Narrative Report

Project summary abstract

Applicant: Western Michigan University

Project Principal Investigators: The principal investigator is Dr. David A. Barnes, and Dr. William B. Harrison is Co-Principal Investigator. Both are researchers at the Michigan Geological Repository for Research and Education (MGRRE), part of the Department of Geosciences, Western Michigan University, Kalamazoo, Michigan.

Project Title: Establishing MICHCARB, a geological carbon sequestration research and education center for Michigan, implemented through the Michigan Geological Repository for Research and Education, part of the Department of Geosciences at Western Michigan University

Project Objectives:
The primary objective was to establish MICHCARB, a geological carbon sequestration (GCS) resource center for Michigan at which:

1. Basic and applied research would be conducted,
2. Partnerships with industry, governmental agencies and education institutions would be established, and
3. Outreach programs for all stakeholders and the general public would be implemented to promote a better understanding of GCS.

MICHCARB was established at MGRRE in conjunction with the acquisition, inventory, and archival of subsurface geological samples and data relevant to geological carbon sequestration. A key work product is the generation of databases related to these data for use in GCS research. These statewide and site-specific digital research databases were developed for Michigan's deep geological formations relevant to CO2 storage, containment and potential use for enhanced oil recovery. All these data were compiled in a digital atlas. Researchers at MGRRE conducted basic and applied research using these data and analyzed Michigan's oil and gas and saline reservoirs for CO2 storage potential volume, injectivity and containment. They also took advantage of opportunities to gather new data, primarily from the oil and gas industry, as it became available. MGRRE researchers addressed specific predictive uses of CO2 storage and enhanced oil recovery through the preliminary application fluid-flow models using these data. MGRRE researchers presented workshops for industry and governmental agencies in order to conduct technology transfer to these stakeholders. They also conducted meetings for the general public. Partnerships were forged with Geo-resource industries, energy utility companies, State and local governments, K-12 classrooms and teachers. MGRRE created education materials including physical demonstration models, classroom exercises, and displays that can be used in outreach and education events and by stakeholders for in-house use.

Potential benefits and outcomes of this work
The potential benefits and outcomes of this work include: evaluation of the potential to use carbon

capture and geological sequestration (CCGS) to reduce the negative environmental and economic impacts of global warming by reducing industrial, point source CO2 emissions; cost-effectively developing GCS technology and safety measures that can be transferred nationally; assisting Michigan's citizens, government and industry members to better understand not only the science behind GCS, but also its practicality and safety; acquisition of new geological data, leading to a greater understanding and use of subsurface geological resources and a positive impact economic impact; and increasing domestic oil and gas production through enhanced oil recovery resulting in a positive economic impact and reducing America's dependence on foreign oil and gas.

Project Objectives and Resulting Achievements

A) Establish a geological carbon sequestration resource center for Michigan at the Michigan Geological Repository for Research and Education (MGRRE), part of the Department of Geosciences at Western Michigan University (WMU) at Kalamazoo, Michigan:

1. *Archive and maintain a current reference collection of carbon sequestration published literature.*

   Extensive digital and paper archives of published articles have been accumulated at the MGRRE facility for MICHCARB, These references are available to the public or for researchers.

2. *Develop statewide and site-specific digital research databases for Michigan's deep geological formations relevant to CO2 storage, containment and potential for enhanced oil recovery.*

   Enormous collections of cores, cuttings, wireline logs and well records were acquired, including the State of Michigan's entire collection of drill cuttings from wells throughout the state, accumulated over a thirty-year period, representing about 25,000 wells. Acquisition and cataloging of cores was accomplished from several gas storage fields in Michigan (previously held by private industry). We received five semi-truckloads of cores obtained from the oil and gas industry that had been previously stored in Texas, representing formations of particular value to research in carbon sequestration and CO2-enhanced oil recovery such as the Niagaran, Glenwood, St. Peter and Prairie du Chen formations. We acquired drill cuttings from over 100 deep wells that had been stored in Kansas and help define the basic geology of the deeper formations that have CO2 storage capacity. We have received an extensive set of wireline logs used in research at another university, representing about 18,000 wells which help define the stratigraphy and reservoir quality throughout the Michigan basin. We added several collections of shallow bedrock cores that had been held by the Michigan Department of Transportation (MDOT) that will help define the near surface geology around the state. We received digital data from thousands of mineral well files from the Michigan Department of Environmental Quality (MDEQ) that contain additional valuable geological information. Finally, as part of our conversion of paper records to digital files, we have more than1800 paper mudlogs which were scanned and entered into databases.

Additionally, several quality control issues were dealt with so as to assure that the available data was at its most useful, including re-boxing and conserving cores and cuttings, which were at risk because of previous damage and degraded packing. We organized thousands of wireline logs and properly identified the types of data recorded and checked the identity of the wells represented against all public databases and corrected errors. Data from more than 2,000 paper records of core analyses were hand entered to make these data (largely porosity and permeability) digitally usable. To allow digital access to thousands of mineral well file records, we converted the scanned images to pdf format and used optical character recognition to create a searchable dataset. The entire collection can now be searched for key words relating to lithology, geological formations, fluid characteristics or any other technical category that would appear in the records. We have compiled and merged data from all our on-site collections with datasets maintained by the Michigan Department of Environmental Quality (MDEQ). This work involved combining and curating data in one relational database including 63,302 wells and we have formatted all data for use in subsurface data analysis software (IHS Petra).

3. *Produce maps and tables of physical properties as components of these databases*

   Examples of maps generated in this project are shown below in the research report section.

4. *Compile all information into a digital atlas*

   Extensive digital data about various formations in the Michigan basin are reported in the research report section.

B) Conduct geologic and fluid flow modeling to address specific predictive uses of CO2 storage and enhanced oil recovery, including:

1. *Compile data for geological and fluid flow models*

   We investigated methodology used by the Illinois EPA for injection test analysis. Hydrogeological data generated from deep waste injection wells was found useful to determine the potential for a saline aquifer to accept injected CO2. Pressure fall-off test (PFT) data and can used to make inferences about the size of an aquifer/reservoir or to quantitatively describe the hydraulic conductivity of an aquifer/reservoir. We cataloged PFT data according to its utility, which is dependent on the rigor in which the data was collected. The data that is of lower quality can be used to make inferences about reservoir compartmentalization and the best data can be used to calculate the hydraulic conductivity of aquifers. We made scale and injectivity inferences from PFT analyses about important CO2 injection targets. Analysis was conducted for two saline aquifer injection targets in Michigan: the Mount Simon Sandstone and Sylvania Sandstone formations, from 25 wells with approximately 60 discrete test data sets. We obtained academic licensing for Fekete FASTWELLTEST reservoir engineering software for injection-PFT test /Pressure Transient Analysis.

2. *Deploy static and dynamic, numerical simulation models for evaluation of geological*

sequestration reservoir and confining layer formations, integrate appropriate data, and conduct preliminary runs of the models

We have compiled subsurface saline reservoir data and generated new data for static reservoir and injection simulation model parameter values as input for Schlumberger *Petrel*, PNNL *STOMP-WC,* and CMS *GEMS* software application suites. Most subsurface geological data for static reservoir and injection simulation modeling has been compiled for the Devonian Sylvania Sandstone and the Mount Simon Sandstone formations in Lower Michigan. We developed geostatistical (static geological) models for several areas of interest to pattern and interpolate important subsurface fluid flow variables such as permeability and porosity. We have acquired academic licensing for and student researchers are exploring the relative merits of SGeMS (Stanford Geostatistical Modeling Software), Schlumberger- *Petrel* geological modeling software, and CMG *GEM* (academic license). Recent simulations are far more realistic and successful than initial efforts as a result of the integration of more comprehensive and quantitative geological and petrophysical input parameters. We now have a better understanding of the relative importance/need for accuracy of simulation input parameters. Substantial work was done to augment incomplete documentation of the STOMP-WCS software. The Pacific Northwest National Laboratory scientists/software developers have been extensively consulted to fill in significant gaps in software documentation. Our research group is now mostly using Schlumberger *Petrel* and CMG *GEMS* software platforms and work is ongoing.

3. *Apply models to specific predictive uses of CO2 storage and enhanced oil recovery*

Our research group acquired data from 27 waste disposal wells from the State Department of Natural Resources and Environment (MDNRE). The State requires annual injectivity tests for continued well use. These tests yield pressure fall-off data that is very useful to determining CO2 sequestration potential. The data address the ease which fluids can be injected into a reservoir and the degree to which local boundaries impede injectivity/fluid flow. Several of these wells injected fluid into the Mt. Simon and Sylvania formations, our two primary targets. Data from these wells were analyzed.

Dr. Duane Hampton supervised students who conducted modeling research using Stomp-WC software. One of these students, Tony Clark, prepared a paper for the 2010 Carbon Capture and Sequestration Conference. The paper addressed the sequestration potential of the Sylvania Formation. Mr. Clark worked with the second student, Farsheed Rock, who has done the geological characterization work. Mr. Clark input Mr. Rock's data into Stomp. Mr. Rock's data were derived from wireline logs (neutron porosity, gamma ray, and bulk density) and some rock samples from Sylvania wells.

He also worked with student Farsheed Rock who calculated the location for 12,687 mineral wells from footage and/or location descriptions given by Township, Range, Section, and quarter location, adding that data to the MRCSP Master Project. Rock also hyperlinked spreadsheets of 1964 core analyses to the Master Project for easy access.

Together with several graduate students, Dr. Hampton analyzed pressure falloff tests for class I injection wells in Michigan in the Sylvania and Mt. Simon formations; produced various analytical injectivity simulation models for the Sylvania Sandstone Formation in Michigan; and co-presented a poster with Farsheed Rock and Tony Clark on Reservoir Characterization and CO2 flow modeling of Sylvania Sandstone at 9th Annual Conference on Carbon Capture and Sequestration.

Dr. Hampton acquired new modeling software, including Petrel, ECLIPSE, and GEM, which became the main modeling software.

Students Clark and Rock presented a paper at the Eastern Section meeting of the AAPG entitled: Numerical Simulation of Carbon Sequestration in the Sylvania Sandstone.

Dr. Hampton worked extensively with students Amy Manley and Nick Bull in developing computer models for simulating supercritical CO2 injection and the geomechanical effects of injection. The main program we used was GEM from CMGL. Many different modeling scenarios were carried out. Their work included:

- Simulate a specific injection site in the Mount Simon saline aquifer to determine the injection pressure limits to avoid breaching the confining Eau Claire formation or otherwise inducing failure. For this geomechanical simulation a location near Holland, Ottawa County, Michigan, was chosen. Multiple model scenarios were created and studied. All models assume dual permeability of the formation. This allows the models to have permeability values for the formation and for any fractures rather than the formation alone. Each simulation covered 15 years, with CO2 injected during the first ten.
- Various supercritical CO2 injection rates ranging from 10,000 ft3/day to 2,000,000 ft3/day were modeled. Injection well perforation depths and lengths were varied. Perforations were located just below the cap rock layer, just below the upper Mount Simon and also at the bottom of the middle Mount Simon layer. Several rock strength parameters were tested for sensitivity as well. Variable cap rock thicknesses were simulated. The default boundary conditions which were applied to all models constrained both the bottom and sides of the grid leaving only the top to move freely in space.
- All the simulations used the Barton-Bandis model for the Eau Claire cap rock layer. The Barton-Bandis model allows for fracture permeability to be computed from effective stress in GEM.
- The first model is based on a 3D model created using Schlumberger's Petrel with permeability and porosity values obtained from the wells in Ottawa County. A second model was created in 2D also using permeability and porosity values obtained from the wells in Ottawa County. The third and fourth models were homogenous (or "layer cake") models with single permeability and porosity values for each of three layers: Eau Claire, Upper Mount Simon and Lower Mount Simon. These models were 2D and 3D. These latter model studies included sensitivity analysis of permeability values in the Eau Claire.
- When up scaling the original Petrel Mount Simon model, maximum permeability was used for the up scaled grid blocks. Although this likely represents reality, it was not ideal when attempting to break the cap rock. Breaking the cap rock was not seen in these models. However, leakage was shown in all scenarios. Leakage is considered failure, because CO2 is entering the Eau Claire cap rock layer. Where permeability is heterogeneous and distributed naturally, leaks occur rather than breaks.
- The timing and amount of CO2 leakage depended on many variables. Injection rates, heterogeneity, well perforation depths, and thickness of the cap rock all had impacts.

C) Conduct technical research on CO2 sequestration and enhanced oil recovery by:

1. *Conduct basic and applied research of characterizing Michigan oil and gas and saline reservoirs for CO2 storage potential volume, injectivity and containment*

   The technical research phase of this project is summarized in detail below in the Technical Research Report Section

2. *Integrating any new data as it may become available from wells drilled primarily by the oil and gas industry.*

   Extensive new data was compiled during the technical research phase of this project. See the Technical Research Report Section below.

D) Effect technology transfer to members of industry and governmental agencies by:

1. *Establish an Internet Website at which all data, reports and results are easily accessible (site usage statistics have been recorded)*

   We created the MichCarb website at: http://wsh060.westhills.wmich.edu/MichCarb/ for access to data and outreach. Links lead to resources, multimedia, data, and K-12 educational materials.

2. *Publish results as they become available in relevant journals and conducting annual technology transfer workshops as part of our role as the Michigan Center of the Petroleum Technology Transfer Council or other appropriate organization*

   Several papers addressing Geological Carbon Sequestration in Michigan were published relating to this project in a theme edition of the Journal of Environmental Geosciences:

   Barnes DA, Bacon, DH, and. Kelley, SR, (2009), *Geological Sequestration of Carbon Dioxide in the Cambrian Mount Simon Sandstone: Regional Storage Capacity, Site Characterization, and Large Scale Injection Feasibility; Michigan Basin, USA.* Environmental Geosciences, v. 16, no. 3 (September 2009), pp. 163–183.

   Kirschner, J.P. and Barnes, D.A., (2009); *Geological Sequestration Capacity of the Dundee Limestone, Michigan Basin, USA.* Environmental Geosciences, v. 16, no. 3 (September 2009), pp. 127–138.

   Harrison, WB, III, Grammer, GM, and Barnes, DA, (2009) *Reservoir Characteristics of the Bass Islands Dolomite in Otsego Co., Michigan – Results for a Saline Reservoir CO2 Sequestration Demonstration*. Environmental Geosciences, v. 16, no. 3 (September 2009), pp. 139–151

   Written program description and brief introduction to program was presented to 61 industry and government representatives at a PTTC workshop in Mt. Pleasant, Michigan in 2009.

Dr. Barnes addressed the Michigan PTTC workshop, organized by MGRRE, in Mt. Pleasant in 2010. The meeting was attended by 190 professionals from industry, government and academia. He discussed the application of traditional subsurface reservoir characterization methodology to geological sequestration studies in the Michigan Basin. He also emphasized that geological sequestration investigations are rapidly expanding applications of many familiar petroleum geology and engineering applications and methodologies and discussed how this work represents an opportunity for such work to even more professionals.

We presented a one-day PTTC conference in Mt. Pleasant, at which several graduate students presented poster papers about subsurface geological formations, some of which are candidates for sequestration. About 200 people attended in 2011.

Additional Publications related to MICHCARB research include:
Barnes, David, Froese, Robert E., Mannes, R.G., Warner, Brian, (2011), Combined sustainable biomass feedstock combustion, CO2/EOR, and Saline Reservoir Geological Carbon Sequestration in Northern Lower Michigan, USA: Towards negative CO2 emissions, [Proceedings of GHGT 10, 2010, Amsterdam, Netherlands) Energy Procedia, Volume 4, 2011, Pages 2955-2962, ISSN 1876-6102, http://dx.doi.org/10.1016/j.egypro.2011.02.204.

Barnes, D. A., W. B. Harrison III, and A. Wahr (2009), Assessment of regional geological carbon sequestration potential in Upper Silurian to Middle Devonian strata of the Michigan Basin, in M. Grobe, J. C. Pashin, and R. L. Dodge, eds., Carbon dioxide sequestration in geological media—State of the science: AAPG Studies in Geology 59, p. 99–124.

Grammer, G. M., D. A. Barnes, W. B. Harrison III, A. E. Sandomierski, and R. G. Mannes (2009), Practical synergies for increasing domestic oil production and geological sequestration of anthropogenic CO2: An example from the Michigan Basin, in M. Grobe, J. C. Pashin, and R. L. Dodge, eds., Carbon dioxide sequestration in geological media—State of the science: AAPG Studies in Geology 59, p. 689–706.

3. *Conduct additional workshops, meetings and seminars as appropriate to assure dissemination of project results, especially as described below at (E)*

Many additional public presentations were made for disseminating the results of this project including:

- Dr. Barnes was an invited attendee at the annual EPA Midwest Carbon Sequestration Conference, Angola, IN, July 28 - 29, 2009
- Barnes was a presenter at a Joint conference with AAPG/SEG/SPE Hedburg Research Conference on *Geological Carbon Sequestration: Prediction and Verification* in Vancouver, BC, Canada on August 16-19, 2009. Poster presentation: *Geological Sequestration of Carbon Dioxide in the Cambrian Mount Simon Sandstone: Regional Storage Capacity, Site Characterization, and Large Scale Injection Feasibility; Michigan Basin, USA*
- Barnes was a participant in a briefing presented to Stanley (Skip) Pruss (Michigan Director of Energy, Labor, Economic Development) and Brandon Hofmeister (Gov Granholm’s deputy Legal Counsel) along with a Wolverine Power Cooperative Inc.-led group

concerning the Wolverine Clean Energy Venture initiative and a Phase I DOE funding application for the “Beneficial uses of Industrial Emissions” funding. The meeting was held in Lansing, Michigan, on Monday, Sept 21, 2009.

Key points in the presentation were: Significance of the CC&GS project in light of objectives laid out by the MGA Carbon Capture and Storage Policy Principles and strength of the team involved in the proposed CC&GS projectWPC, Core Energy, Hitachi, Dow Chemical, Burns and Rowe Engineering, and Western Michigan University for a post combustion-based advanced amine carbon capture and geological sequestration with CO_2 /EOR program and potential economic impact of CO_2/EOR to Michigan’s economy.

- Barnes was invited to participate in a briefing to State Representative Douglas A. Geiss (Majority Vice Chair of the Michigan House of Representatives Energy and Technology Committee) and staff regarding a legislative initiative to establish indemnification for components of Carbon Capture and Geological Sequestration in Michigan. This initiative was championed by the Holland Board of Public Works and CC&GS research collaborators, Praxair, Inc. The meeting was held in Lansing, Michigan, on Tuesday, Nov. 10, 2009.
- Dr. Barnes Participated in discussions with Oakland Co. Road Commission staff Engineers (Darryl Heid) concerning piggy-back drilling opportunities with Road Commission Brine wells, May 4.resented Spatial Variability of Reservoir Properties in a Stratigraphically Complex Geological Sequestration Target: The Devonian Sylvania Sandstone, Michigan Basin USA at the Rocky Mountain Section, American Association of Petroleum Geologists Annual Meeting, Durango, CO, June 14.

- Dr. Hampton attended meetings of the carbon sequestration research group; previewed and prepared Mike Celia’s Webinar for that group; presented Webinar by colleague from U. Wyoming for that group.

- Dr. Barnes met several times with colleagues from Consumers Energy to discuss potential CO2 sequestration.

- Dr. Barnes had several conferences with personnel from Core Energy concerning on-going CO2 injection by that group in the Niagaran Reef trend.

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- Dr. Harrison met with representatives of private industry to discuss potential EOR opportunities using CO2 derived from Michigan ethanol plants. Industry was interested and is developing a business plan using two existing ethanol plants and flooding Niagaran reefs.

- Dr. Harrison also answered an industry inquiry about developing some existing reefs that are nearing depletion through primary production, possibly using CO2 sequestration.

- Dr. Barnes attended EPA Region 5 Carbon Sequestration Workshop in Chicago ILDr. Barnes and Harrison and graduate students Katherine Pollard and Stephen A. Zdan attended the Eastern Section AAPG Meeting in Washington D.C. Dr. Barnes co-Authored a paper for the Eastern Section AAPG meeting: Geological Controls on Geological Carbon Storage Capacity, Efficiency, and Security in the Middle Devonian Sylvania-Bois Blanc Saline Aquifer, Central Lower Michigan, USA by *Farsheed Rock, Katherine Pollard, and David A. Barnes*

- Dr. Barnes also supervised this poster presentation by graduate student Stephen A. Zdan at the Eastern Section AAPG meeting:
- Stratigraphic Controls on Diagenetic Pathways in the St. Peter Sandstone, Michigan Basin: An Investigation into Reservoir Quality Prediction for Carbon Sequestration by Stephen A. Zdan

- Katherine Pollard gave an oral presentation on the Sequestration potential in the Sylvania/Bois Blanc Formation.

- Harrison attended a Workshop on Co2 enhanced oil recovery and had discussions with industry professionals on EOR in Michigan and elsewhere.

- MICHCARB's WebPages served more than 1600 visitors. This is in addition to over 2800 direct requests from our online data pages.

- We continue to resolve discrepancies in our inventory and update our metadata.

- MICHCARB's WebPages served more than 1500 visitors. This is in addition to over 3336 direct requests from our online data pages.

- The MichCarb website continues to attract attention with over 2557 visitors this past quarter with an additional 4775 requests for data.

- Dr. Harrison gave two presentations at the Eastern Section of AAPG Annual Meeting in Cleveland, in September. One presentation was to a PTTC Workshop on Enhanced Oil Recovery, titled "Secondary and Enhanced Oil Recovery in Niagaran Reef.s" The second was at the general meeting in a session on Enhancing Hydrocarbon Production, titled "Secondary and Tertiary Oil Recovery in the Michigan Basin." The PTTC Workshop had about 20 attendees, the technical session had about 45 attendees.

- Dr. Barnes submitted an abstract for Poster presentation at the DOE-NETL, Carbon Storage R&D Project Review Meeting (July, 5, 2012); *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, Dave Barnes[1], Kevin Ellett[2], John Sosulski[1], John Rupp[2] and Hannes Leetaru¬[3], [1]Western Michigan University, Kalamazoo, MI, [2]Indiana Geological Survey, Bloomington, IN, [3]Illinois State Geological Survey, Champaign, IL

- Dr. Barnes attended a DOE-NETL Carbon Storage R&D Project Review Meeting in August, 2013 at Pittsburgh, PA. He presented a poster paper: 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

E) Establish a CO2 geological sequestration outreach and education center for Michigan at MGRRE by:

1. *Creating education materials including physical demonstration models, training and educational exercises, and displays that can be used in outreach and for education events*

   MICHCARB website at: http://wsh060.westhills.wmich.edu/MichCarb/ links to our K-12 outreach, CoreKids, at http://www.wmich.edu/corekids/. CoreKids:

   We have established partnerships with K-12 schools, scouting groups and other youth organizations and created brochures announcing MICHCARB and sent those to contacts on the CoreKids' mailing list and state educators' mailing list.
   We have also created educational materials including posters and classroom presentations on climate change, CO2 sequestration, and natural resources.

