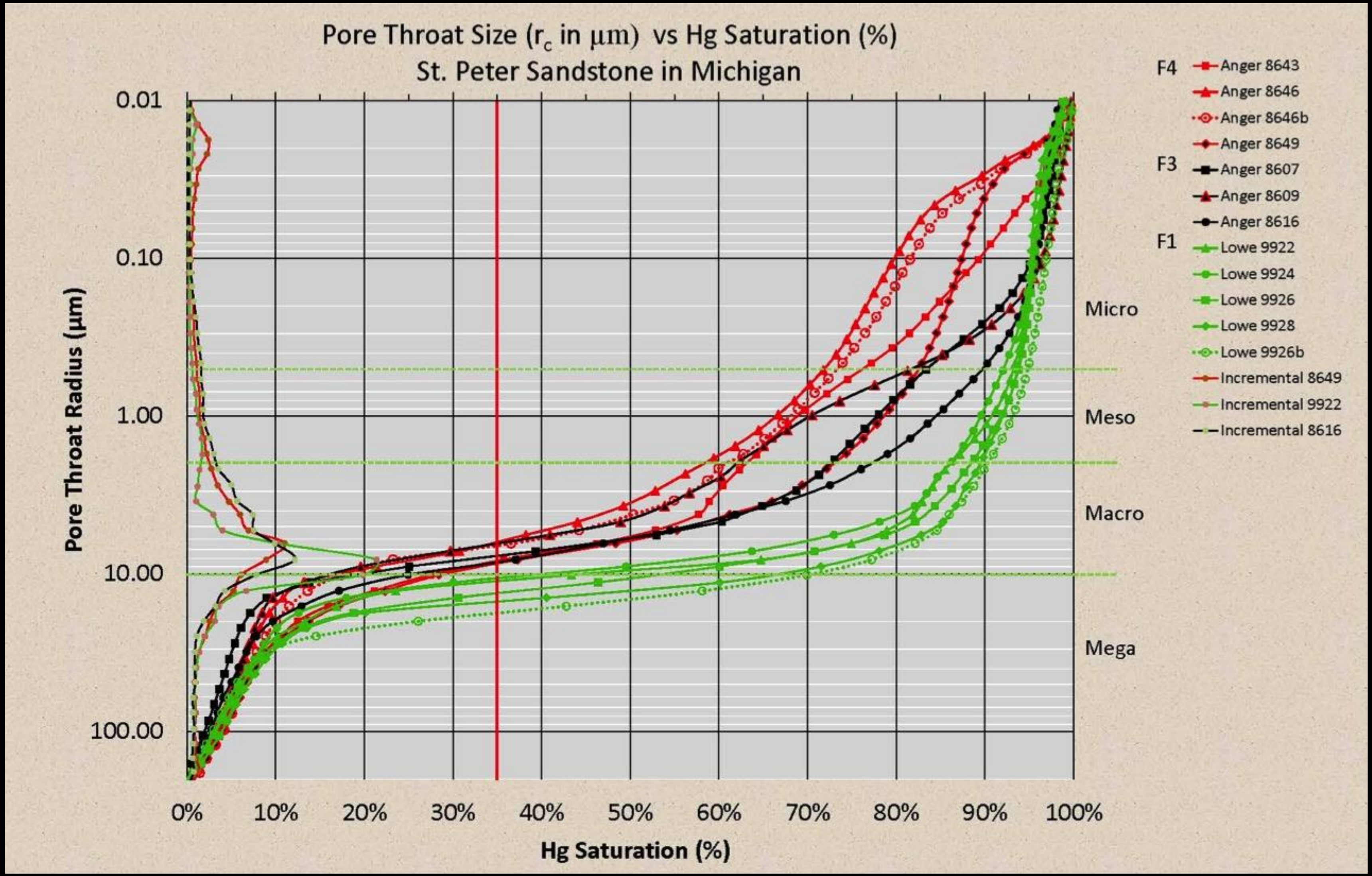








Reservoir Facies and MICP Characterization



Reservoir Facies 4; Poro-Perm transform
5 md = 10.8% cut-off porosity

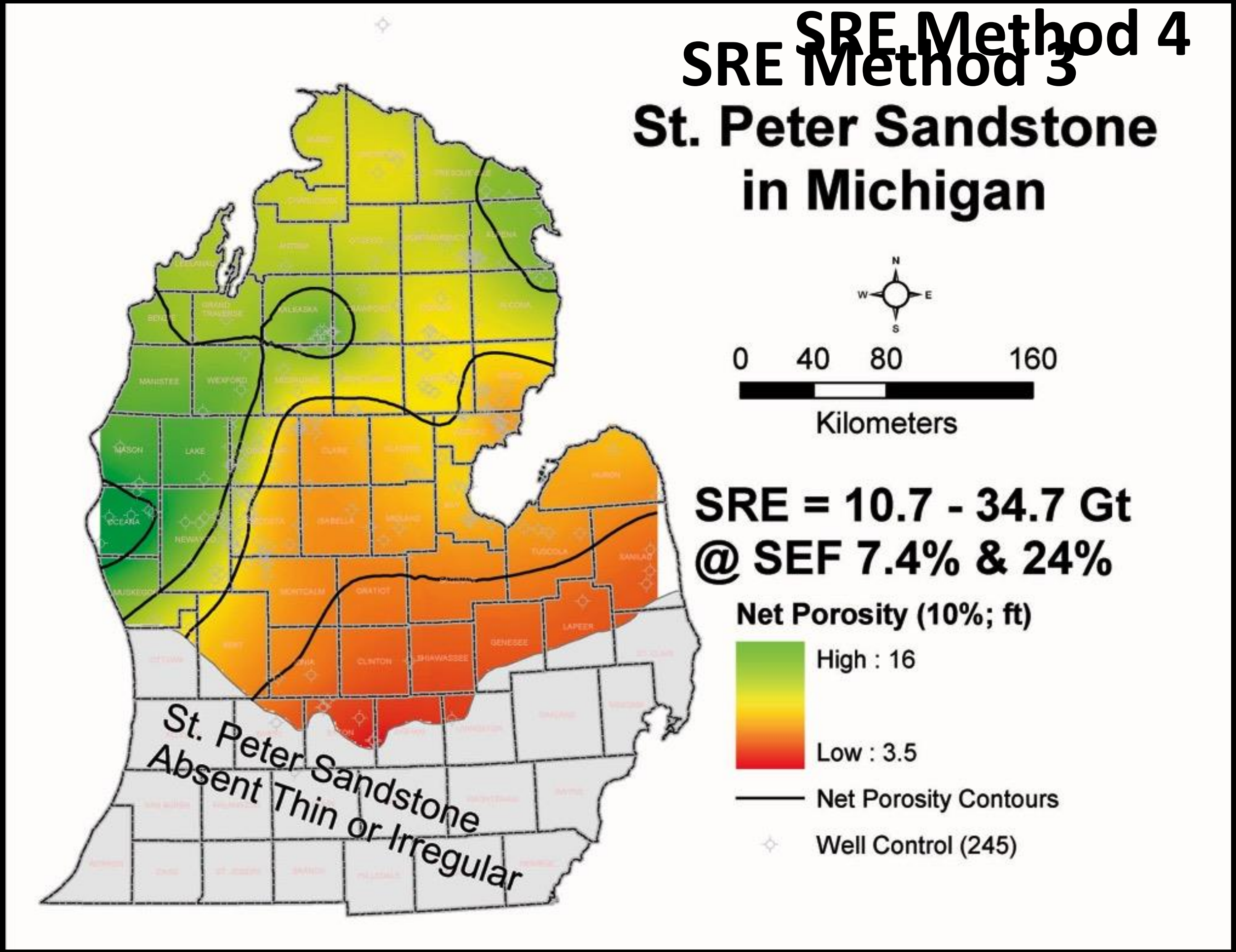
Reservoir Facies 3; Poro-Perm transform
5 md = 8.5% cut-off porosity

Reservoir Facies 1; Poro-Perm transform
5 md = 7.6% cut-off porosity

SRE $(GCO_2 = A_t * h_g * \O_{tot} * \rho * \xi_{saline})$ with Improved Knowledge:

Consideration of Depositional Facies & Diagenetic Controls on Reservoir Quality

Porosity cutoff from transform using core analysis (Ø & K) Cross Plots at 5 md Permeability				
Core Name	Well Permit #	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
Avg. Porosity Cutoff by r-f:		7.6% ϕ	8.7% ϕ	10.8 %ϕ
Std. Deviation		0.98	0.99	1.17
Min		6	7	9.6
Max		8.8	10	13.6



One Porosity Cutoff = 10.5%

Three Facies Porosity Cutoffs

SRE $(GCO_2 = A_t * h_g * Ø_{tot} * \rho * \xi_{saline})$ with Improved Knowledge:

Consideration of Depositional Facies & Diagenetic Controls on Reservoir Quality

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Hunt-Martin	35090	6	7	11.2
Lowe	40556	7.9		10.2
Patrick	39856		8.8	11
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State Garfield	45446	8.1		
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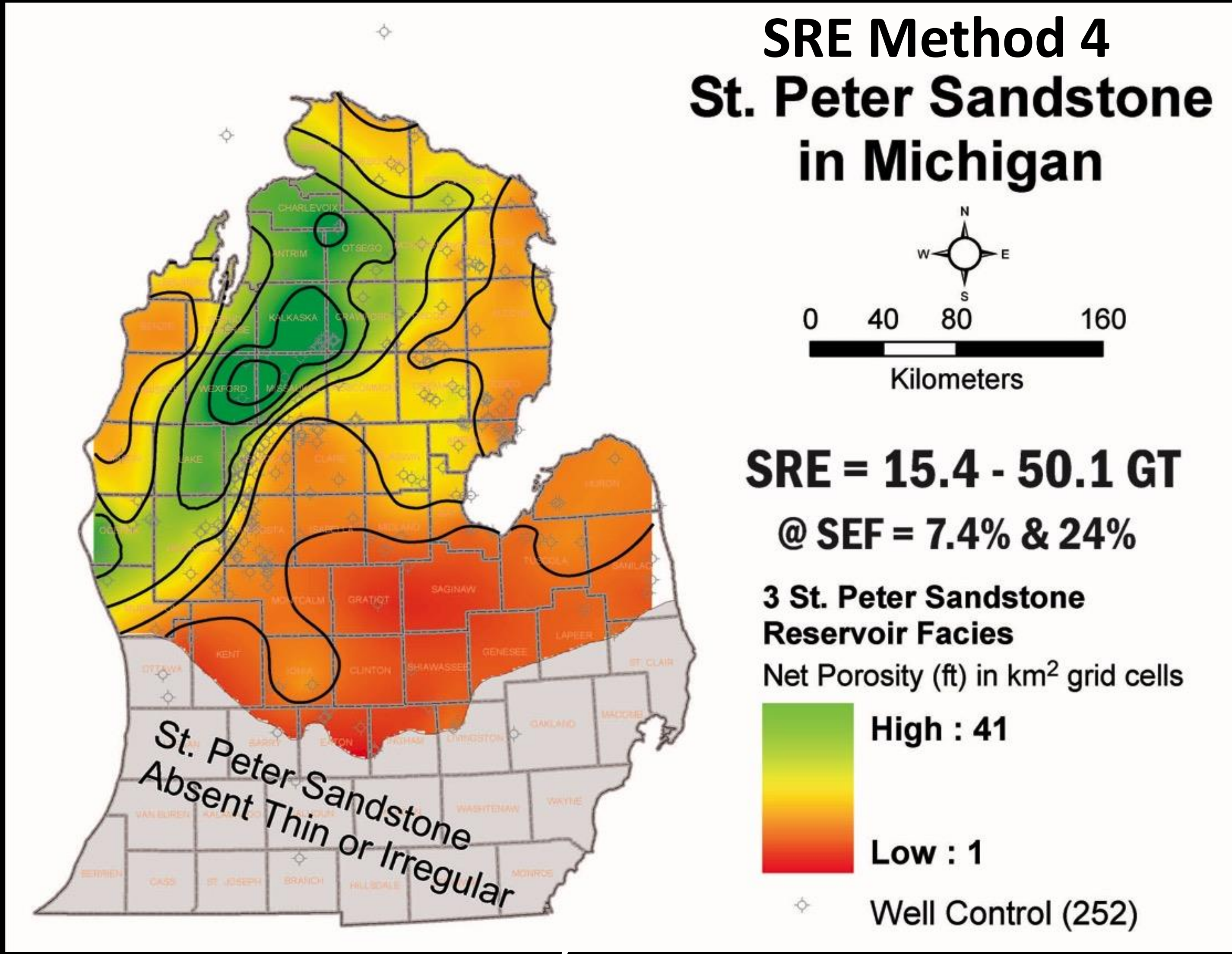
Avg. Porosity Cutoff by r-f:		7.6% ϕ	8.7% ϕ	10.8 %ϕ
Std. Deviation		0.98	0.99	1.17
Min		6	7	9.6
Max		8.8	10	13.6



Three Facies Porosity Cutoffs

Comparison: 4 SRE for the St. Peter Ss in Michigan

Including Enhanced Reservoir Characterization Techniques

Method	Method Description	MI CO2 Storage Capacity P10 Estimate (Gt)	MI CO2 Storage Capacity P50 Estimate (Gt)	MI CO2 Storage Capacity P90 Estimate (Gt)	Total Pore Volume (MI) in km^3
Method 1	Gross Isopach, constant porosity (6.7%), constant CO2 density (.737 ton/m3), ξ = 0.51 & 5.4% (from CO2 Atlas III for clastics)	3.3	13.0	35.1	881.2
Method 2	Gross Isopach, depth dependent porosity, constant CO2 density (.737 ton/m^3), ξ = 0.51 & 5.5% (from CO2 Atlas III for clastics)	3.0	11.7	31.6	793.0
Method 3	Net Porosity methodology (1 STPR cutoff value), constant CO_2 density (.737 ton/m3), ξ = 7.4% & 24% (from CO2 Atlas III for clastics)	10.7	20.2	34.7	196.0
Method 4	Net Porosity methodology (3 STPR facies in MI), constant density (.737 ton/m3), ξ = 7.4% & 24% (from CO2 Atlas III for clastics)	15.4	29.2	50.1	283.2

Conclusions:

- The St. Peter Sandstone in the Michigan basin is a major CO_2 storage reservoir with

15-50 Gt SRE (P10-P90); ~100-350 years of MI annual emissions

- This study supports substantial reduction in uncertainty in SRE related to:
  - Efficiency factors ($\xi_{saline,}$ sum of uncertainty) due to CO_2 displacement efficiency uncertainty only
  - Better estimates of total reservoir pore volume through:

High Resolution, Basin Scale Geological Characterization

- St. Peter Ss SRE are comparable to Mount Simon Ss in Michigan

(~40Gt, at P50) with very different spatial distribution

THANK YOU!