   These materials have been used to develop Outreach programs to schools, scouts and summer camps.

   We also conducted a teacher workshop about CO2 sequestration as part of a Keystone Science School Climate Status Investigations teacher training held at WMU July 27-28, 2010.
   We have prepared exhibits for the Michigan Science Teachers' Association Meeting in March 2010 and at Southwest Michigan Science Educators Conference. We presented CO2 sequestration educational content to regional elementary and middle school classes

2. *Provide these materials to stakeholders for in-house use*

   These materials are available to anyone who is interested in the subject matter.

3. *Present workshops for professionals to transfer technical information and knowledge*

   Some of the key outcomes these projects are:
   - Reducing negative environmental and economic impacts of global warming by reducing CO_2 emissions

- Cost-effectively developing GCS technology and safety measures that can be transferred nationally
- Assisting Michigan's citizens, government and industry members to better understand not only the science behind GCS, but also its practicality and safety
- Acquisition of new geological data, leading to a greater understanding and use of subsurface geological resources and a positive impact economic impact
- Increasing domestic oil and gas production through enhanced oil recovery resulting in a positive economic impact and reducing America's dependence on foreign oil and gas

Technical Research Report

Regional Geological Framework - Michigan Basin

The Michigan basin is a major intracratonic basin in the Eastern United States (Figure 1). The basin is a roughly elliptical and centered on the Lower Peninsula of the State of Michigan (Figure 2). A structural basin of over 100,000 square miles in area, the Michigan basin also includes the eastern half of Michigan's Upper Peninsula, portions of northern Ohio and Indiana, northeastern Illinois, eastern Wisconsin and southwestern Ontario, Canada. The basin is bounded by the persistent, structurally stable (or high) areas of the Wisconsin and Kankakee Arches to the west and southwest, the Findlay Arch of Ohio to the southeast, the Algonquin Arch of Ontario to the east, and the Canadian Shield to the north. The bedrock sedimentary formations in the basin attain a maximum thickness of nearly 16,000 feet and include sandstone, shale, carbonate and evaporite formations from Cambrian through Pennsylvanian age (Figure 3). Discontinuous, thin, redbeds of Jurassic age occur in the basin center. A Pleistocene veneer of glacial deposits blankets nearly all of the Lower Peninsula with thicknesses up to 1,200 feet.

Natural bedrock outcrops occur in numerous areas around the Great Lakes shoreline and a few are known inland in stream and river valleys. Quarries expose bedrock in areas where the glacial drift is thin or absent. Bedrock (subcrop), structural (depth), and isopach (thickness) maps can be effectively made for these sedimentary rock formations using well data from over 60,000 oil, gas and other type wells. For Geological CO_2 Storage Assessment in Michigan, approximately 24,000 well boreholes, that reached true vertical total depth of 3,000 feet or more, were used for subsurface data analyses.

Variation in subsidence rate and resultant accommodation space, from the basin center to the basin margin, also produced formation isopach thickness variations for any given formation. Facies changes, local faulting and folding, differential compaction, variable local sediment accumulation and differential erosion at unconformities may also contribute to variations in formation thicknesses and sedimentary lithofacies.

The reliability of geological interpretations for formations of interest is generally dependent on the depth of burial of those formations. The shallowest formations have the highest bore-hole penetration and spatial distribution density so that maps of these shallowly buried formations are better constrained by larger amounts of data. Maps and other data for older (more deeply buried) formations are a product of far fewer penetrations so that geological information and interpretations for these intervals are less well constrained.

Paleozoic Bedrock Stratigraphy

The Paleozoic sedimentary succession in Michigan (Figure 3) can be subdivided on the basis of major inter-regional unconformities originally identified by Sloss (1963) in the North American cratonic interior. The basin scale, “Native American Cratonic Sequences” constitutes a “first order” partitioning of the stratigraphic succession in the Michigan basin, as well as much of the Mid-Continent, due to interregional variation in sediment accommodation associated with global eustatic change.

In a general way, the gross lithology of the Michigan basin can also be subdivided into three dominant lithologic packages that partially conform to the mega-sequences shown in Figure 3. The Lower Paleozoic, Cambrian through Upper Ordovician, succession comprises dominantly sandy and argillaceous clastics with lesser interspersed, carbonate-dominated formations. The Middle Paleozoic, Silurian through Middle Devonian, succession consists of carbonate- and evaporite-dominated strata with minor argillaceous and quartzose sandstone formations. The Upper Paleozoic, Upper Devonian through Pennsylvanian, is a mostly argillaceous- (with noteworthy, organic carbon-rich formations) and sandy clastics-dominated succession. A common, large scale stratigraphic motif is of karsted carbonate strata overlain by an inter-regional unconformity and then by a transgressive sandstone to argillaceous carbonate strata up section (see Figure 3; base Tippecanoe, base Kaskaskia, and base Absaroka unconformity surfaces). These unconformity-related stratigraphic relationships are also punctuated by periodic influxes of fine-to coarse-grain sand size clastics due to the episodic reactivation of sediment source terrains in the Appalachian orogenic belt to the (modern) east and clastic source terrains in the Canadian Shield and Wisconsin highlands to the (modern) north and northwest.

Geological Carbon Sequestration Opportunities in the Michigan Basin

The preliminary identification of subsurface formations suitable for large-scale, regional geological storage of carbon dioxide, geological carbon sequestration (GCS), was undertaken on the basis of existing geological information resulting from subsurface drilling activity in the Michigan basin dating from the late nineteenth century to present. Most information pertinent to the bedrock geology in Michigan is derived from data generated in the course of drilling activities for oil and natural gas exploration/production, saline brine mining, underground waste injection, and other economically driven activities.

The fundamental characteristics necessary for consideration of prospective GCS targets are:

1) Storage Capacity

   a) Volume requirements of anthropogenic CO2 sources vs
   b) Pore volume, area, temperature/pressure (>2,600 ft, measured depth in Michigan)
2) Injectivity Potential
   a) Permeability, porosity, and thickness
3) Containment/Security
   a) Seal and trap suitable for CO2
4) Site Details
   a) Site technical and economic viability
   b) Distance from source, depth to reservoir
5) Non-interference with Existing Natural Resources

Borehole penetrations and the subsurface geological data generated during drilling activities, including log data, cuttings, conventional core samples, and other well testing results provide the basis for determining the properties described above. These data have been curated by the agencies described above and are the basis for the identification of potential GCS systems, geological reservoir formations (formations capable of producing or receiving injected fluids at a substantial rate) and superjacent buoyant fluid (relative to formation brines) impermeable sealing formations.
Furthermore, a suitable GCS system must occur at sufficient depth in the subsurface so that ambient pressure and temperature conditions are consistent with maintenance of injected CO2 at supercritical phase condition (a dense, liquid-like gas phase). These conditions, in the Michigan basin, are described in Figure 4 A, B, and C. On the basis of subsurface geological data sets, along with pressure temperature considerations resulting from depth of burial, three parts of the stratigraphic column in Michigan are identified as the most prospective targets for GCS (Figure 5); 1) Middle Paleozoic (Silurian-Devonian) carbonate and clastic formations, 2) Middle Paleozoic (Middle Silurian) Carbonate Reef reservoirs, and 3) Lower Paleozoic (Cambrian-Ordovician) Sandstone reservoirs.

The context for CGS can be further discriminated on the basis of trapping mechanisms including residual or capillary entrapment of CO2 in deep saline brine-bearing formations and buoyancy trapping in geological structures that provide hydrodynamic trapping mechanisms typically associated with hydrocarbon accumulations (Figure 6). These GCS opportunities are described in more detail, below.

Deep Saline Formation Characterization

Data used in the geological characterization of deep saline injection and confining layers in Michigan is mainly taken from subsurface data records maintained by the Michigan Department of Natural Resources and Environment (MDNRE), Office of Geological Survey (OGS) and also from data and sample materials maintained at the Michigan Geological Repository for Research and Education (MGRRE) at Western Michigan University. Wire-line, geophysical log data (referred to here as "log data") is the most abundant subsurface geological data source and is typically available as raster-format digital logs. Quantitative, petrophysical evaluation of deep injection and confining zone layers requires conversion of raster image logs to digital log (LAS format) files. A subsurface well data software system (IHS Petra) was used extensively in this study to manage, display, and analyze subsurface data. All tops and reservoir characterization data reported here is quality assured data as a result of in-house analysis. The quality assured data is typically (especially for up-hole formations) a small subset of all available subsurface data but was chosen to provide comprehensive areal coverage in Michigan's Lower Peninsula. Although these data sets may be small (typically from one hundred to a few thousand wells) we have a high level of confidence in these data sets.

A key methodology in the characterization of deep saline reservoir and confining zones for CO_2 injection and sequestration is the correlation/calibration of log data with much less common rock core sample material. Direct measurement of petrophysical properties (porosity, permeability, etc.) from conventional core and petrographic thin section analysis of reservoir injection zones provides refined characterization of reservoir rock properties including reservoir rock pore types, effective porosity, and injectivity. Confining zone characterization is also more confidently established by direct measurement, from core, of petrophysical properties and then correlated/calibrated to log response. These relationships are incorporated into the gross, net, net to gross and average reservoir interval porosity data presented in data tables. Appropriate cutoff porosity values were used to establish the above values for control wells.

Deep Saline Formations (Residual/Capillary Entrapment Reservoirs)

Regional geological assessment of geological carbon sequestration potential in the Michigan basin (Wickstrom, et al, 2005; US DOE-NETL, 2008) suggests the largest capacity saline reservoir storage targets occur in lower Paleozoic sandstone (Figure 7) and Middle Paleozoic sandstone and carbonate formations (Figure 8). Significant storage capacity, and especially enhanced oil recovery opportunities, also exist in Middle Paleozoic Niagaran Pinnacle Reef (Guelph Formation also called the “Brown Niagaran”) oil fields (Figure 9). Confining layers for these sequestration targets, in accordance with USGS criteria, are as follows: 1) Utica/Collingwood shale formations (Figure 7), 2) Evaporite prone (anhydrite and halite) strata of the Lucas Formation, Horner and Iutzi members, (Figures 8, and 10) Salina Evaporite (anhydrite and halite) prone units (Figure 9), respectively.

An exception to previous regional assessment of sequestration potential, which results from the criteria used in the course of the USGS national assessment program, is exclusion of a major saline reservoir and hydrocarbon producing formation in Michigan; the Dundee Limestone formation (sensu latto) studied by Kirschner and Barnes, 2009. The Dundee was found to possess significant residual and buoyancy storage potential in the Michigan basin in this study but, due to the criteria of a minimum 100 ft thick shale or evaporite confining layer below the 3,000 foot burial depth level, the Devonian Bell Shale confining layer was found to be inadequate (Figure 11). Injection target characterization data was not compiled for the Dundee Limestone for the current study.

Oil and Gas-producing Formations (Buoyancy Entrapment Reservoirs)

Oil and gas has been commercially produced in Michigan since 1925 with the discovery of the Saginaw Field. Cumulative production through 2010 is 1,300,221,446 barrels of oil and 7,198,570,255 mcf of natural gas. Major strata for hydrocarbon production occur in Ordovician through Devonian age rocks (Figure 3). Ordovician gas production comes from the St. Peter Sandstone (aka. PdC), while oil and associated gas comes from fractured, hydrothermal dolomite reservoirs in the Trenton/Black River formations. Most of the Silurian oil and gas production comes from the Niagaran Pinnacle reefs and superjacent Salina A-1 Carbonate. Devonian oil production is most abundant in the Richfield member of the Lucas Formation, The Dundee and Rogers City Limestone formations and the Traverse Limestone. Devonian natural gas production is primarily from the Antrim Shale. Smaller amounts of gas and limited oil are produced from Mississippian sandstones. Production from the St. Peter Sandstone, most Devonian carbonate reservoirs and Mississippian sandstone reservoirs occur on low amplitude anticlinal structures related to basement faulting or drape over deeper structures. Most of the hydrocarbon traps in the Michigan Basin are limited in areal extent and form discrete fields controlled by structural or stratigraphic events.

Depth to the top of these reservoirs ranges from less than 1000 feet to over 12,000 feet. All Mississippian fields, Antrim Shale reservoirs and most Devonian Traverse Limestone fields are at depths less than 3000 feet. Most Niagaran reefs, Devonian Dundee/Rogers City, Richfield, Trenton/Black River and St. Peter fields are at depths greater than 3000 feet (Tables 1 and 2).

Summary of Saline Reservoir, Capillary Entrapment, GCS Targets

Lower Paleozoic Sandstone Reservoirs and Seals;

The lower Paleozoic stratigraphic succession in the Michigan basin is shown in Figures 3, 5, and 7. As described above, variations in thickness and lithologic properties of individual formations has resulted from differential subsidence in the basin through time and due to other geological controls. A series of regional cross sections compiled from key wells are shown in Figures 7 A-D.

Mount Simon Sandstone

The Mount Simon Sandstone is recognized as a significant deep saline Geological Sequestration reservoir target in the Midwest, USA. The Mount Simon in Michigan consists primarily of sandy terrigenous clastics, and grades upwards to the Eau Claire Formation, a regional confining zone (Figure 13). The Mount Simon lies at depths from about 3000ft (914m) to more than 15,000ft (4572m) in the Michigan basin (Figure 14A) and ranges in thickness from over 1,300ft (396m) to near zero adjacent to basement highs

(Figure 14B). The Mount Simon has variable reservoir quality characteristics dependent on sedimentary facies variations and depth related diagenesis. On the basis of well log-derived net porosity from wells in Michigan estimates of total GCS capacity were determined to be in excess of 41 billion metric tons (Gmt). The majority of this capacity is identified in the southwestern part of the state although substantial GCS storage capacity is also present in south-eastern Lower Michigan (Figure 15).

St. Peter Sandstone

The St. Peter Sandstone formation is recognized as a significant deep saline Geological Sequestration reservoir target in the Midwest, USA (Figure 16). The St. Peter in the Michigan basin ranges in thickness from a regional 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 (Figure 17A and B). GCS estimates were developed in order to identify and characterize important storage opportunities in the St. Peter Sandstone and it is found that the formation is a noteworthy, deep saline aquifer CO2 storage target in Michigan with GCS potential of between 15 to 50.1 GT of CO2 on the basis of various estimation methodologies and a range of confidence intervals (Figure 18).

Regional Confining Layers

One of the fundamental requirements for significant GCS is the occurrence of suitably impermeable layers capable of retaining buoyant CO2 injectate and precluding upward migration of those fluids into more shallowly buried formations, including potable groundwater-bearing formations, or to the surface. Various general definitions exist for suitable, regional confining layers; although dense shale, carbonate, and evaporite (salt/anhydrite) dominated formations are the most common lithological units necessary for permanent confinement of injected CO2. The thickness of satisfactory, impermeable confining formation is typically expected to be in excess of 100ft. Additionally, some mechanically brittle and carbonate dominated formations, despite general very low permeability properties, have been considered unsuitable as regional confining layers due to the possibility of large scale fracturing and/or dissolution creating pathways for the upward migration of CO2. The designation of “primary” and “secondary” confining layers indicates the regional reliability of geological formations for the retention of CO2.

The Primary confining layer for lower Paleozoic GCS injection targets is the combined, calcareous to argillaceous mudrock formations including the Collingwood and Utica Shale formations (Figure 19). Detailed petrophysical studies are currently underway to evaluate the regional variation in mineralogical composition and mechanical properties of the Utica Shale in the Michigan to validate the suitability of this unit as the regional, primary confining layer for Lower Paleozoic injection targets.

Middle Paleozoic Carbonate and Sandstone Reservoirs

The stratigraphic relationships of Middle Paleozoic Carbonate and Sandstone reservoirs and seals are shown in Figures 3, 5, and 8. Although preliminary assessment of the lower Paleozoic clastics units, the Cambrian Mount Simon Sandstone and Ordovician St. Peter Sandstone (described above), possess the largest carbon sequestration capacities in the Michigan basin, large areas of the central Michigan basin may contain little CO2 storage potential in these intervals due to depth related, occlusion of porosity by compaction and secondary mineral cements. Other stratigraphic units in Upper Silurian to Middle Devonian carbonate, cherty carbonate, and mixed siliciclastics, and evaporite-bearing strata of the Bass Islands Group, Bois Blanc Formation, and Detroit River Group, (Figure 8) are also identified as important potential saline reservoir, carbon sequestration targets and cap-rock units. These prospective middle Paleozoic GCS targets are of particular interest because they occur in large areas of the central Michigan basin at or below depths with subsurface pressure and temperature conditions sufficient to maintain CO2 at or above critical point density.

Upper Silurian to Middle Devonian strata (Figure 8) are routinely penetrated during drilling to Ordovician and Silurian oil and gas exploration/production targets in Michigan. The Upper Silurian to Middle Devonian section is relatively poorly known, however, because these strata are not significant hydrocarbon bearing units in the basin. Porosity and injectivity have been recognized in portions of this interval and has been exploited for brine and liquid waste disposal, and solution mining/natural brine production for halides since early in the 20th century. Literally thousands of petroleum industry and other industrial boreholes have penetrated the Upper Silurian to Middle Devonian succession, throughout the basin for the last 80-100 years. A generalized cross section of these units is presented in Figure 20.

Silurian Bass Islands Group; Bass Islands Dolomite

The Bass Islands dolomite is a distinctive, map-able unit in the Michigan basin subsurface and is probably equivalent to the upper portions of the Bass Islands Formation, Raisin River and Put-In-Bay members, recognized in outcrop, in the Bass Islands of Lake Erie in Ohio. This predominantly dolomitic interval is commonly underlain by anhydrite throughout most of the central Michigan basin, which is readily identified as a high density; >2.9 g/cm^3 unit on the bulk density (RHOB) log (Figure 21A and B). For the purposes of this report, this anhydrite unit is informally referred to as the Bass Islands “evaporite” but may more appropriately correlate to the Tymochtee member in outcrop.

Examination of wireline logs and regional mapping in central Lower Michigan counties indicates that the Bass Islands reservoir is as much as 100 ft (30 m) thick in some areas and a large area in the northern half of the state has a gross reservoir thickness of more than 50 ft (15 m) (Figure 22A & B). The Bass Islands reservoir interval is laterally persistent and can be identified in counties surrounding the Bass Islands dolomite type

well section in the St. Charlton #4-30 well in Otsego County (Figures 20 and 22 A).
The Bass Islands dolomite is a regionally significant geological sequestration target within the Michigan basin. In the basin, it has an estimated geological storage capacity of nearly 1,700million T (1.5 Gt) of CO2 (Figure 23). These estimates are based on determination of net porosity from porosity logs (calculated average neutron porosity- density porosity) in available regional wells. A trend line relationship between conventional core porosity versus permeability data in the State Charlton #4-30 was used to establish a cutoff porosity of 10 percent (equating to permeability of 0.5 md in the Bass Islands dolomite). Calculated net porosity using cross plot calculated log porosity was established for 77 wells in the state (see Figure 23, control wells). These net porosity values were then gridded and mapped to determine a net porosity grid. This net porosity grid was used to calculate storage capacity of CO2 using a density of supercritical CO2 0.7 g/cm3) and storage efficiency factor of 4 percent.

Middle Devonian Detroit River Group and the Bois Blanc Formation

The Detroit River Group in the Michigan basin consists of the Sylvania Sandstone (oldest), the Amherstburg Formation, and the Lucas Formation (youngest) (Figure 8). In addition to these units, related strata of the Bois Blanc Formation overlie the base- Kaskaskia unconformity (Figure 3 and 8). Most of what is known about these units is based on limited surface exposures in Michigan and analysis of drill cuttings, logs, and limited core material in the Michigan basin subsurface. The Garden Island Formation is also recognized in Michigan (Landes and others, 1945) but is found as a laterally discontinuous unit present in only small areas and is not considered important here.

Bois Blanc Formation and Sylvania Sandstone

Distinctive cherty and fossiliferous carbonate rocks of the Bois Blanc Formation are present throughout most of the Michigan basin subsurface and overlie the pronounced base-Kaskaskia unconformity in most locations. The Sylvania Sandstone is the basal formation of the Detroit River Group, and along with the Bois Blanc and Garden Island formations, overlies the base-Kaskaskia unconformity in a complex relationship that has not been clearly defined throughout the Michigan basin. The Sylvania Sandstone overlies the base-Kaskaskia unconformity in southeastern Michigan above the truncated Silurian Bass Islands Group. The Sylvania is thin, discontinuous, or completely absent in some areas, especially on the southern and western margins of the Michigan basin.
The Bois Blanc underlies the Sylvania although the stratigraphic relationship between these two units in many areas is unclear.

Regional lithologic variations within the Sylvania Sandstone are known mainly from the analysis of geophysical logs. The discrimination of calcareous sandstone and sandy carbonate of the Sylvania Sandstone from cherty limestone and dolostone of the Bois Blanc is problematic, however, and subsurface picks of these units are more confidently based on cutting samples or core where available. A representative log section for the Sylvania Sandstone and underlying Bois Blanc Formation is shown in Figure 24. More recent log analysis and core to log calibration have resulted in more refined interpretation of regional lithostratigraphic relationships amongst Middle Devonian strata of the Detroit River Group and the Bois Blanc Formation (Figure 25A and B). Sylvania "Sandstone" strata transition from high energy, subtidal to lower-intertidal mixed carbonate-siliciclastic facies to more distal, subtidal, mixed biogenic cherty carbonate facies of the Bois Blanc Formation down dip from the Southwest to the Northeast in the Michigan basin. The distinctive sandstone and porous cherty dolomite of the Sylvania Sandstone defines a northwest to southeast oriented depositional trend (hinge line). The lithologic assemblage of the Sylvania Sandstone comprises high energy, mixed carbonate-siliciclastic, tidally influenced strata that is transitional to a more basinal, subtidal, mixed carbonate and biogenic chert facies of the Bois Blanc Formation down dip to the northeast (Figure 26A and B).

Sylvania Sandstone Saline Reservoir Target

Core-to-wireline-log correlation can be used to subdivide the Sylvania Sandstone into conventional reservoir sandstone and mixed dolostone, low permeability reservoir tripolitic chert, and low permeability limestone lithologies. Isolith maps and cross sections indicate that the reservoir sandstone lithology dominates in southeast Michigan and is transitional to a mixture of sandstone, dolostone, tripolitic chert and limestone lithologies toward the northwest that in turn are completely replaced by tripolitic chert and dolostone in northwestern lower Michigan. Net porosity maps demonstrate that reservoir lithologies are distributed along a southeast-northwest trending fairway approximately 60 to 75 miles wide. Vertical stacking of distinct facies in shoaling upwards parasequences and lateral facies transition compartmentalizes reservoirs.

Using various assumptions, estimates of CO2 storage capacity could show a wide range of values from a low of 1.9 Gt considering only conventional reservoir rock types with 4% efficiency to 7.2 Gt considering conventional and unconventional, low permeability tripolitic chert rock types with 10% efficiency. This range of CO2 GCS capacity values is supportive of Sylvania Sandstone and equivalent strata as an important CO2 geological storage formation in Michigan. (Figures 27 A and B)

Middle Devonian Dundee and Rogers City Limestone formations

The Dundee Limestone formation is a complex carbonate succession that stratigraphically underlies the Bell Shale and overlies the Lucas Formation in the Michigan basin (Figure 8, Figure 28). Formal Michigan Basin stratigraphic nomenclature separates the Rogers City and Dundee in outcrop but combines them in the subsurface as the Dundee Limestone (Catacosinos et al., 2001). The primary Rogers City facies is nodular wackestone, which was deposited in an open-marine setting (Curran and Hurley, 1992). Compared to the relatively homogeneous Rogers City, the Dundee has a variety of primary sedimentary facies. The Dundee contains dolomitized sabkha- lagoonal facies and anhydrite deposits in the western part of the basin (Gardner, 1974). In the central and eastern basin, the Dundee was deposited along an eastward-dipping ramp in generally unrestricted open-marine conditions (Gardner, 1974). Common Dundee facies in these areas include crinoid grainstones, skeletal- peloidal grainstones and packstones, skeletal wackestones, and restricted fauna mudstones and wackestones (Curran and Hurley, 1992). Shoal-water and more restricted facies occur at the top of the Dundee, across the basin, suggesting a regional relative sea level fall at the top of the formation. The Rogers City-Dundee contact is readily apparent in core on the basis of a distinct pyritized and bored hard ground. This contact has been interpreted as a sequence boundary or flooding surface (Curran and Hurley, 1992). Isopach maps of these two formations are shown in Figures 29A and B.

Dundee Limestone Saline Reservoir Target

The Dundee limestone is a wide-spread injection zone for oil/gas brine disposal produced in many hydrocarbon producing formations. Abundant storage capacity and injectivity is present in a variety of facies and locations in the Michigan basin. The Dundee is overlain by a suitable confining layer, either the Bell Shale or dense, low permeability limestone of the Rogers City Limestone, where the latter formation has not been altered to porous dolomite. Using the strict criteria for suitable confining zone formations described by the US Geological Survey, neither of these seal units (although effective seals for significant, commercial oil and gas accumulations in the basin) are considered adequate confining zones for large scale GCS (see discussion, above, and Figure 8. Furthermore, the large number of penetrations of the Dundee Limestone for either commercial oil and natural gas production or brine disposal renders this formation a very dubious GCS target due to possible leakage pathways through these boreholes. Despite these very significant obstacles to regional GCS deployment in the Dundee Limestone-Rogers City saline reservoir Kirschner and Barnes (2009) did assess th storage capacity of these units and determined that approximately 2.1GT of GCS capacity is present at a 4% storage efficiency factor.

Oil and Gas-producing Formations (Buoyancy Entrapment Reservoirs)

Oil and gas reservoirs can be utilized in two ways for CO2 sequestration: (1) the CO2 can be injected as part of a designed program to enhance additional oil and/or natural gas production from the reservoir, or (2) the CO2 can be injected solely for sequestration into the known space formerly occupied by oil and/or natural gas in a depleted reservoir. In the first instance, the oil or gas produced via the program provides a value-added commodity to the sequestration project. In the second instance, the injection project is similar to that of injecting into a saline aquifer (Riley, et. al., 2009). In either case the primary entrapment mechanism is hydrostatic with containment provided by a low permeability cap rock, which effectively sealed the reservoir hydrocarbons for geologically significant time periods and a hydrodynamic (geological impediment to upward, buoyant fluid migration) traps such as structural or stratigraphic trap. The US Geological Survey (Brennan, et. al., 2010) has discussed the relative efficiency (proportion of known pore space that is effectively used for CO2 storage) of buoyancy versus residual trapping mechanisms and established efficiency factors for these trap types ranging from to high efficiency buoyancy entrapment

(10%-60% of estimated pore volume) to lower efficiency residual entrapment mechanisms (1%-15% of estimated pore volume, dependent on storage formation properties).

Within the Michigan basin, commercially significant oil and natural gas are produced from rocks that range from Cambrian through Mississippian age. Major production comes from Devonian age rocks (Figure 5) and the Silurian Niagaran Group pinnacle- reef trend that occurs in many areas around the margin of the basin (Figure 6). Data relevant to the assessment of the viability of CO2-Enhanced oil recovery (CO2-EOR), the commercial enhancement of oil production through CO2 injection, include:

- Miscible vs. immiscible conditions; oil type.
- Cumulative oil production of the prospective field(s).
- Original oil-in-place (OOIP) of the prospective field(s).
- Oil recovery potential from CO2–EOR of the prospective field(s)*.*

In addition to geological considerations, other factors come into play that should be considered when evaluating CO2-EOR potential (Riley, et. al., 2009). These include:

1. Location of CO2 sources (e.g., power plants, steel mills, cement plants) and proximity to oil reservoirs.
2. Well spacing.
3. Unitization issues.
4. Locations of improperly plugged wells and well-bore integrity.
5. Economic considerations.

Our consideration of CO2-EOR (buoyancy entrapment) GCS targets, (see tables 1 and 2) on the basis of the above criteria, focused on Silurian Niagaran reef trend reservoirs (Figures 9 and 30) and Lucas Formation, Richfield member fields (Figures 8 and 28). These two basin plays have produced well in excess of 500 million barrels of oil (MMBO), have appropriate oil types for CO2 EOR, and have thick, proven regional confining layers (see Figures 8 and 9).

Silurian-Niagaran Pinnacle Reef Trend Reservoirs; Buoyancy Entrapment GCS Targets

Middle Silurian age, Niagaran pinnacle reef trend reservoirs are distributed in an arcuate band surrounding the central Michigan basin and are geographically distinguished as the northern and southern pinnacle reef trend (Figure 30). Due to depth of burial (most southern trend reservoirs are at or above minimum miscibility depth), ownership (many large fields are currently used for gas storage) and oil versus gas fluid content (most large, southern trend fields are dominantly gas-bearing) considerations the main focus of this work has been on Northern Niagaran Pinnacle Reef Trend (NNPRT) reservoirs (Figure 31A).

Early Silurian age, Niagaran pinnacle reef trend (NPRT) oil fields in the Guelph Formation in Northern Lower Michigan (NNPRT) comprise a giant oil province with nearly 63.6 million cubic meters (Mm3) of cumulative petroleum and 680 billion cubic meters (Bm3) of natural gas production (through 2010) from over 700 discrete reservoirs at depths of 800-2100 m (Figure 31C). Several NNPRT fields are the main target of a proposed, DOE-NETL funded, large scale carbon dioxide (CO2) utilization and sequestration project. The NNPRT comprises closely-spaced, but highly geologically compartmentalized and laterally discontinuous oil and gas fields many of which have either reached or are nearing their economic limit in primary production mode.

Total oil production from the largest 207 oil fields in the NNPRT, each with more than 80,000 m3 of cumulative oil production per field, constitutes 86% or 54.6 Mm3 of trend oil production totals and are considered most likely targets for CO2/EOR activities in the future. We have evaluated regional CO2/Enhanced Oil Recovery (EOR) potential in these NNPRT fields from historic production data in addition to recovery efficiencies observed in seven, on-going, commercial CO2/EOR projects and determined that incremental CO2/EOR potential in these fields ranges from 22-33 Mm3. We have also evaluated trend-wide Geological Storage Resource (GSR) potential using 2 different approaches: 1) a produced fluid volumes approach, and 2) a gross storage capacity approach using petrophysical well log estimates of net, effective porosity in NNPRT field wells and estimates of reservoir acreage from GIS data. These approaches provid robust low and high estimates of more than 200 Mmt but less than 500 Mmt (respectively) for Geological Storage Resource (GSR) potential in the NNPRT.

Middle Devonian Lucas Formation-Richfield Member; Buoyancy Entrapment GCS Targets

The Richfield Member of the Middle Devonian Lucas Formation, Detroit River Group (Figure 32) consists mostly of dolomitized, subtidal to supratidal wackestone to packstone, minor grainstone, and alternating layers of anhydrite in the central Michigan basin. The most common reservoir rock type is a classic high porosity, low permeability, peritidal, algal-laminated, dolomicrite (Gardner, 1974). Anhydrite dominates in younger strata, while interbedded anhydrite (caprock) and dolomicrite (reservoir) cycles lower in the section constitute ideal drilling targets (Matthews, 1977).

The Richfield Member is an important oil producer in the Michigan Basin. In the 1980s production from the Richfield and the overlying “Sour Zone” (an informal drillers term) of the Iutzi member accounted for 21 percent of total production from the Michigan Basin (Sullivan, 1986). There are approximately 2,900 wells drilled to producing parts of the Richfield Member. Of those, around 1,800 wells are still active. Well spacing varies between fields, but early regulations designated 40-acre (16 hectares [ha]) spacing with well locations limited to the northwest corner of quarter-quarter sections (Wilson, 1976). Before and after implementation of these across-the-board regulations, well spacing varied depending on the producing formation(s) and/or field location. Therefore, well spacing covers a range of 20 to 40-plus-acre (8 to 16-plus-ha) lots.

Historical monthly well production data available from the State of Michigan shows that initial oil and gas production from the Richfield began in 1939 with cumulative primary production from over thirty fields in excess of 55 million barrels of oil (MMBO).

Secondary recovery in several larger fields has been very successful, with incremental oil production during water flooding ranging from 16 to 83 percent of cumulative primary production. Generalized calculations (15 percent efficiency) of Richfield production data estimate that there is still a large amount of the original oil in place (OOIP) in reservoirs around the basin (estimated OOIP is 558 MMBO). Sequestration with carbon dioxide-enhanced oil recovery (CO2-EOR) may prove to be the most efficient means of flooding and increasing production of these depleted oil fields.

Detroit River Group strata were deposited in a range of normal, epicontinental, marine conditions (Amherstburg Limestone) shifting into a restricted, hypersaline, subtidal to sabkha-cyclic environment in the Lucas Formation. Evaporite-prone (halite and anhydrite) prone strata dominate the upper Lucas Formation and the Richfield member comprises mixed anhydrite and dolomite (Oil fields in the Michigan basin overlie basement (growth?) faults and related structures that have propagated up through the sedimentary succession. Ideal dolostone reservoirs in the Richfield occur in the north center of the Michigan Basin (Figure 33). Anhydrite-dominated facies occur in the western basin and mixed dolostone, anhydrite, and limestone facies occur in the eastern basin around the Saginaw Bay area.

Geologic and Fluid Flow Modeling to Address Specific Predictive Uses of CO2 Storage and Enhanced Oil Recovery

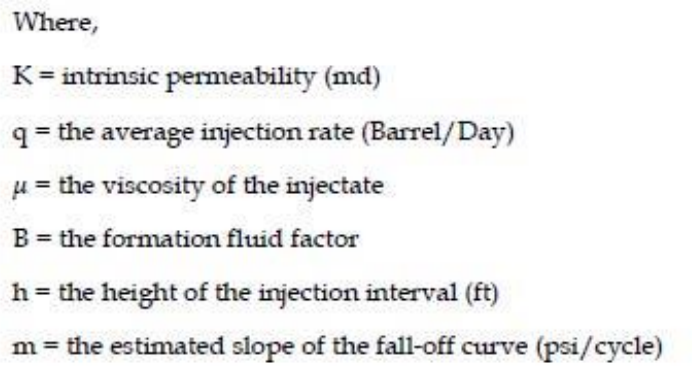
Compilation of data for geological and fluid flow models

Pressure Fall-off Test Data/Analysis

An initial approach to fluid flow modelling of GCS reservoirs and confining layers involved the application of methodology used by the Illinois EPA for deep waste injection test well analysis. Hydrogeological data generated from deep waste injection wells may be used to determine the potential for a saline aquifer to accept injected CO2. Pressure fall-off test (PFT) data is used to make inferences about the size of an aquifer/reservoir or to quantitatively describe hydraulic conductivity of that aquifer/reservoir (see equation, below). Cataloged PFT data was evaluated according to its utility, which is dependent on the rigor with which the data was collected. The data that is of lower quality can be used to make inferences about reservoir compartmentalization and the best data can be used to calculate the hydraulic conductivity of aquifers. Scale and injectivity inferences were made from PFT analyses of Mount Simon Sandstone and Sylvania Sandstone CO2 injection targets because of the availability of PFT data in deep waste injection wells in many areas of the Michigan basin from these units (Figure 34).

Equation 1

$$K = \frac{162*q*\mu*B}{h*m}$$



Where,

K = intrinsic permeability (md)

q = the average injection rate (Barrel/Day)

μ = the viscosity of the injectate

B = the formation fluid factor

h = the height of the injection interval (ft)

m = the estimated slope of the fall-off curve (psi/cycle)

Formulation of static Geological and Dynamic Fluid Flow models, Data Integration, and Results

Initial, geological reservoir characterization studies with emphasis on the Mount Simon Sandstone saline aquifer, were integrated into static and dynamic fluid flow models in the course of our work (Figure 35 and 36). Our group acquired academic licensing for industry standard static geological/geostatistical modeling (Schlumberger, Petrel) and dynamic flow modelling (CMG suite including: Builder, GEM, 3D Vis) software to undertake modelling studies. Dynamic, fluid flow modelling research in progress in the Sylvania Sandstone in Midland County, MI (Figure 37) has confirmed the high degree of injectivity, storage capacity, and containment in this prospective GCS target in Michigan.

Figures

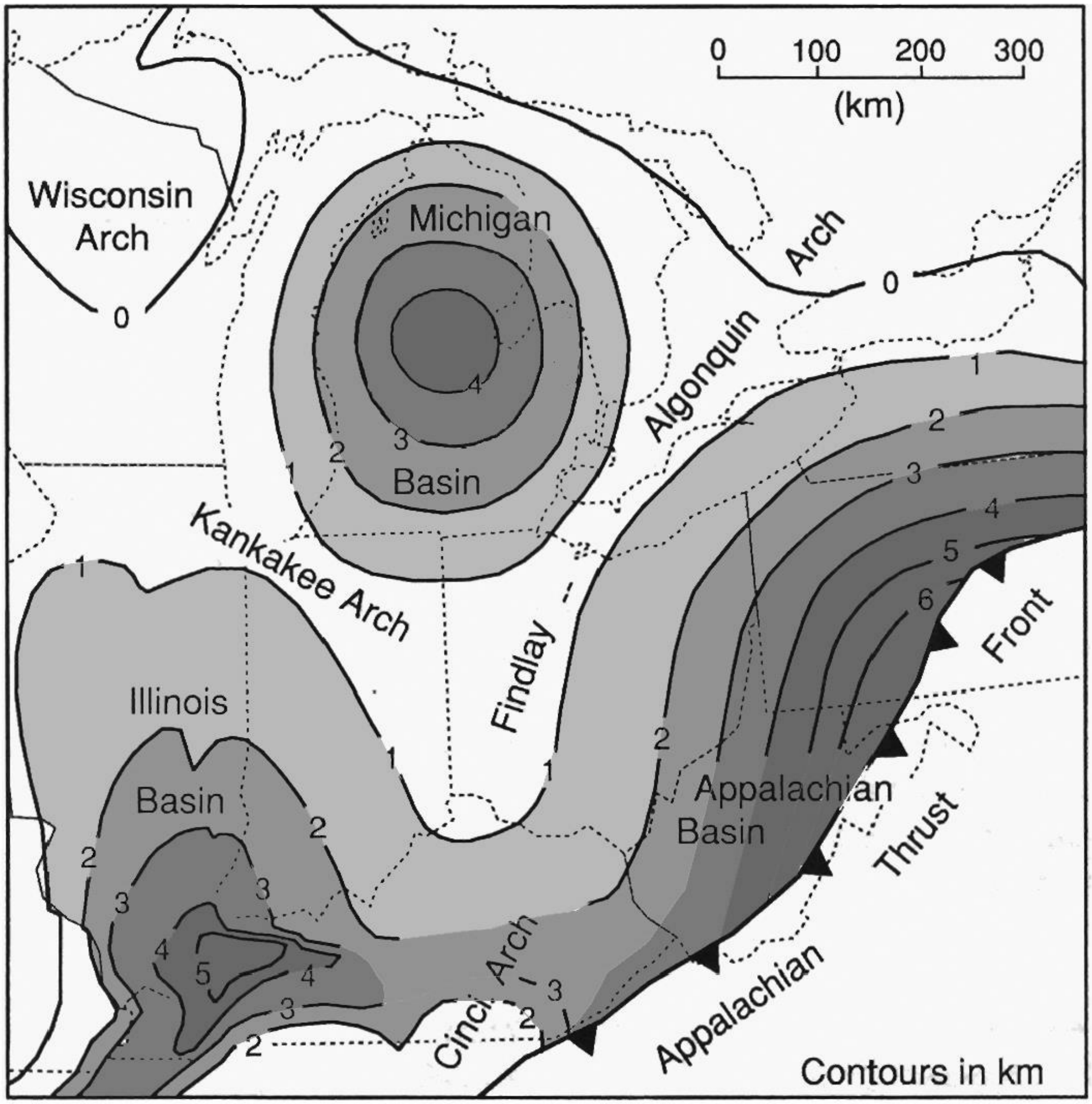


Figure1. Generalized structural setting of the intracratonic Michigan basin, Modified from: Howell and Van der Plujim, 1999. Contours are total thickness of Phanerozoic sedimentary rocks.

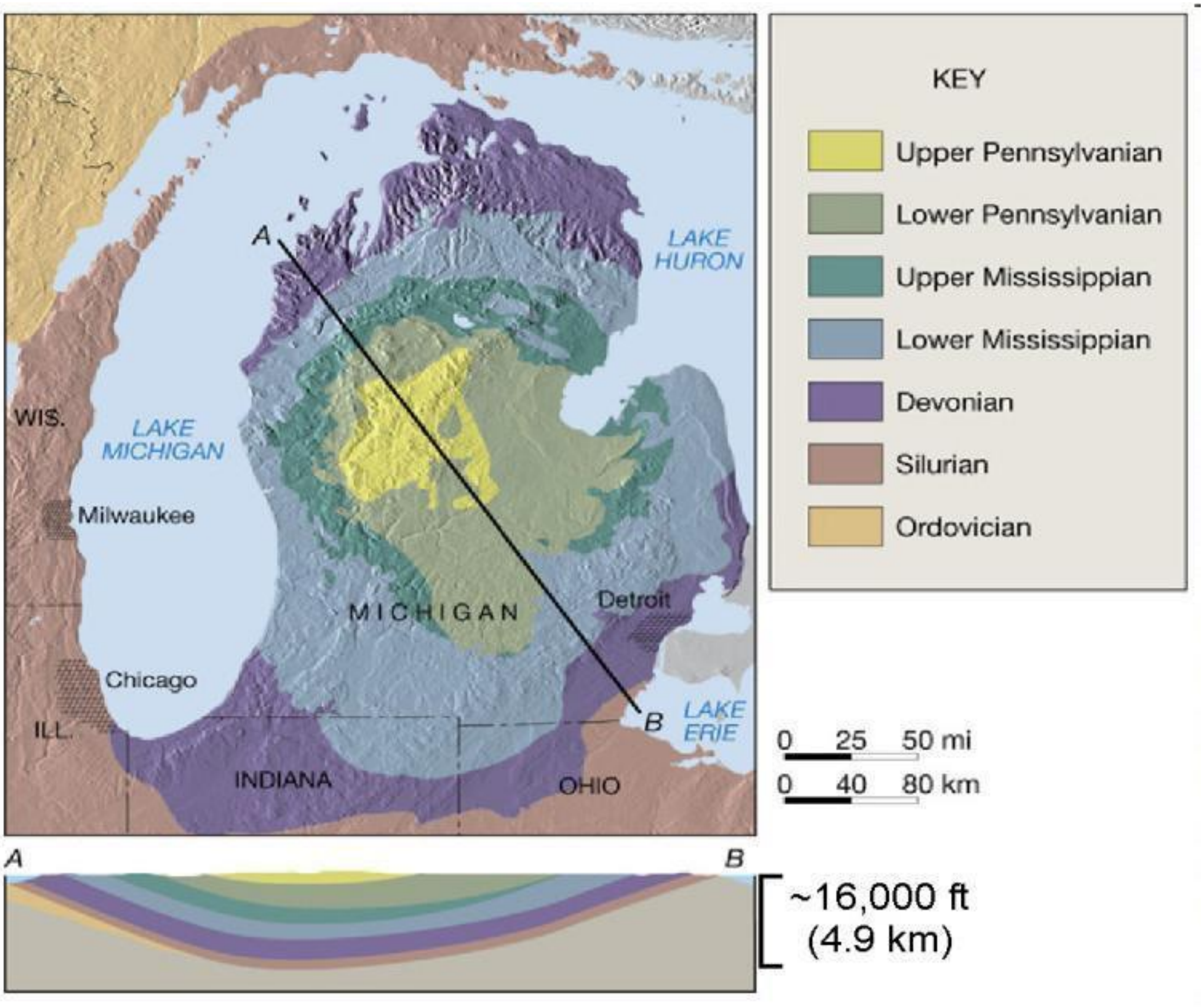


Figure 2. Simplified geological map and cross section of the intracratonic Michigan basin . Ronald C. Schott Modified from the Garrity and Soller, 2009 (http://hays.outcrop.org/images/lutge8e/Chapter_17/Text_Images/FG17_09.JPG).

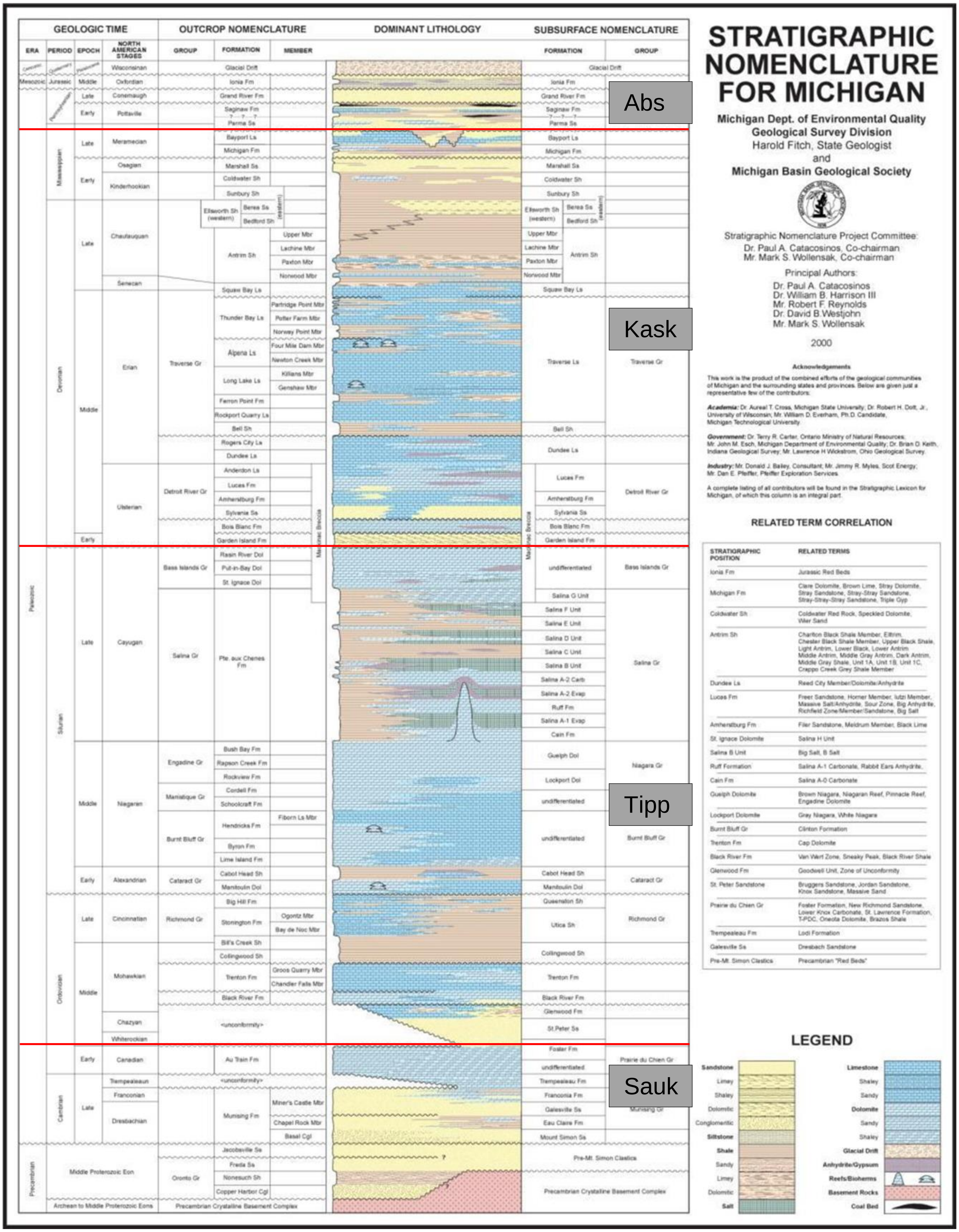


Figure 3. Michigan basin stratigraphy (Catacosinos, et al, 2001). Sloss (1963) sequence (mega-sequences) boundaries indicated by red lines: Abs is Absaroka Sequence; Kask is Kaskaskia Sequence; Tipp is Tippecanoe Sequence; and Sauk is Sauk Sequence.

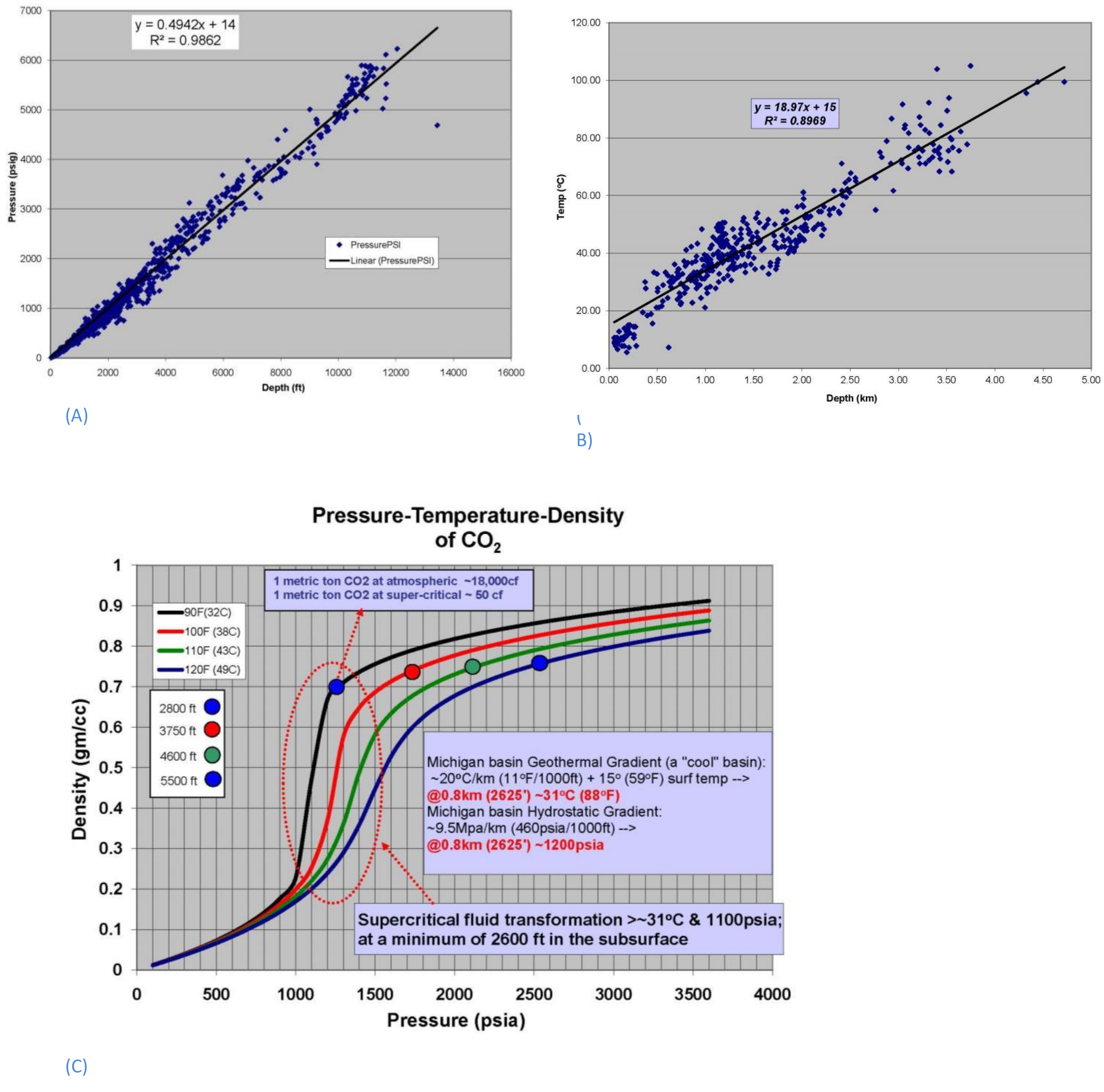


Figure 4A, B, and C. Pressure (A), and Temperature (B) gradient plots (Vugrinovich, 1986 and 1989) and pressure-density-temperature field for CO2 in the Michigan basin.

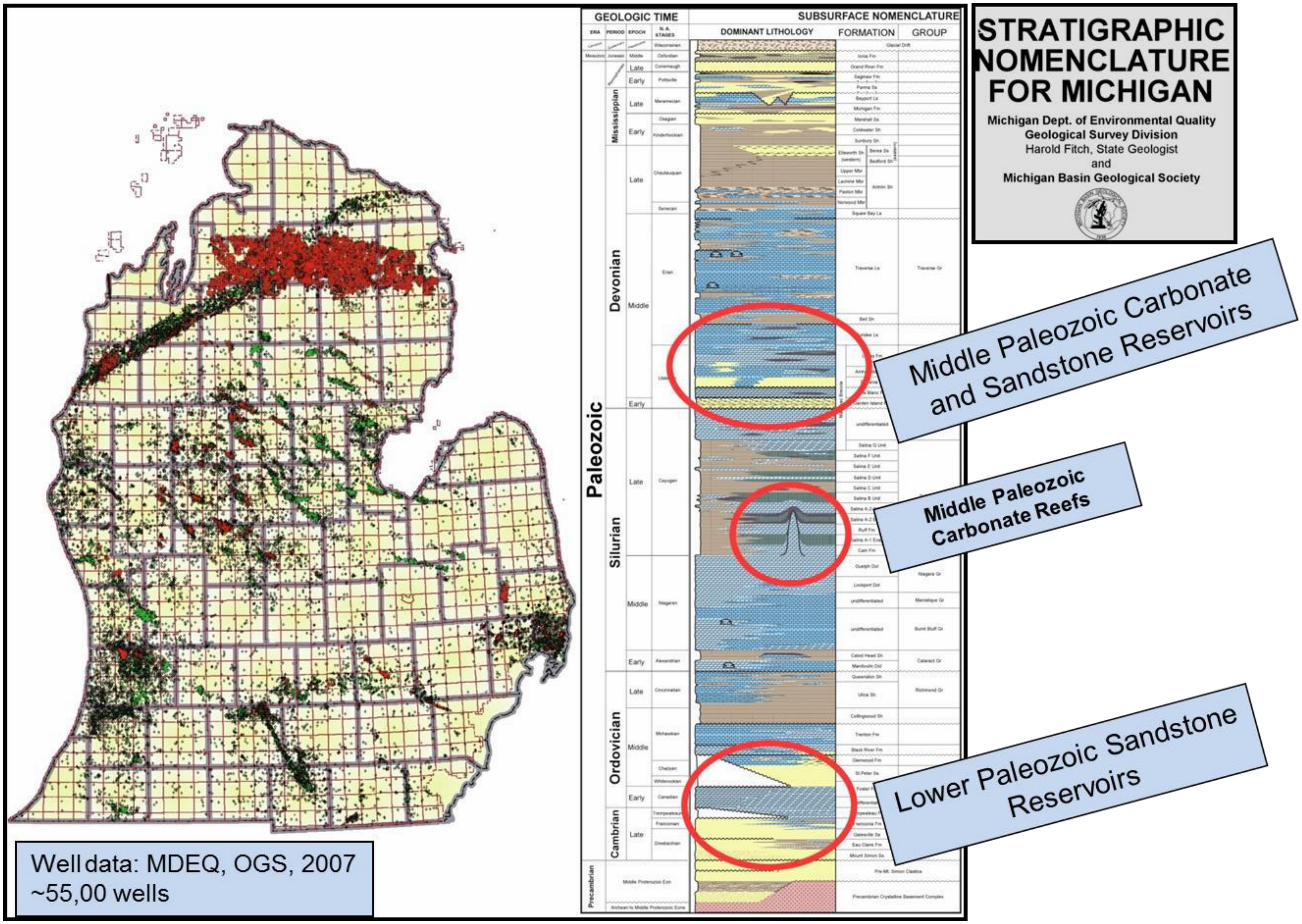
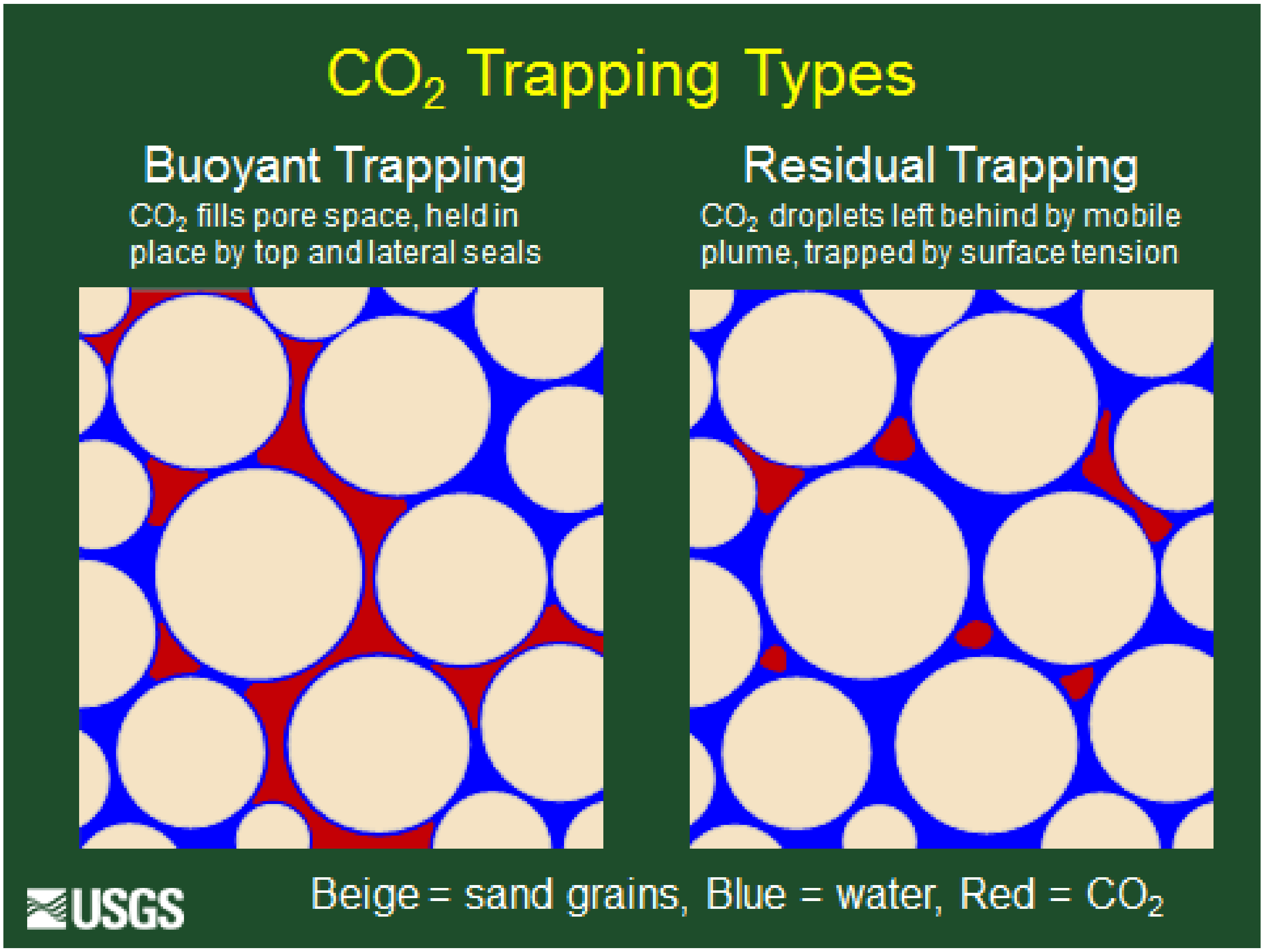


Figure 5. Oil and Gas permitted wells in Michigan (left, as of 2007) and stratigraphic nomenclature for Michigan (right) showing the most prospective horizons for GCS.



CO$_2$ Trapping Types

Buoyant Trapping

CO$_2$ fills pore space, held in place by top and lateral seals

Residual Trapping

CO$_2$ droplets left behind by mobile plume, trapped by surface tension

USGS

Beige = sand grains, Blue = water, Red = CO$_2$

Figure 6. Trapping mechanisms for GCS. Buoyancy traps are typical of oil/gas reservoirs while capillary entrapment is typically the mechanism responsible for CO2 entrapment in either confined or unconfined saline aquifer GCS reservoirs (Brennen, et. al., 2010)

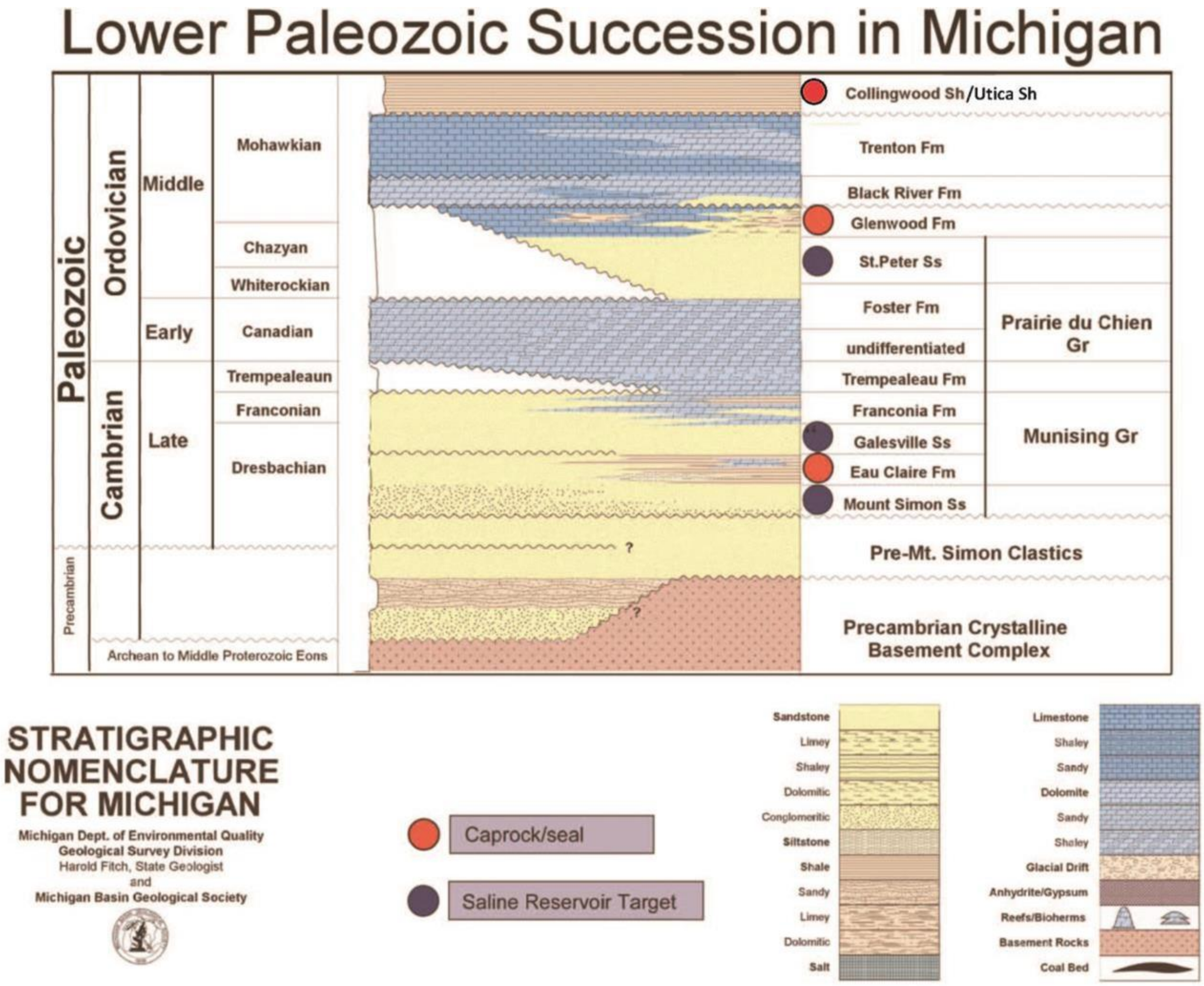
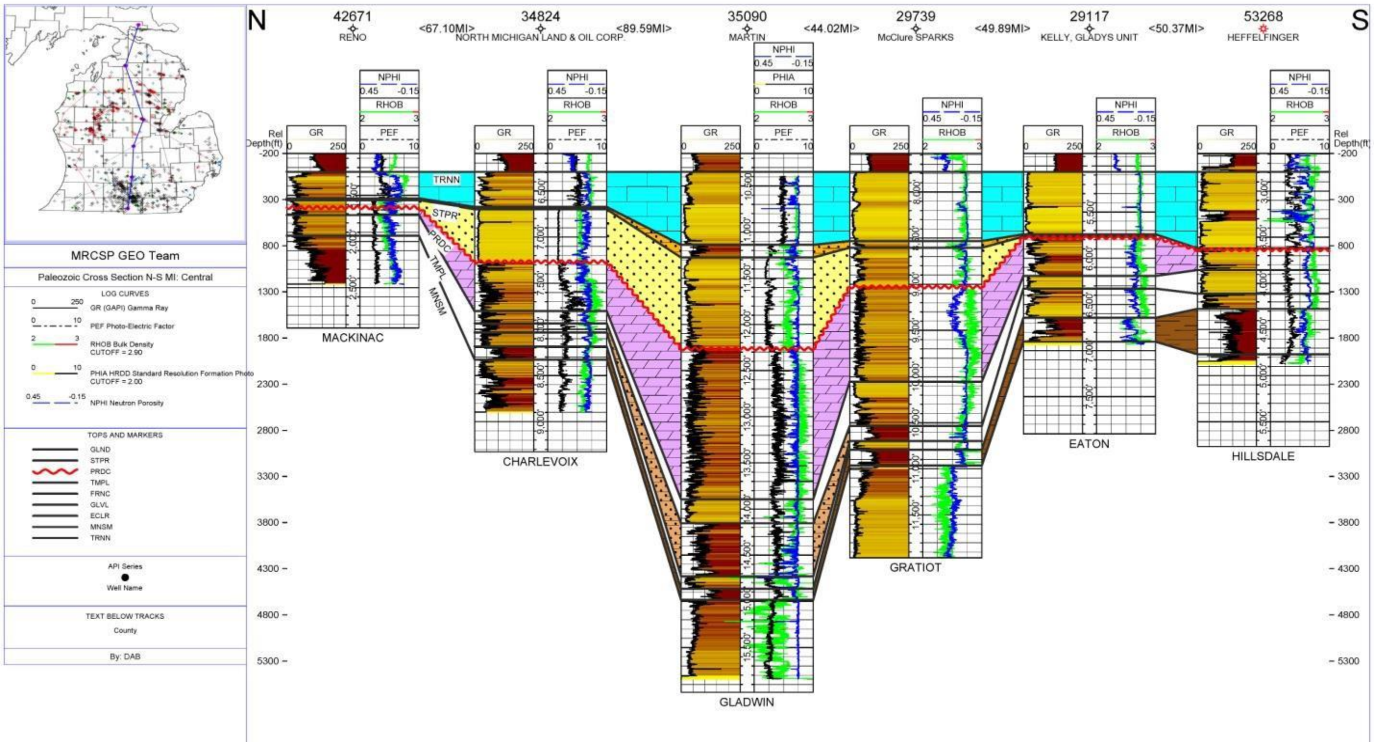
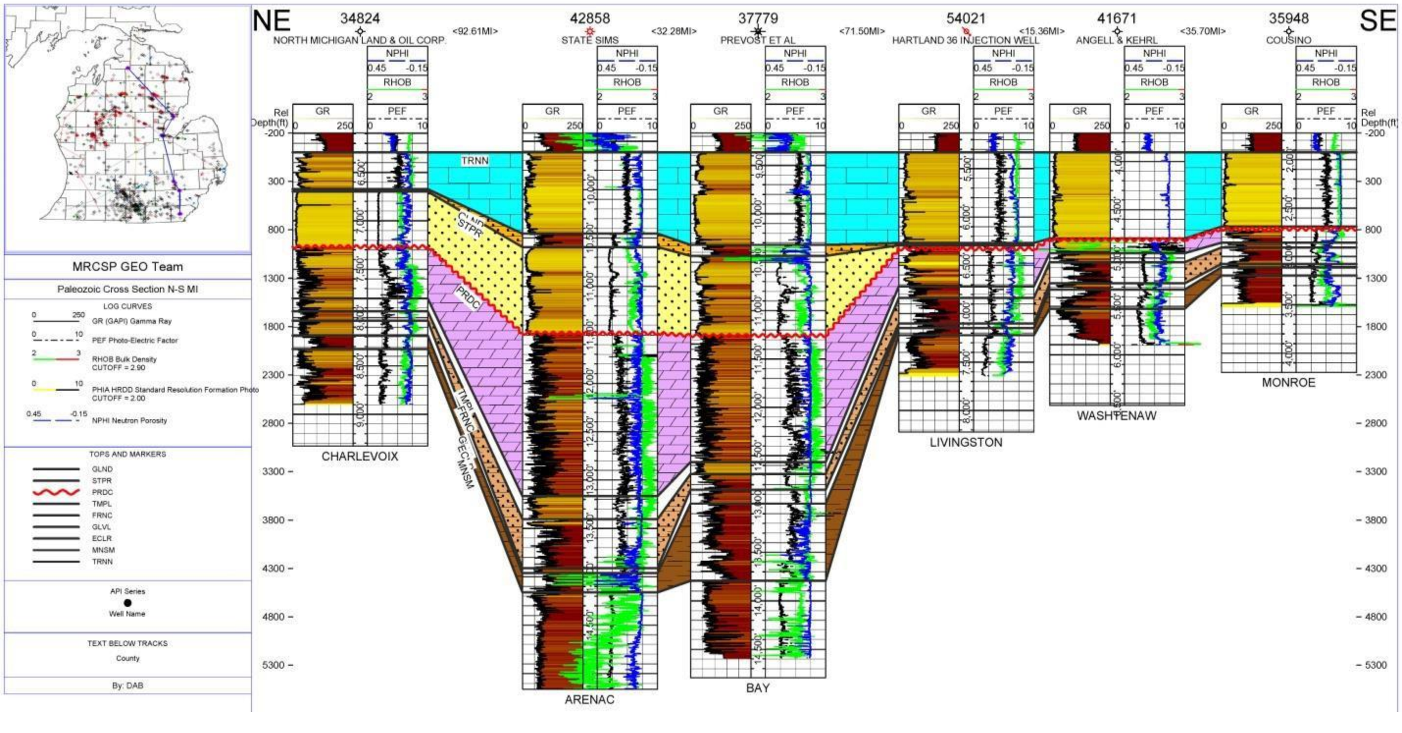


Figure 7. Lower Paleozoic stratigraphy and sequestration targets in the Michigan basin (Catacosinos, et. al., 2001)

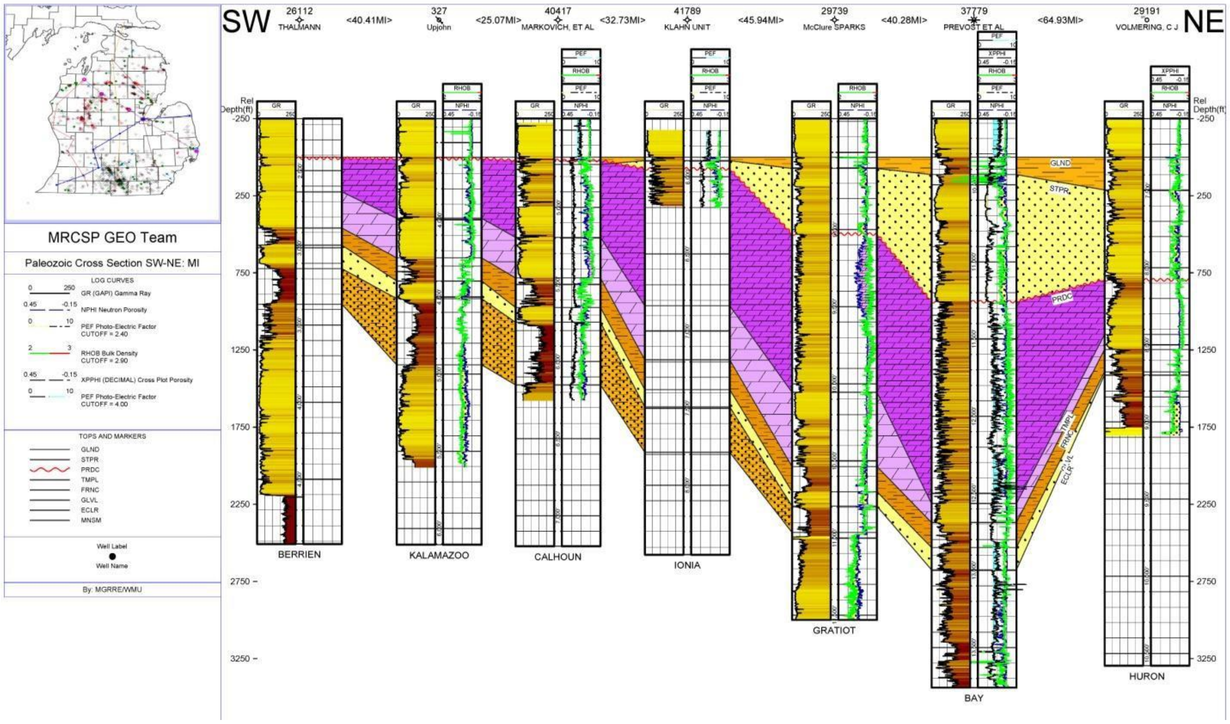


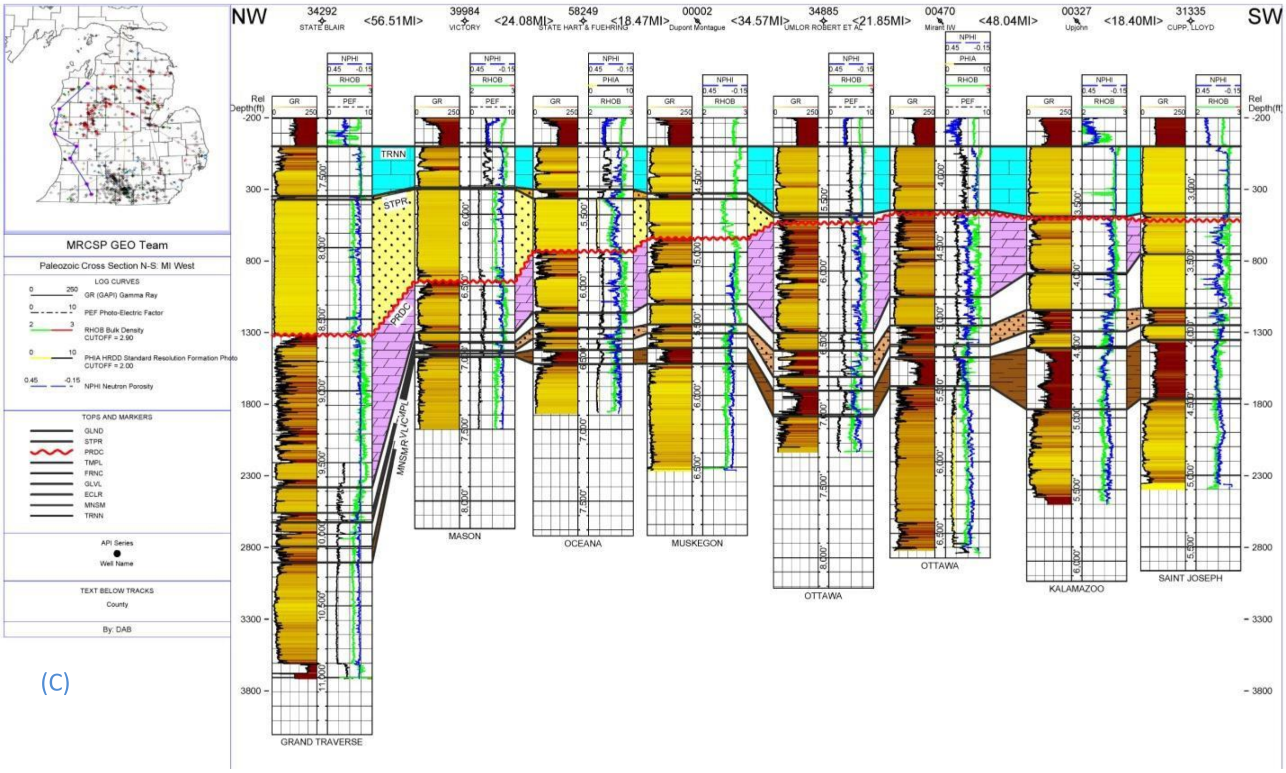
(A)



(B)

Figures 7 (A) and (B). Regional cross sections showing stratigraphic relationships of lower Paleozoic strat in the Michigan basin





(C)

Figures 7 (C) and (D) Regional cross sections showing stratigraphic relationships of lower Paleozoic strata in the Michigan basin

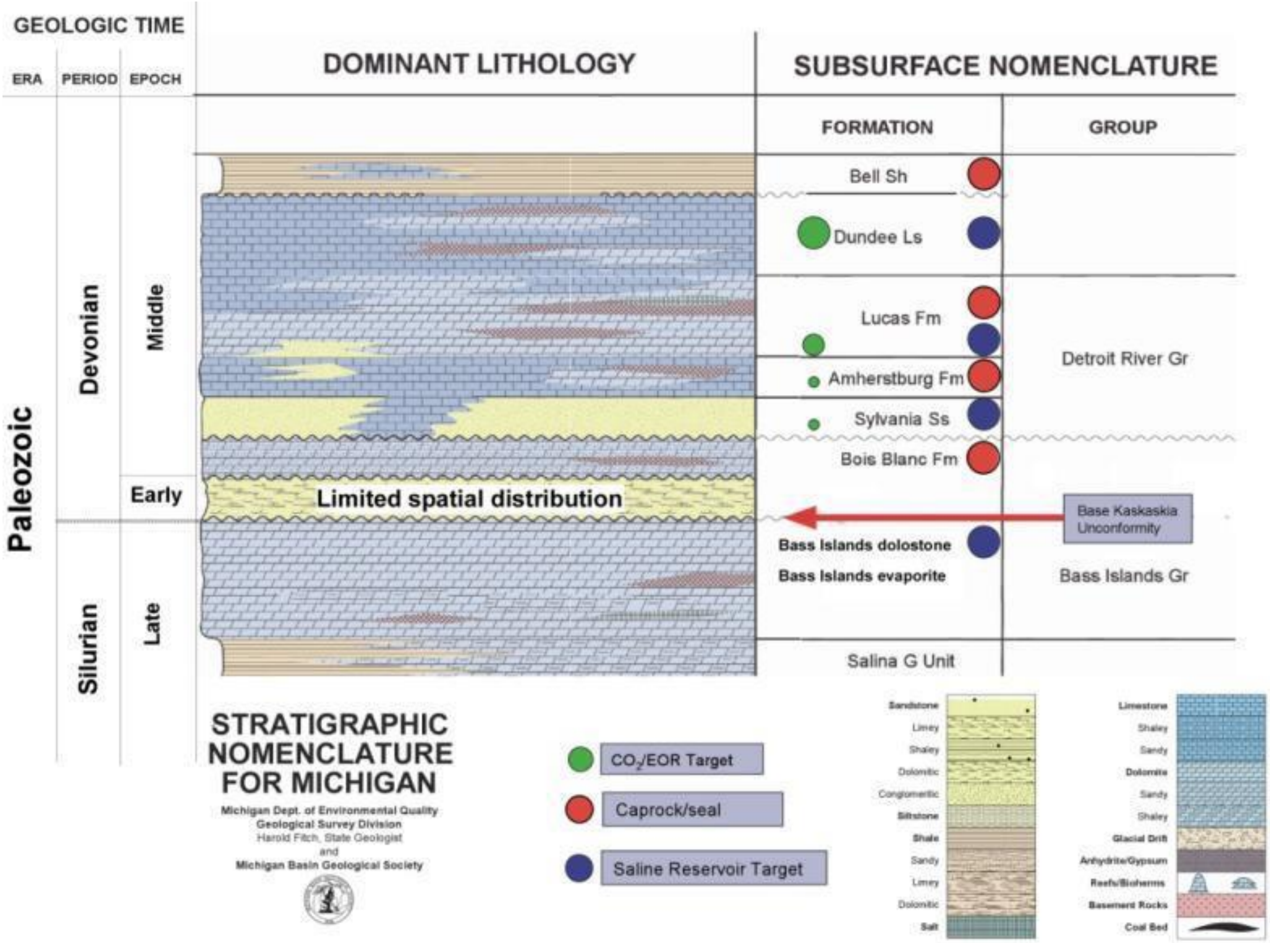


Figure 8. Middle Paleozoic stratigraphy and sequestration targets in the Michigan basin (Catacosinos, et. al., 2001)

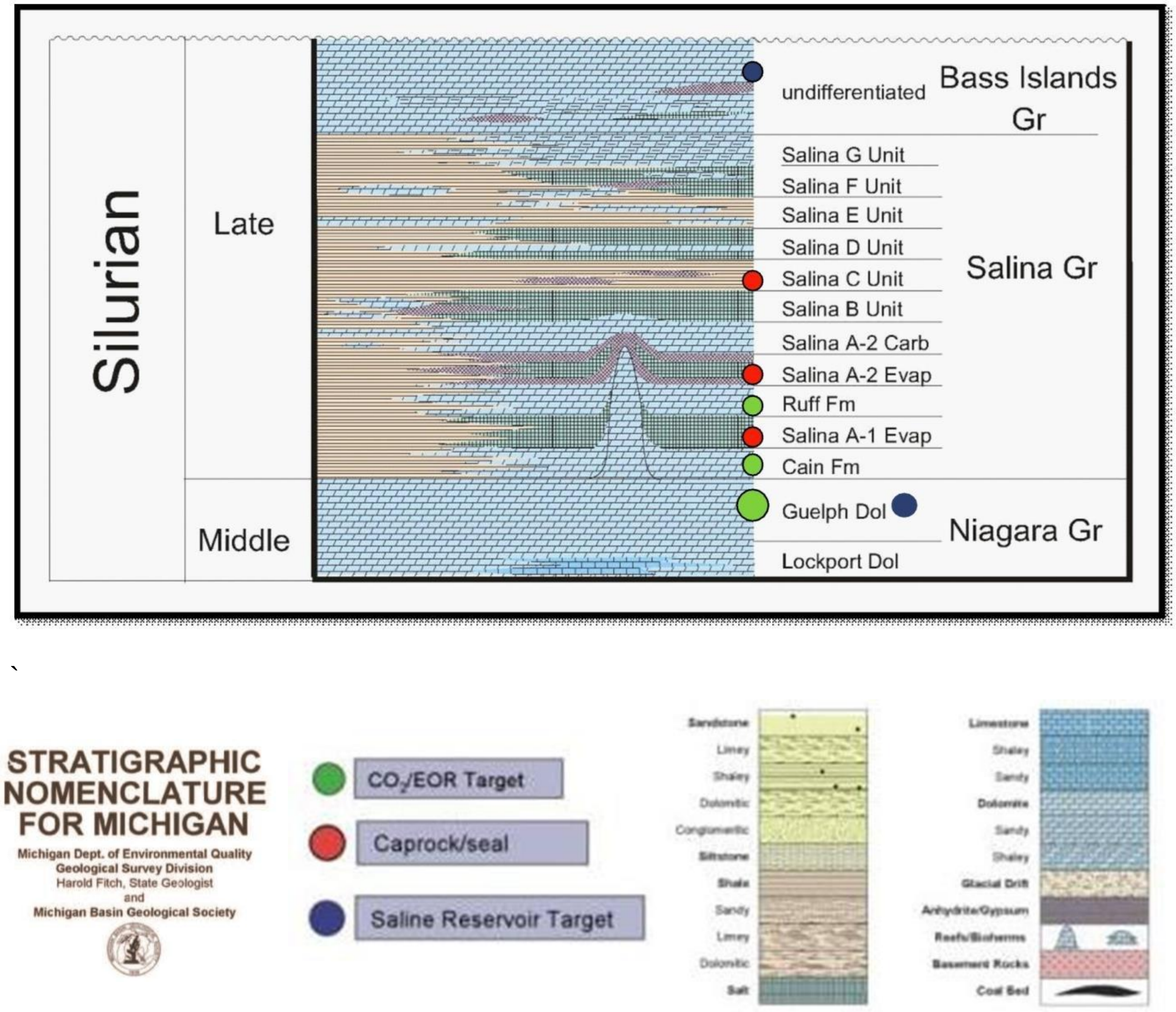


Figure 9. Middle-Late Silurian stratigraphy in the Michigan basin (Catacosinos, et. al., 2001)

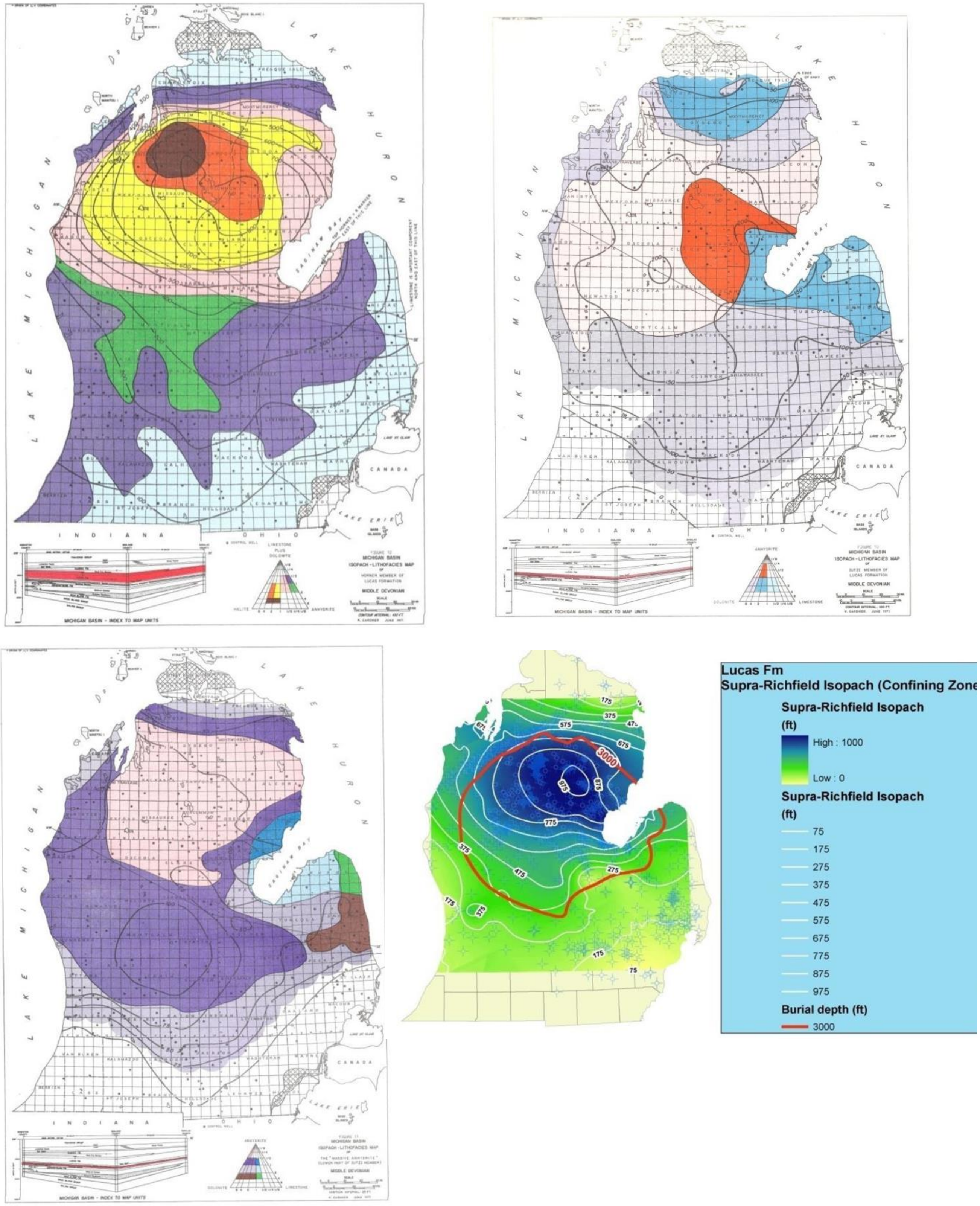


FIgure 10. Isopach maps of Lucas Formation evaporite-prone members; Horner, Iutzi, and Massive Anhydrite (Gardner 1974). Inset: composite thickness of the supra-Richfield Member units of the Lucas.

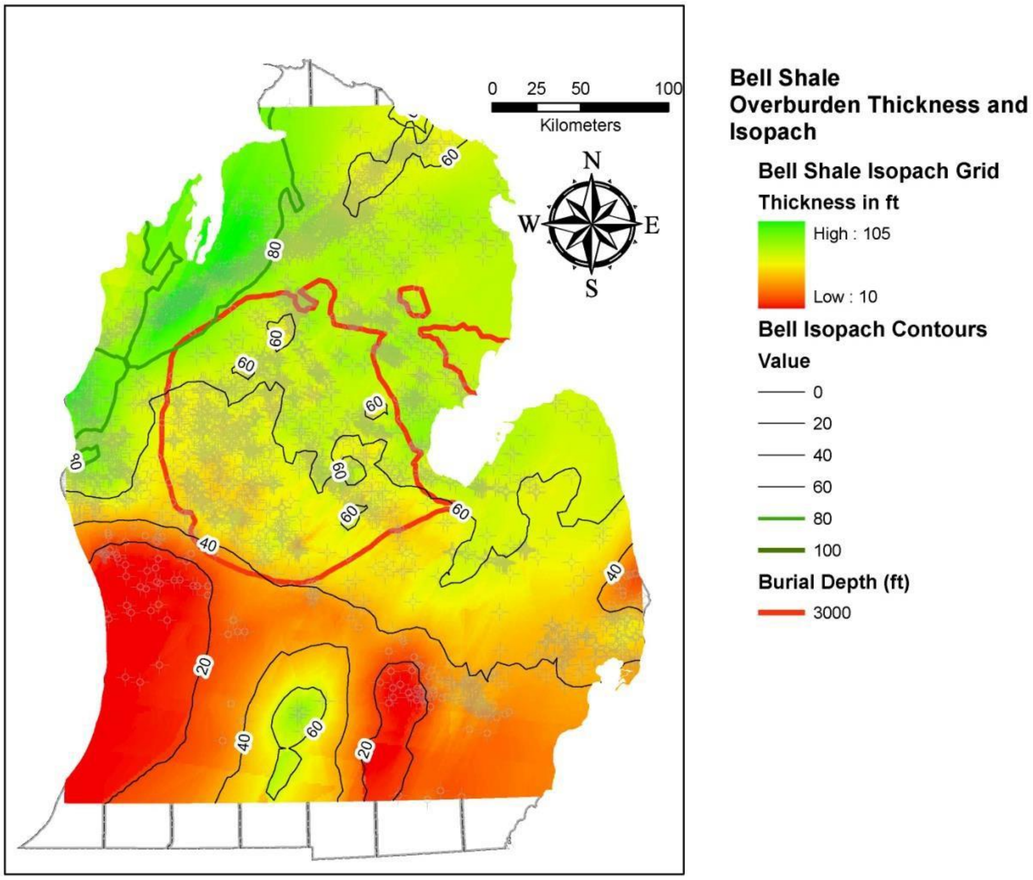


Figure 11. Isopach and burial depth contours for the Bell Shale confining layer in Michigan.

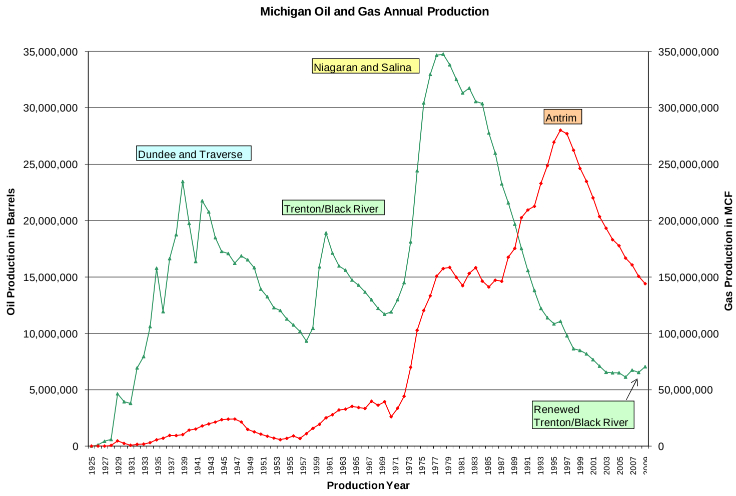
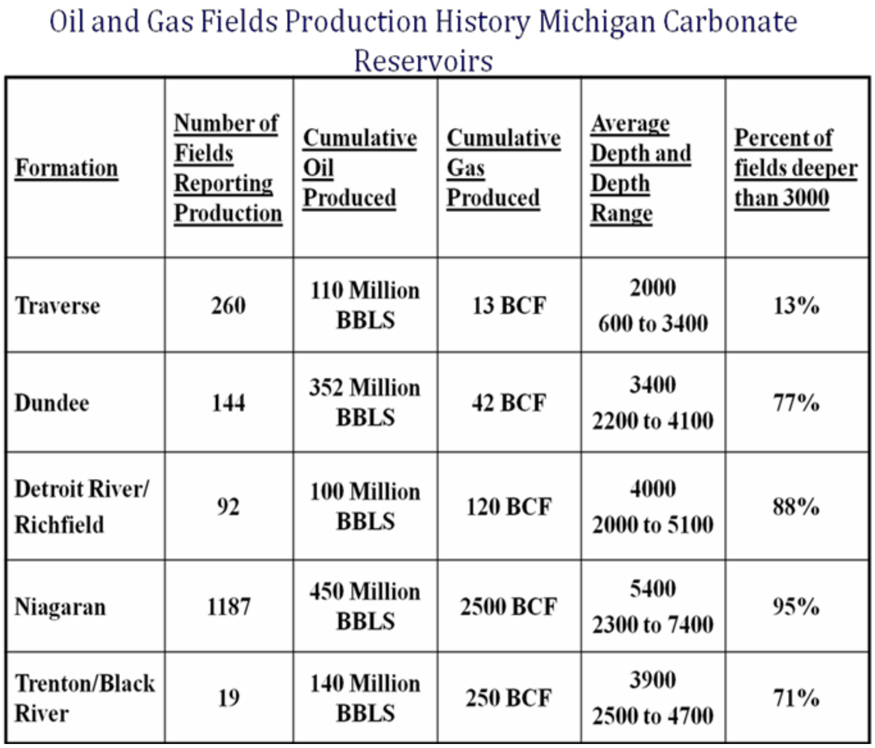


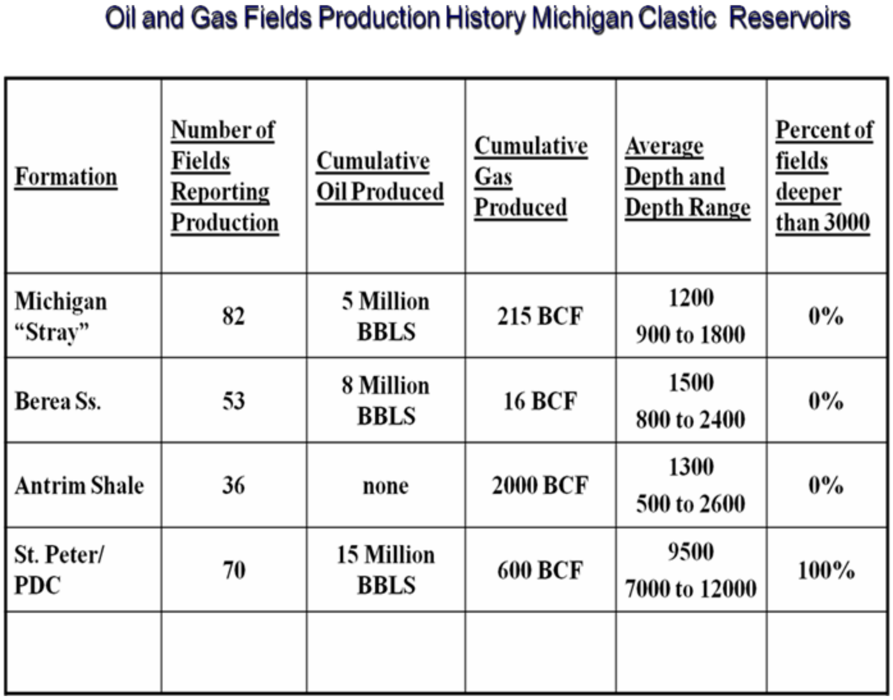
Figure 12. Production history trends of Michigan oil and gas.



Oil and Gas Fields Production History Michigan Carbonate Reservoirs

Formation	Number of Fields Reporting Production	Cumulative Oil Produced	Cumulative Gas Produced	Average Depth and Depth Range	Percent of fields deeper than 3000
Traverse	260	110 Million BBLS	13 BCF	2000 600 to 3400	13%
Dundee	144	352 Million BBLS	42 BCF	3400 2200 to 4100	77%
Detroit River/ Richfield	92	100 Million BBLS	120 BCF	4000 2000 to 5100	88%
Niagaran	1187	450 Million BBLS	2500 BCF	5400 2300 to 7400	95%
Trenton/Black River	19	140 Million BBLS	250 BCF	3900 2500 to 4700	71%

Table 1



Oil and Gas Fields Production History Michigan Clastic Reservoirs

Formation	Number of Fields Reporting Production	Cumulative Oil Produced	Cumulative Gas Produced	Average Depth and Depth Range	Percent of fields deeper than 3000
Michigan “Stray”	82	5 Million BBLS	215 BCF	1200 900 to 1800	0%
Berea Ss.	53	8 Million BBLS	16 BCF	1500 800 to 2400	0%
Antrim Shale	36	none	2000 BCF	1300 500 to 2600	0%
St. Peter/ PDC	70	15 Million BBLS	600 BCF	9500 7000 to 12000	100%

Table 2

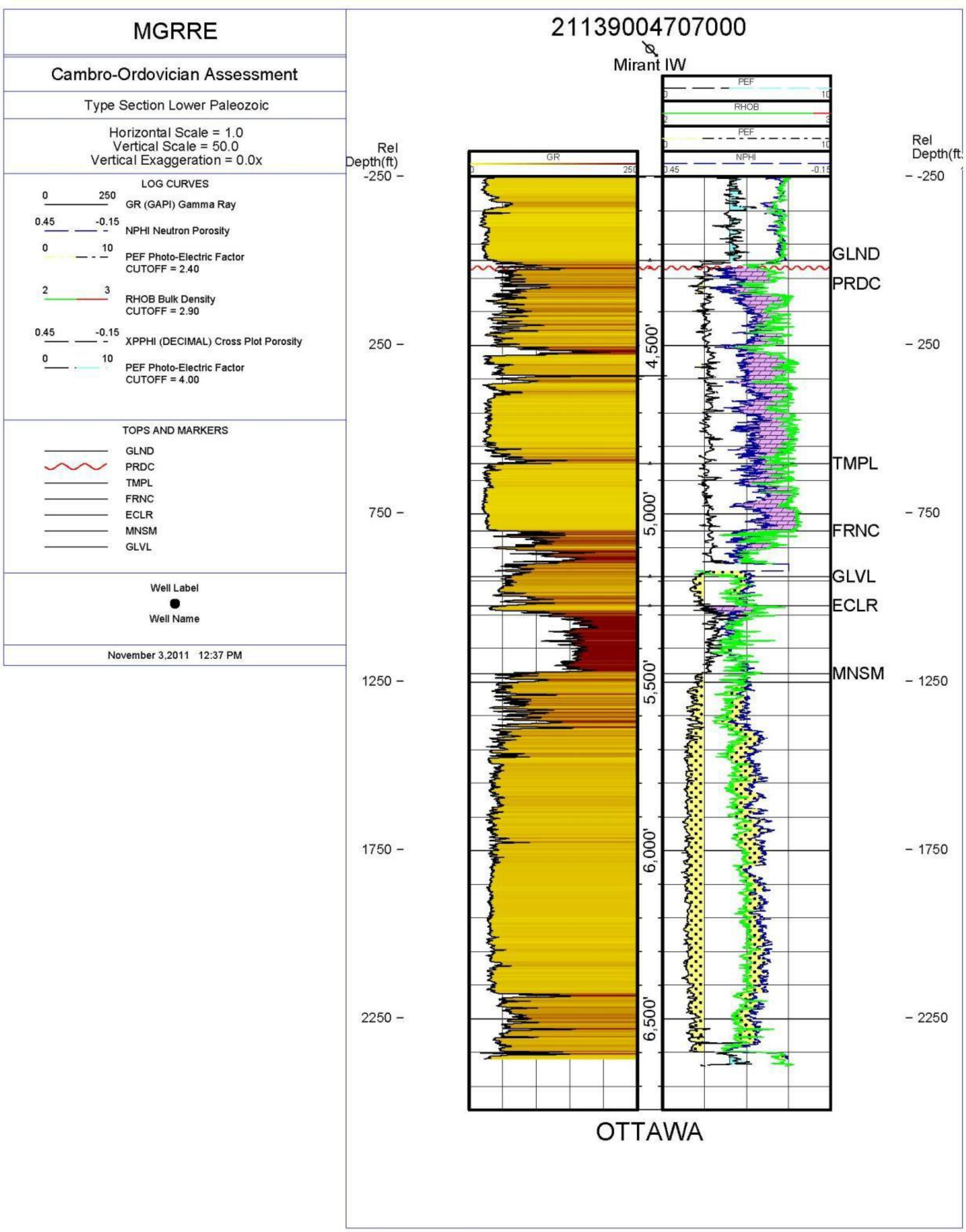
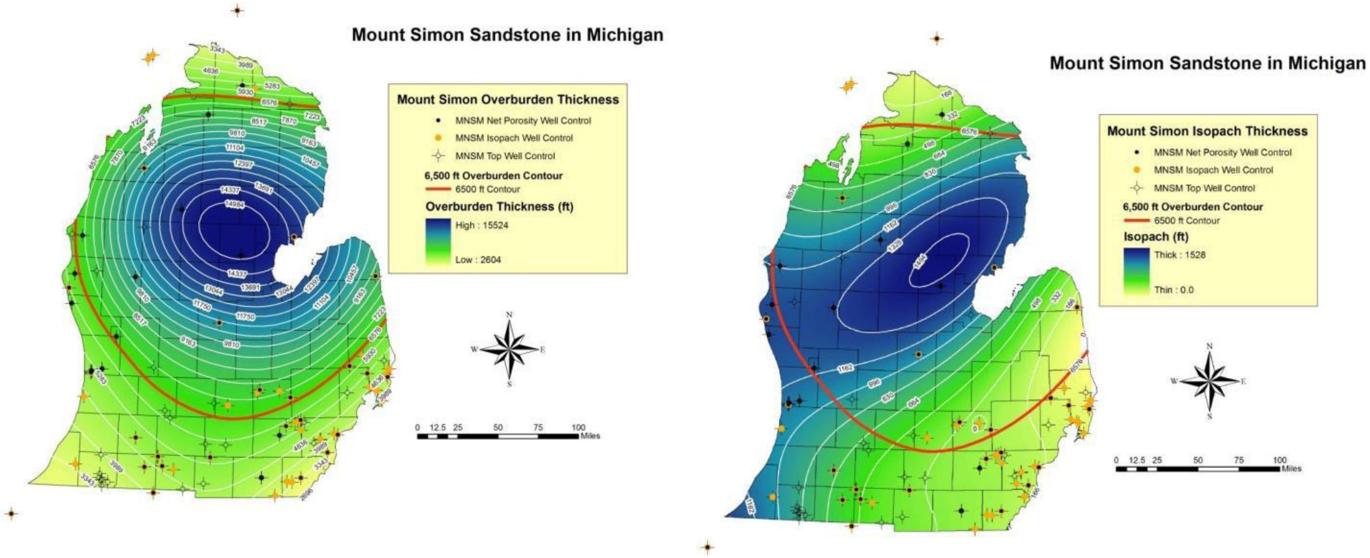


Figure 13. Type log section of the Mount Simon Sandstone formation in Ottawa Co. MI, P#21139004707000, Mirant Injection Well. Log tracs display are gamma ray (trac 1) with color ramp display; density, neutron porosity, and photoelectric factor (see legend). In trac 2. Note that interpretive fill (yellow doted pattern for sandstone, purple brick pattern for dolomite) are included as a "quick look representation of gross lithology in trac 2)



(A) (B)

Figure 14. (A) Drill depth (overburden thickness) map and Isopach (formation thickness) map (B) of the Mount Simon Sandstone in Lower Michigan

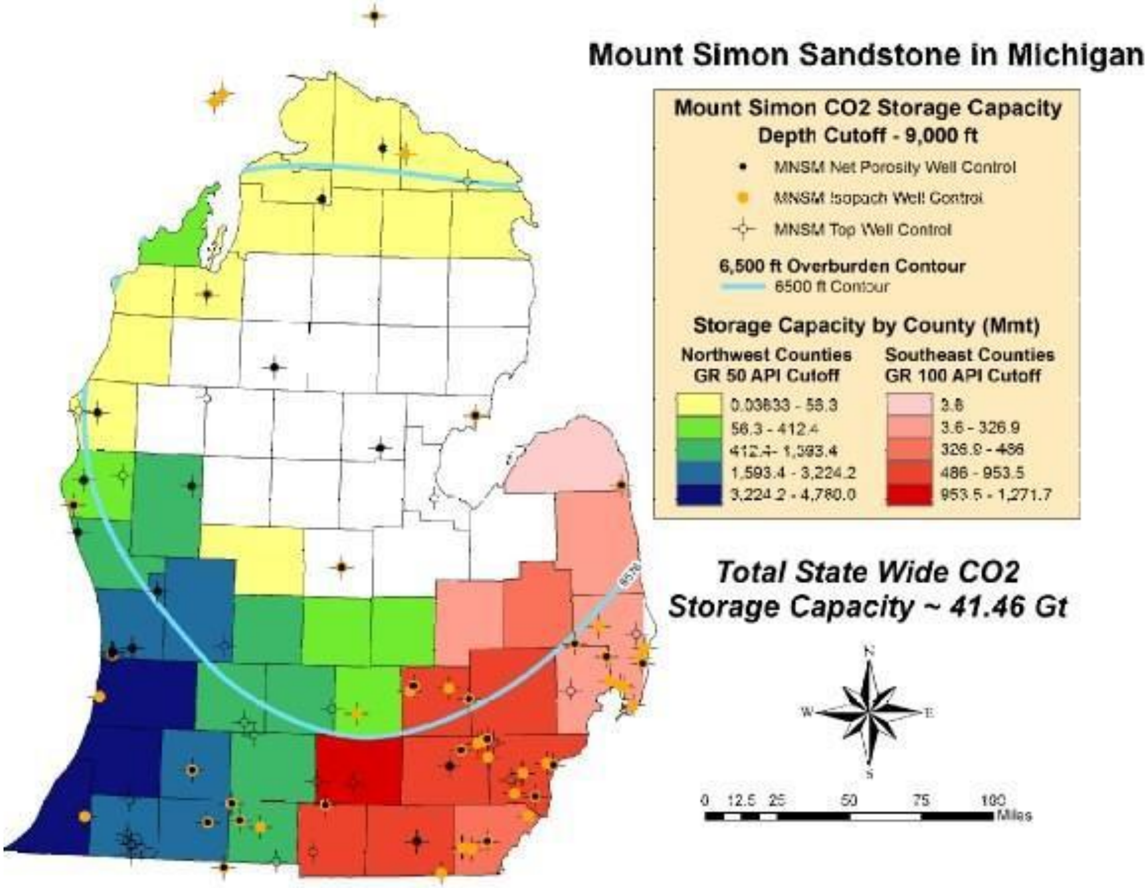


Figure 15. Mount Simon Sandstone GCS capacity estimate map, by county.

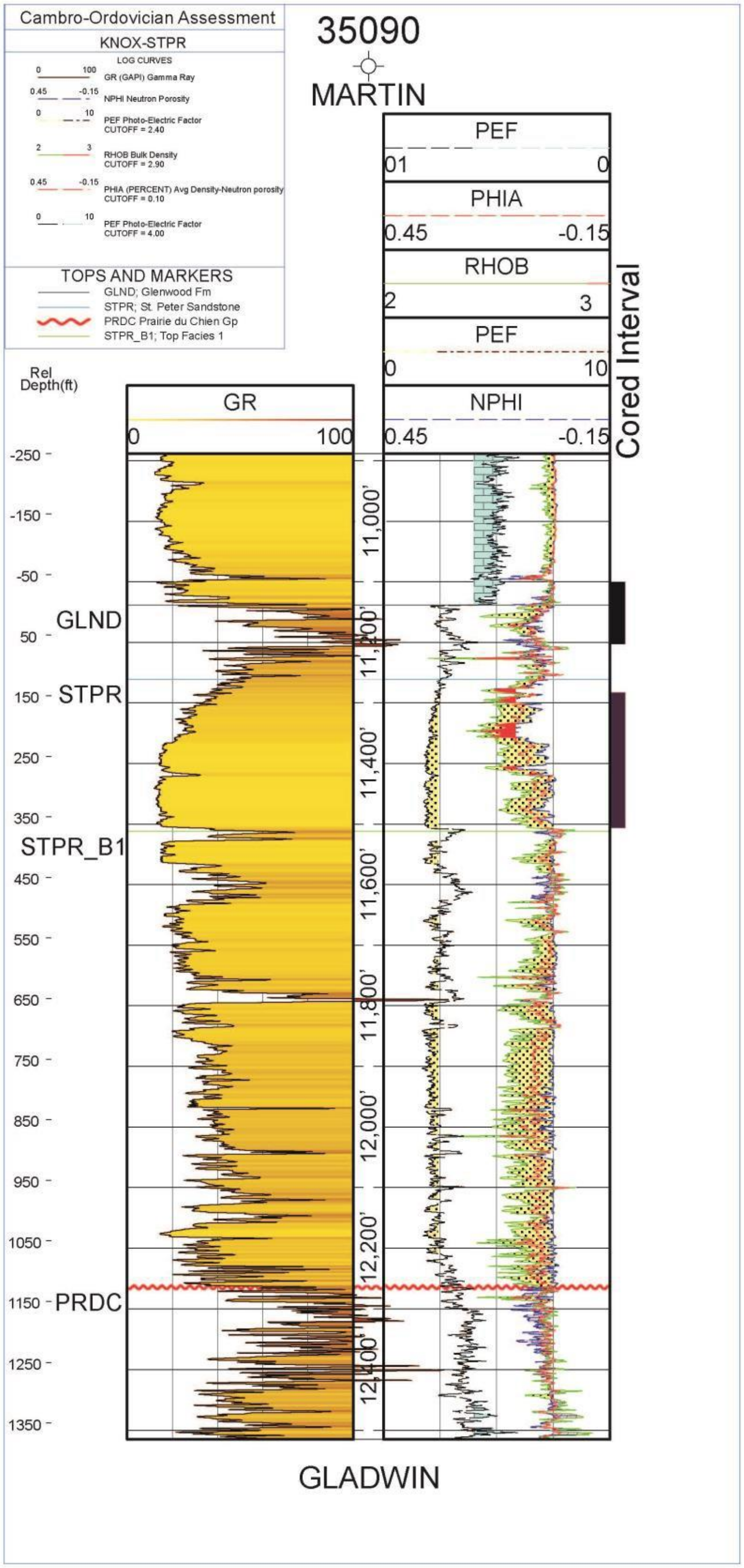
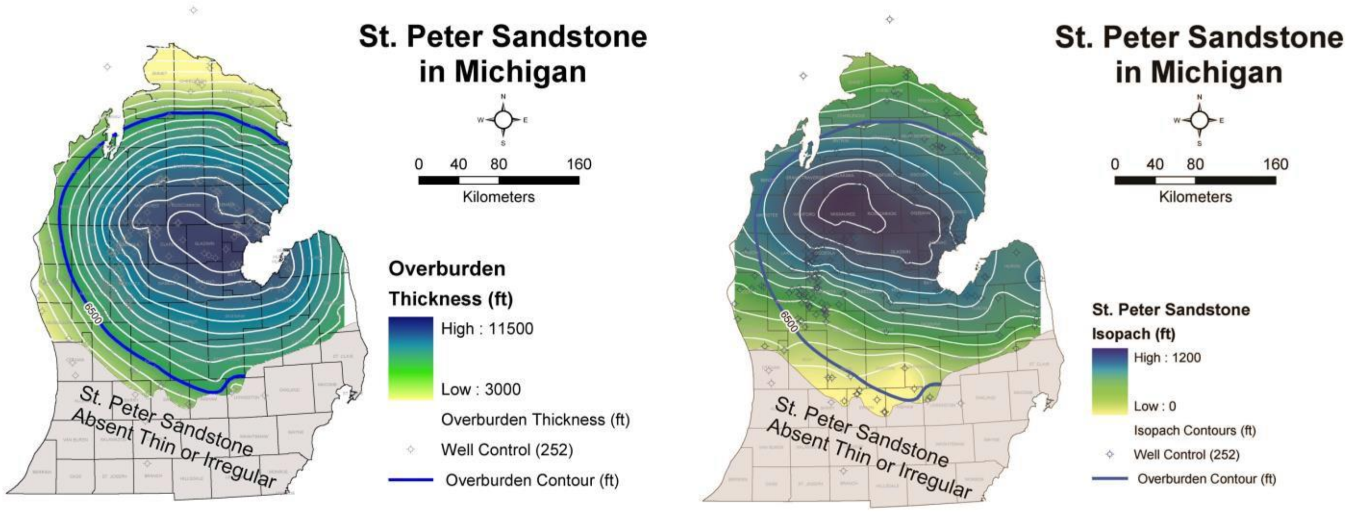


Figure 16. Type log section of the St. Peter Sandstone in well Permit #35090. Graphics similar to Figure 10.



(A) (B)

Figure 17A. Drill depth (overburden thickness) map and Isopach (formation thickness) map (B) of the St. Peter Sandstone in Lower Michigan.

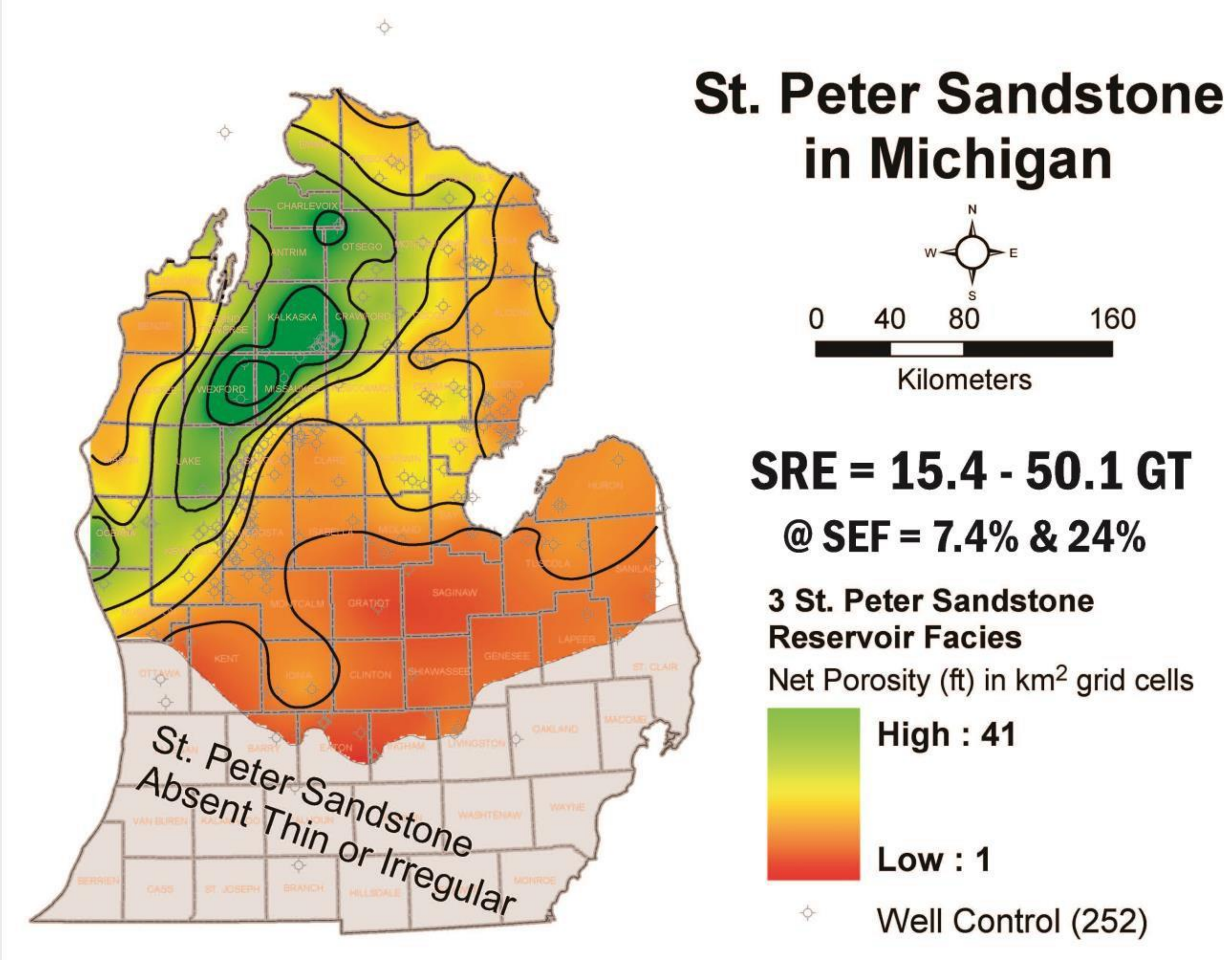
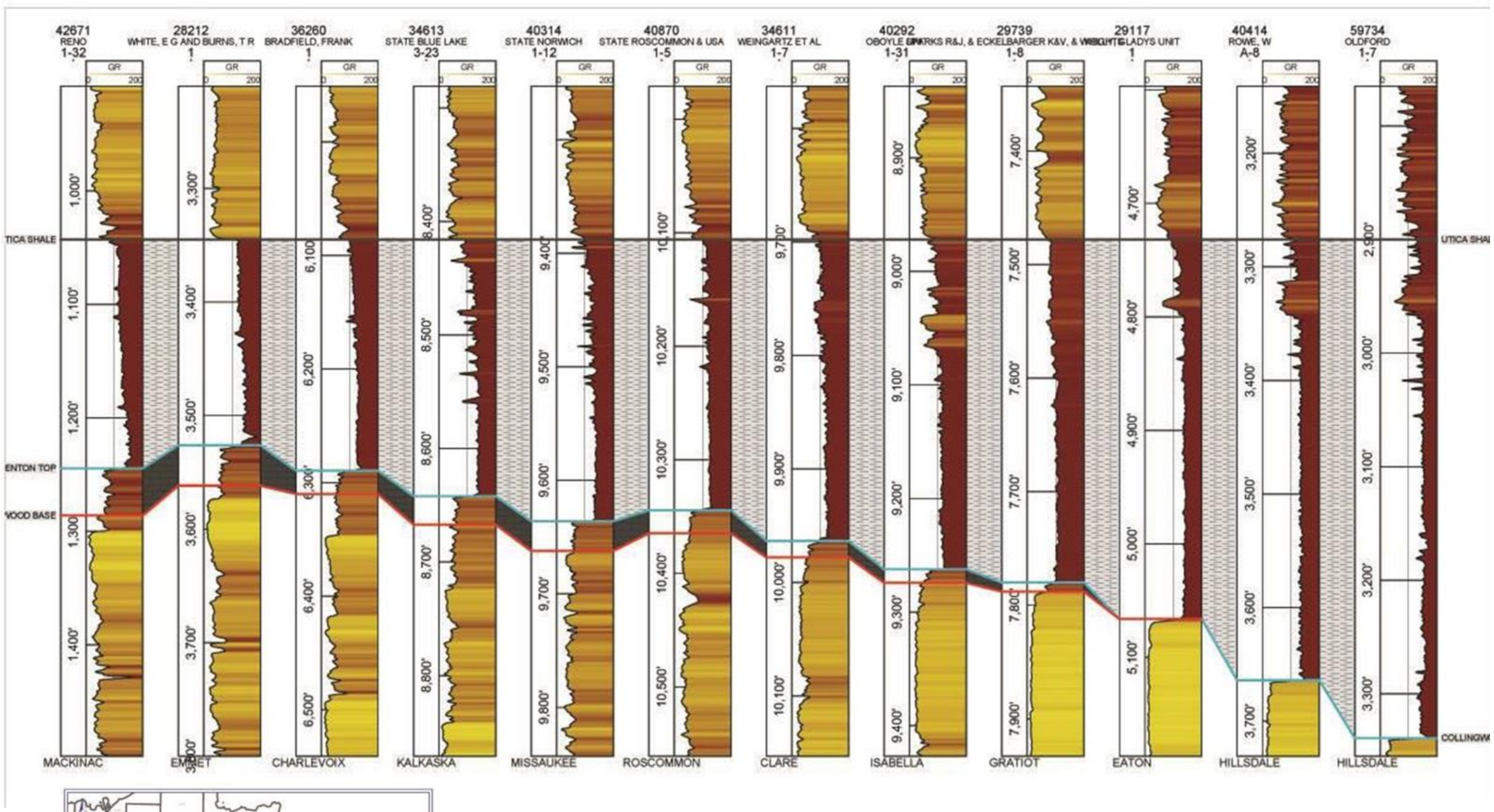


Figure 18. St. Peter Sandstone GCS capacity estimate map.



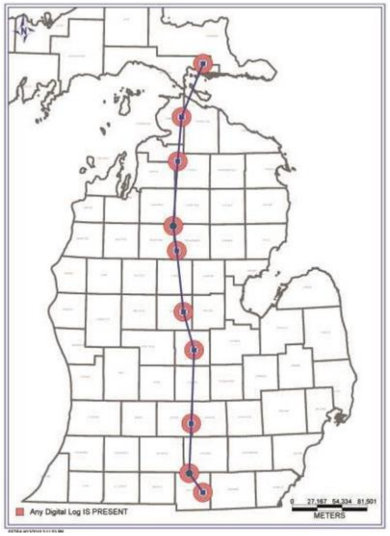


Figure 19. Regional cross section and map showing the persistence and substantial thickness (>100ft) of the combined Utica-Collingwood shale formations demonstrating the stratigraphic suitability of these units as primary confining layers for lower Paleozoic GCS injection targets.

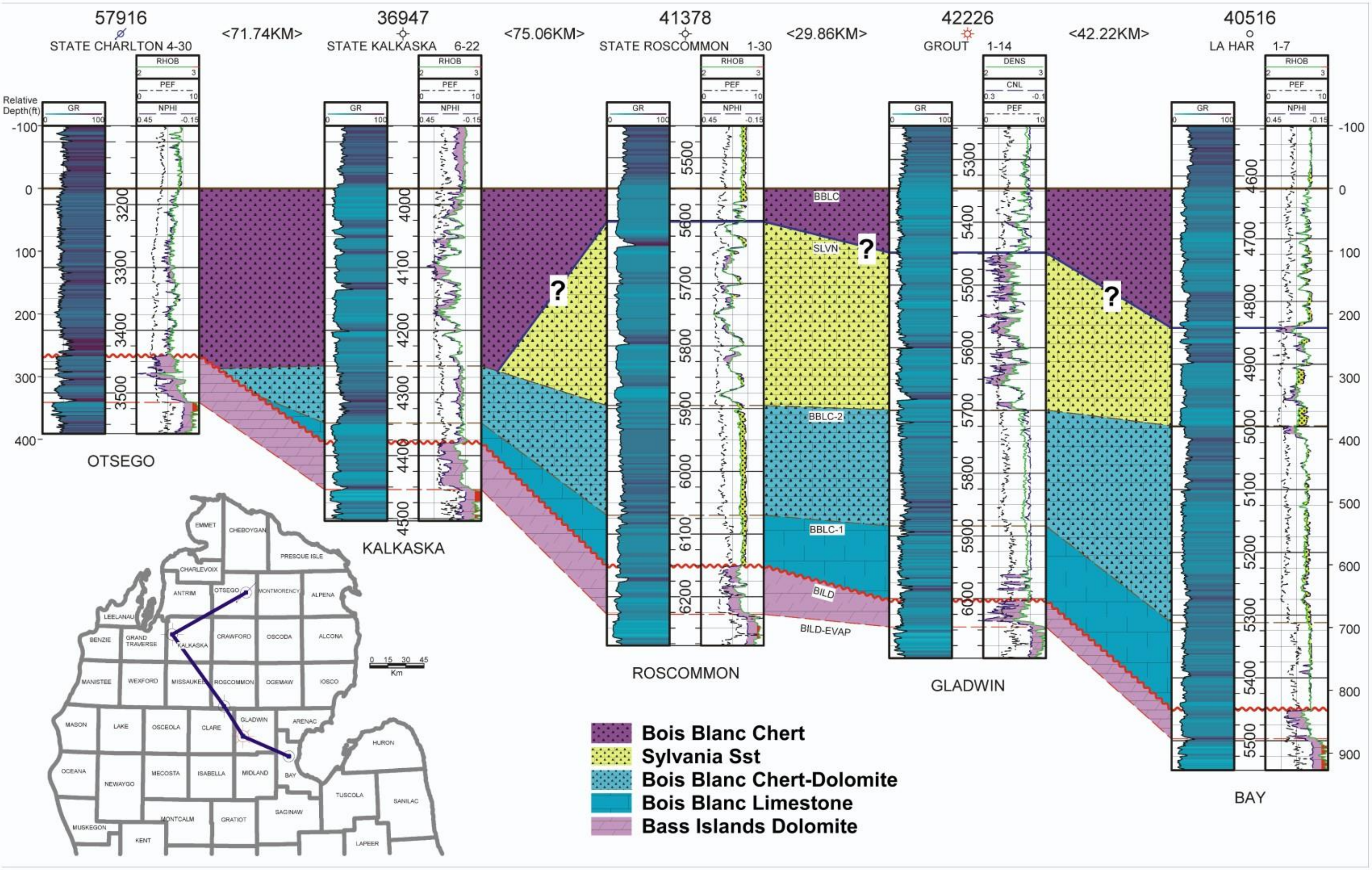


Figure 20. Central Michigan basin regional wireline log cross section(with inset location map) in the Silurian-Middle Devonian. Shaded parts of track 2 are parts of the log where the neutron porosity curve crosses over to the left of the bulk density log suggesting dolomite lithology in carbonate dominated intervals. GR = gamma ray; PEF = photoelectric factor. Red wavey line indicates the base Kaskaskia unconformity.

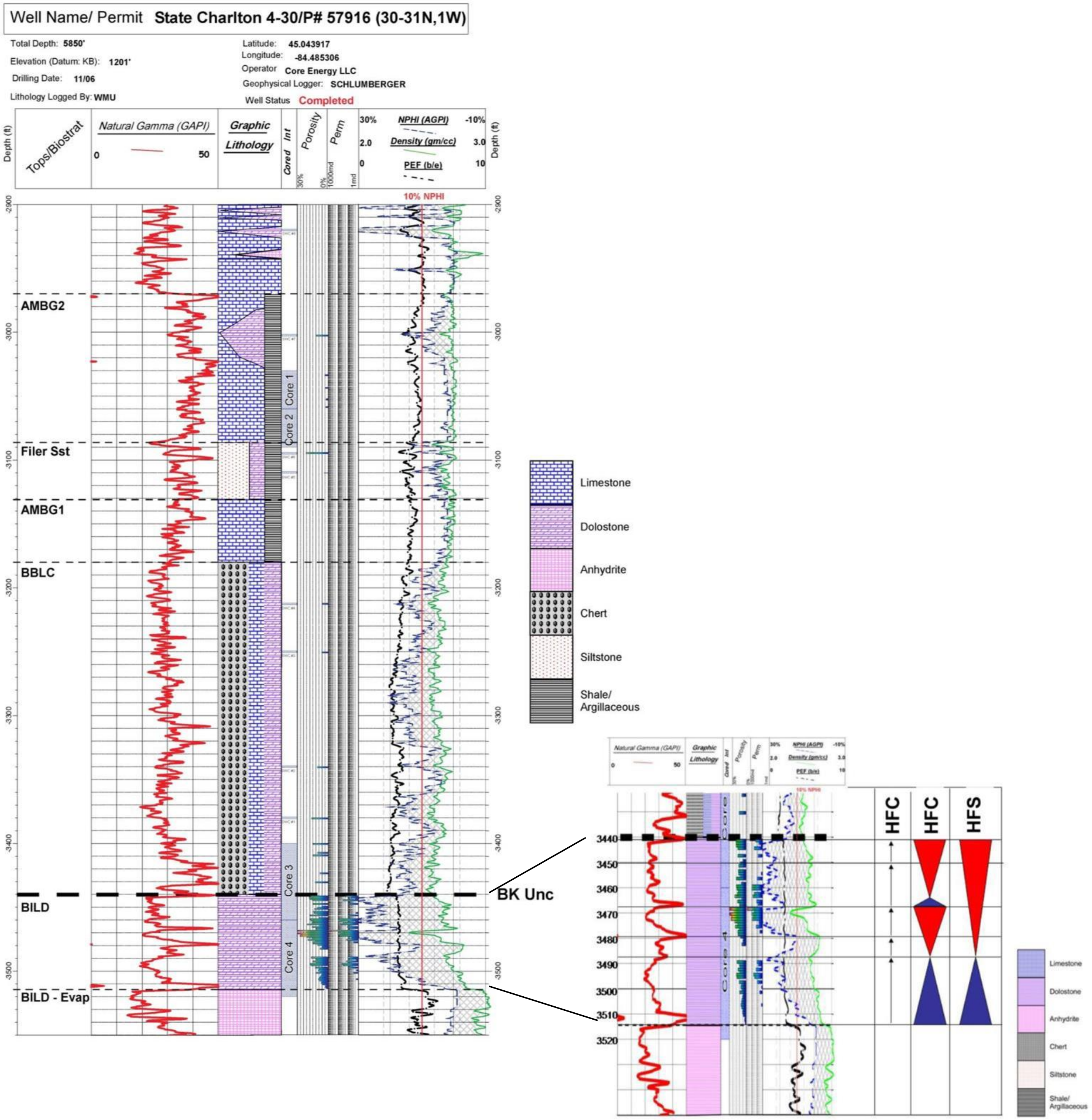


Figure 21A and B. Figure 21A (left) is a type log section of Silurian-Devonian strata in the State Charlton 4-30 well (P#57196) Otsego Co. AMBG1 and 2 are the tops of informal portions of the Amherstburg Formation, Filer Sst is an informal subsurface unit, BBLC is the top Bois Blanc Formation, and BILD and BILD-Evap are the tops of informal Bass Islands Group units (see text for discussion). Figure 21B (lower right) is an enlargement of the Bass Islands dolomite reservoir interval, showing interpreted high frequency sequences (HFS) along with higher frequency cycles, which correlate well to the stratigraphic position of the best reservoir intervals. HFS and cycle (HFC) boundaries are typically manifested by higher gamma ray log values. Red and blue triangles represent regressive and transgressive cycles and sequences, respectively.

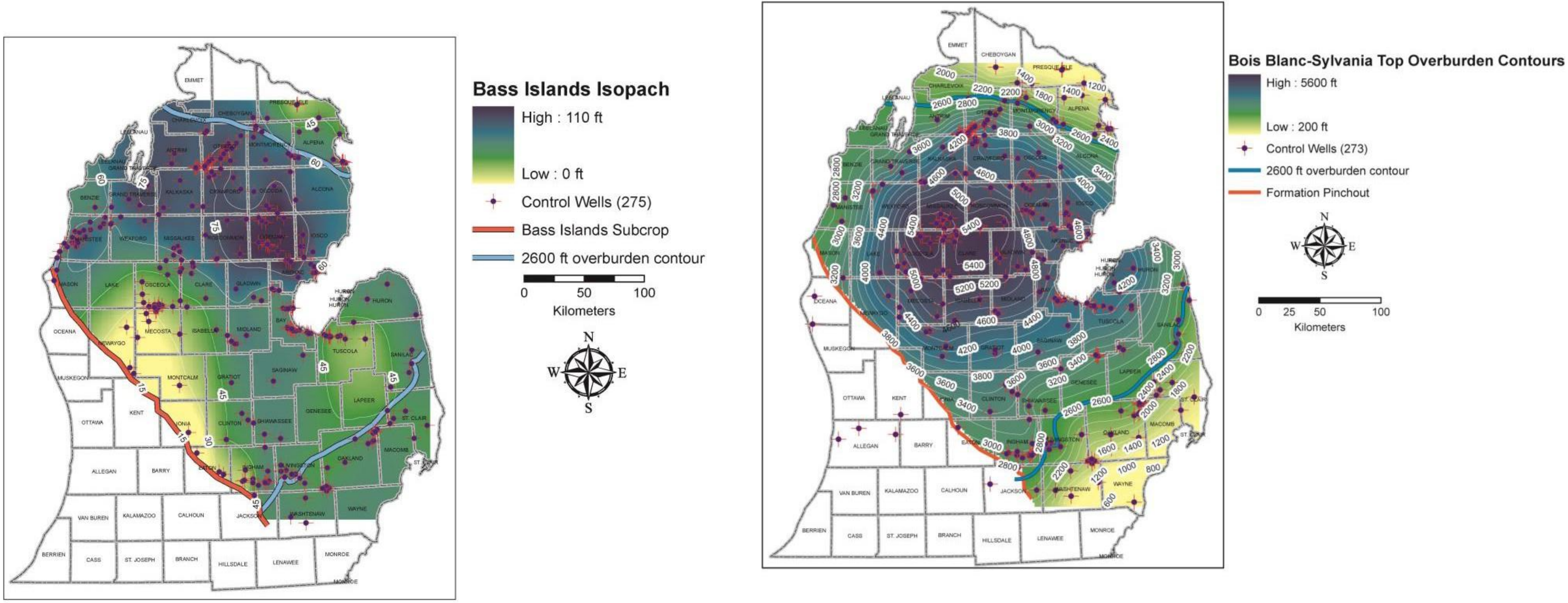


Figure 22. Isopach thickness of the Bass Islands dolomite (A, left) and measure depth (overburden thickness) contour map on the top Bass Islands dolomite (B, right). Both maps include an inferred erosionsl truncation (red solid line) and minimum 2600ft overburden contour (blue solid line)

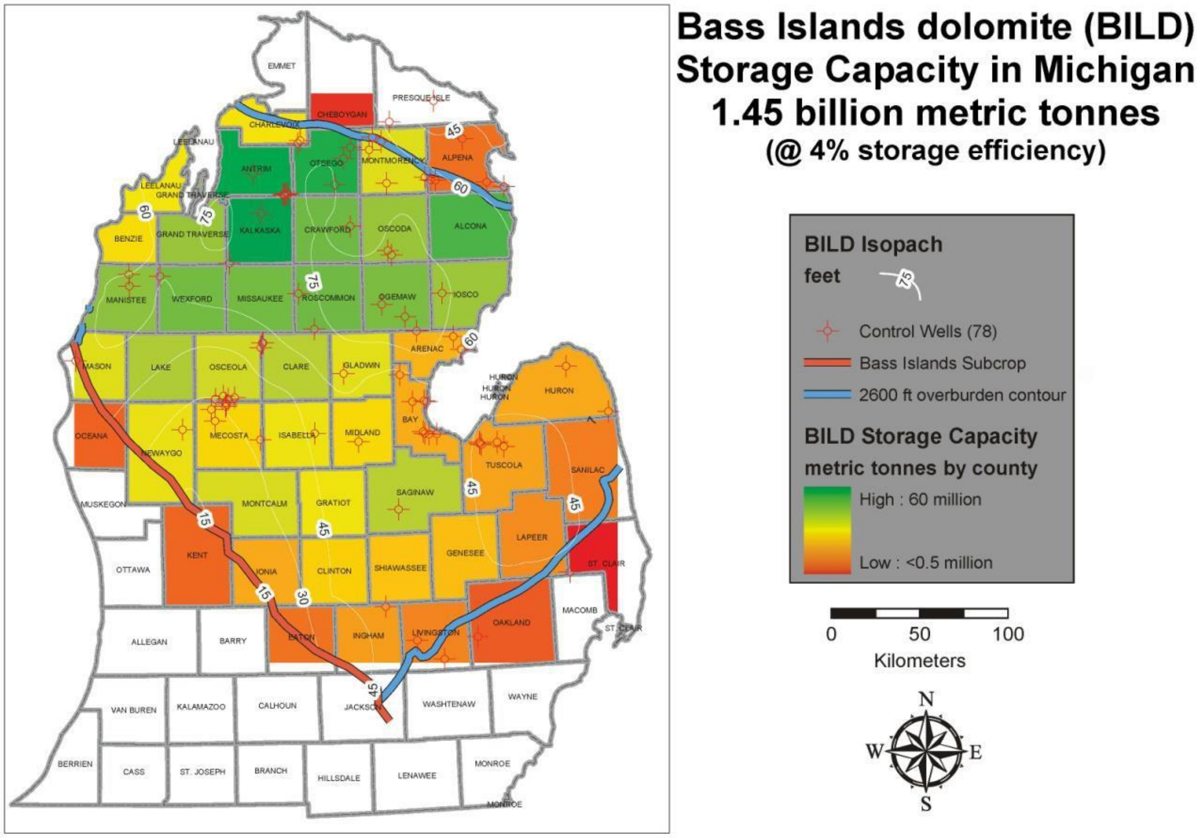


Figure 23. Geological storage capacity for CO2, by county, in Michigan.

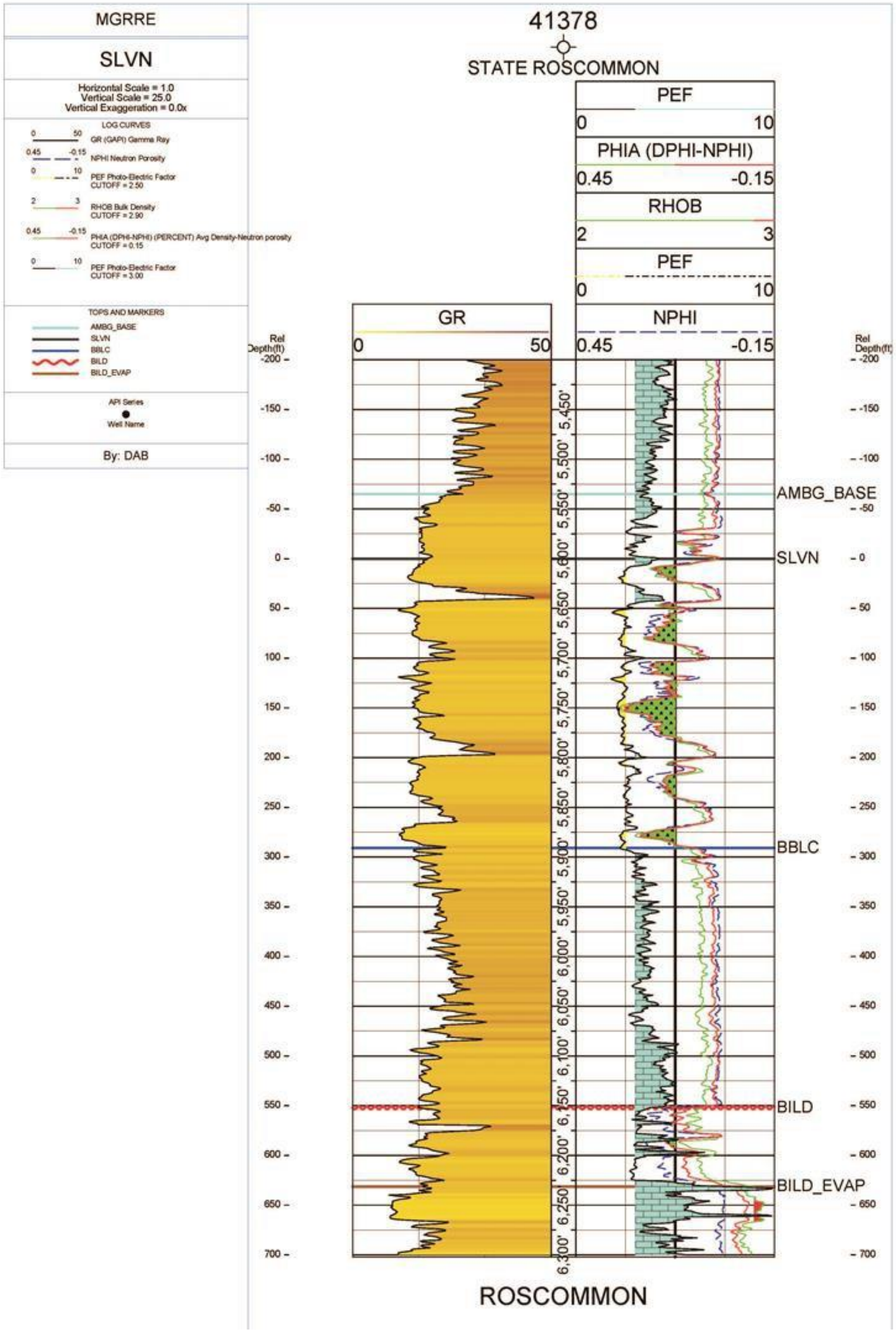


Figure 24. Representative log section of the Sylvania Sandstone in the State Roscommon well Permit #41378. The gamma ray (track 1) is displayed with a color ramp (yellow, low to brown, high); The PEF (solid black curve track 2) is shaded with light blue blocks interpreted as limestone, yellow for sandstone and/or chert. Bulk density (green) and neutron porosity (blue dashed) curves were used to calculate an average density porosity-neutron porosity (red) curve. Shaded portions of this curve above 15% porosity associated with low density (<2.5 gm/cc) are interpreted as micro-porous chert or cherty.

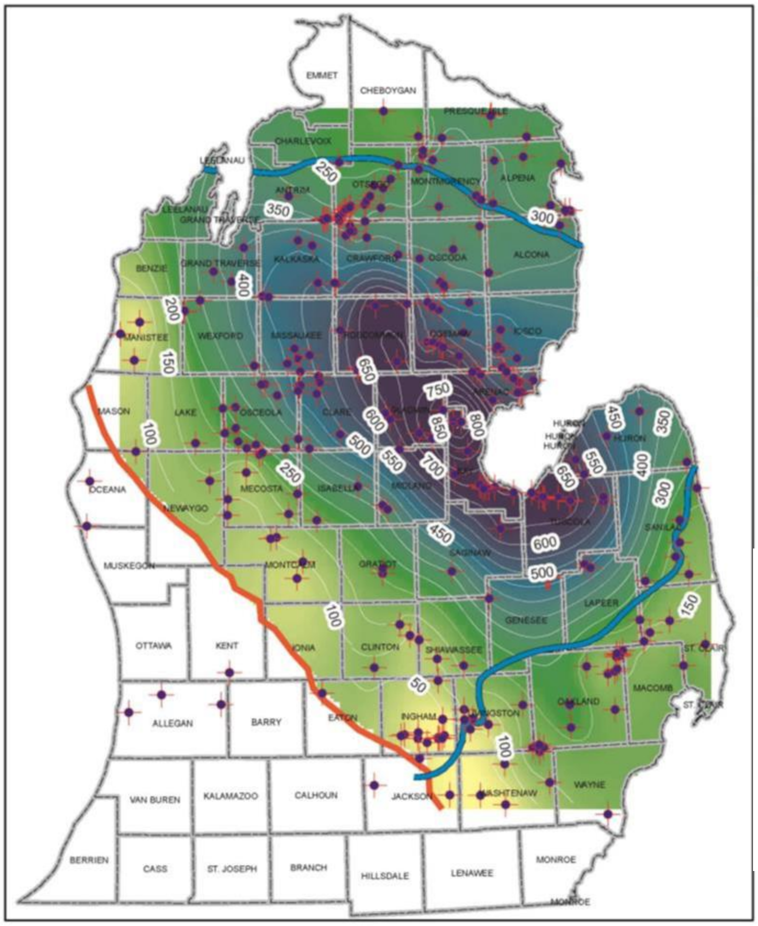
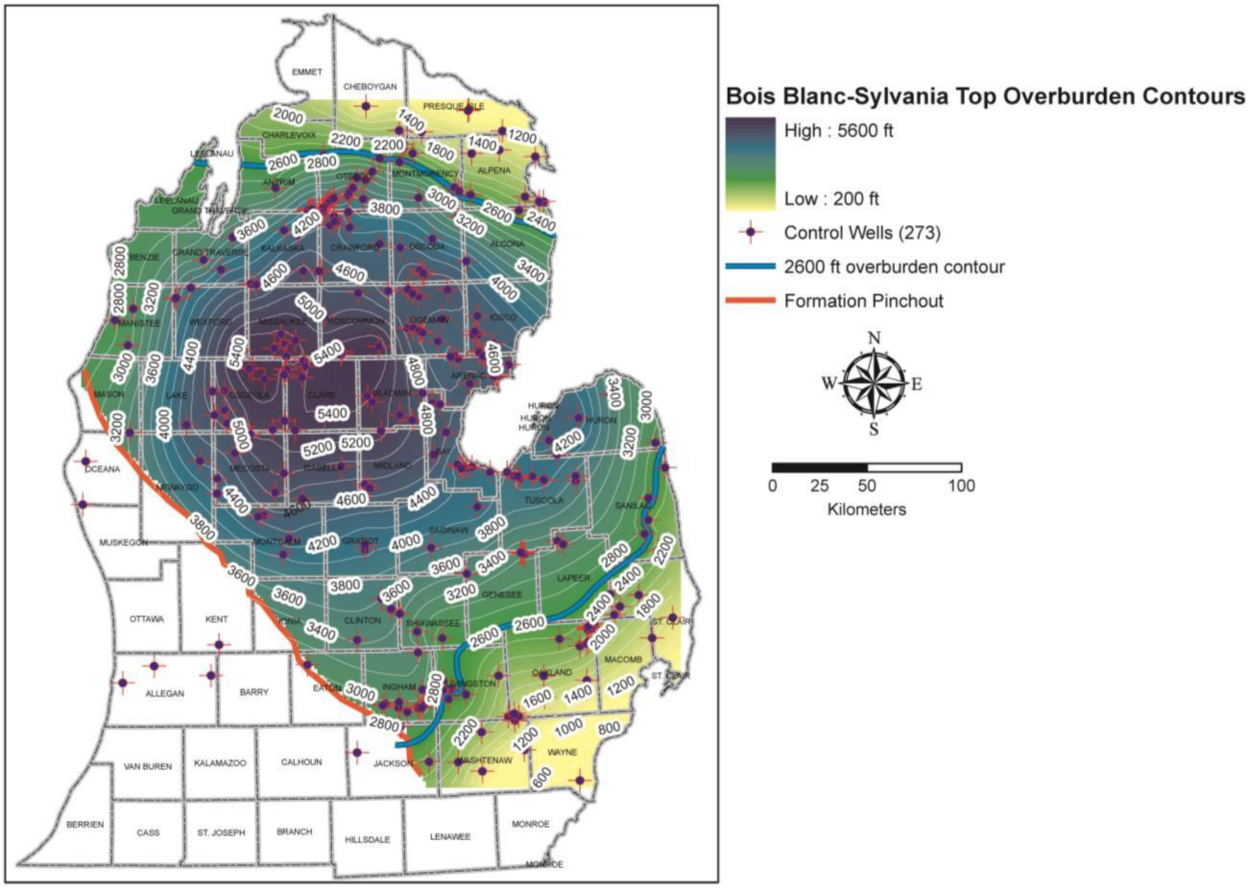


Figure 25. (A, Top), composite isopach of Devonian strata between the top Bass Islands dolomite and base of the Amherstburg Formation (see figure 8). B (Bottom) is overburden thickness (driller's depth to) base Amherstburg Formation. Note that the base Amherstburg is used as reference because this stratigraphic horizon coincides with either the top Sylvania Sandstone or top Bois Blanc in different areas of the Michigan basin.



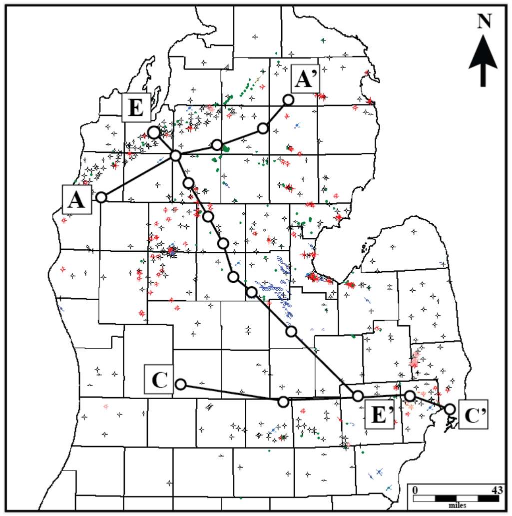
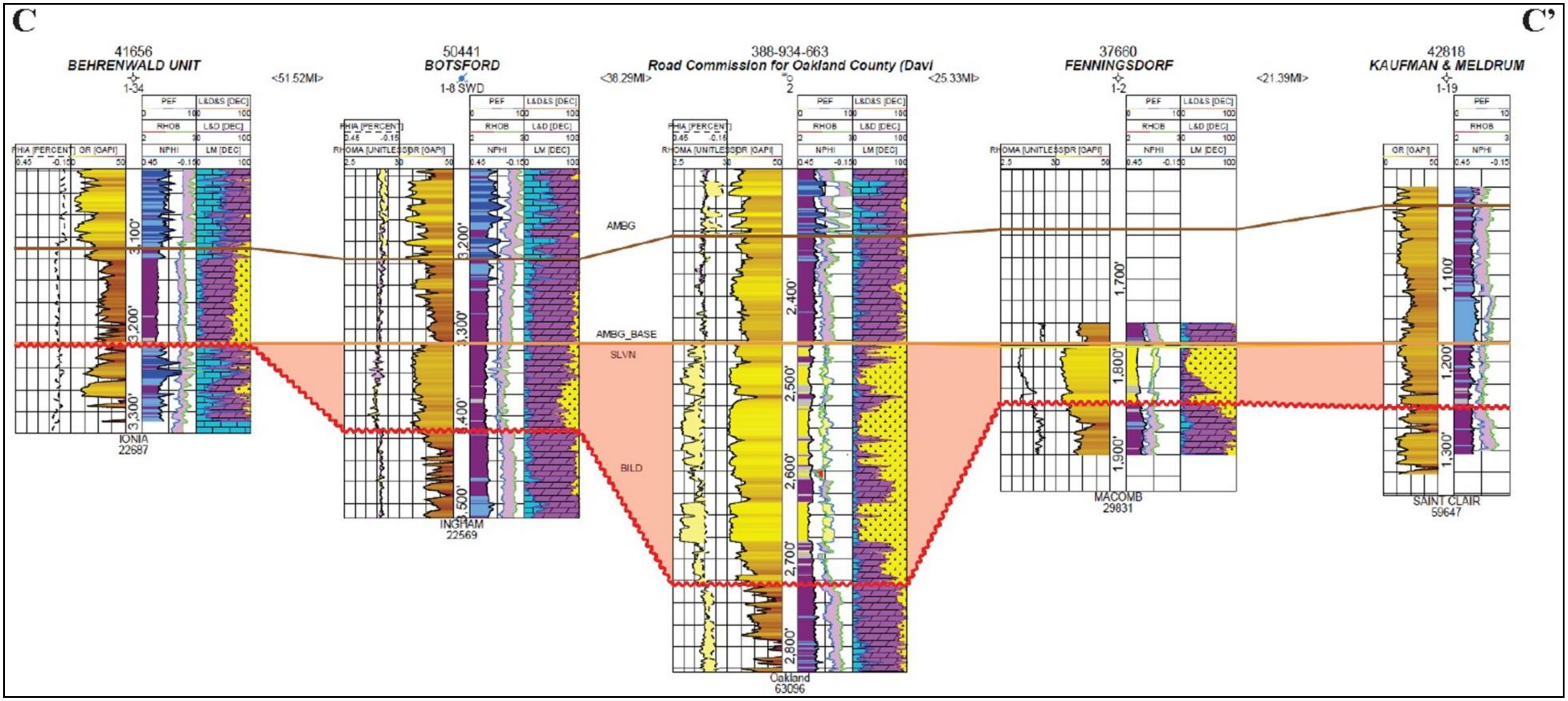
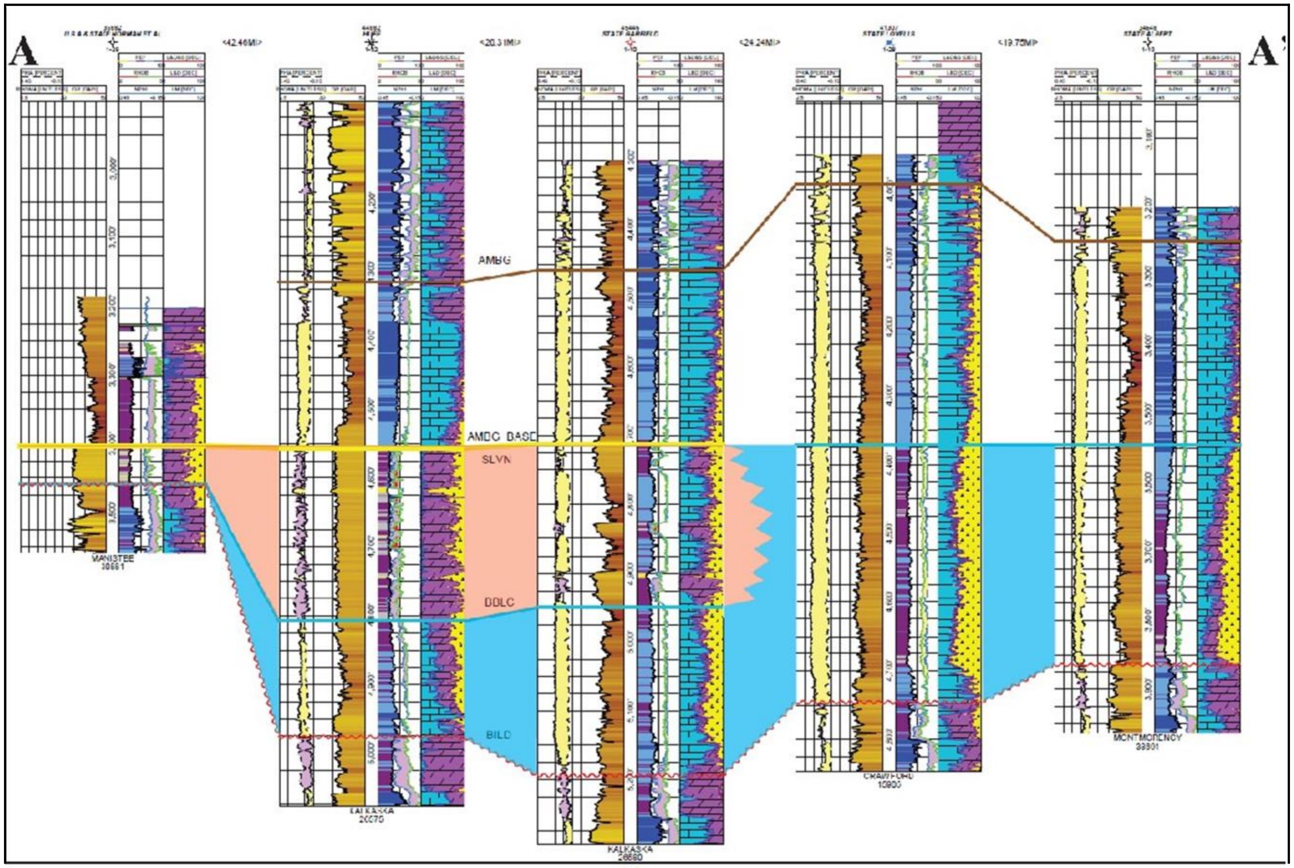


Figure 26A. Map and cross section in south-central Lower Michigan showing Detroit River group stratal relationships. BILD is Bass Islands top, SLVN is the Sylvania Sandstone top AMBG Base is the base of the Amherstburg Formation. The red wavey line is the base Kaskaskia unconformity. This section shows the contact relationship of the Sylvania above Bass Islands and a thick section of predominantly calcareous sandstone in southeastern Lower Michigan.

Figure 26B (next page) contains 2 cross sections with the same legend including BBLC, Bois Blanc Formation. Complex facies relationships in the Sylvania and Bois




A
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STATE LOVELLS
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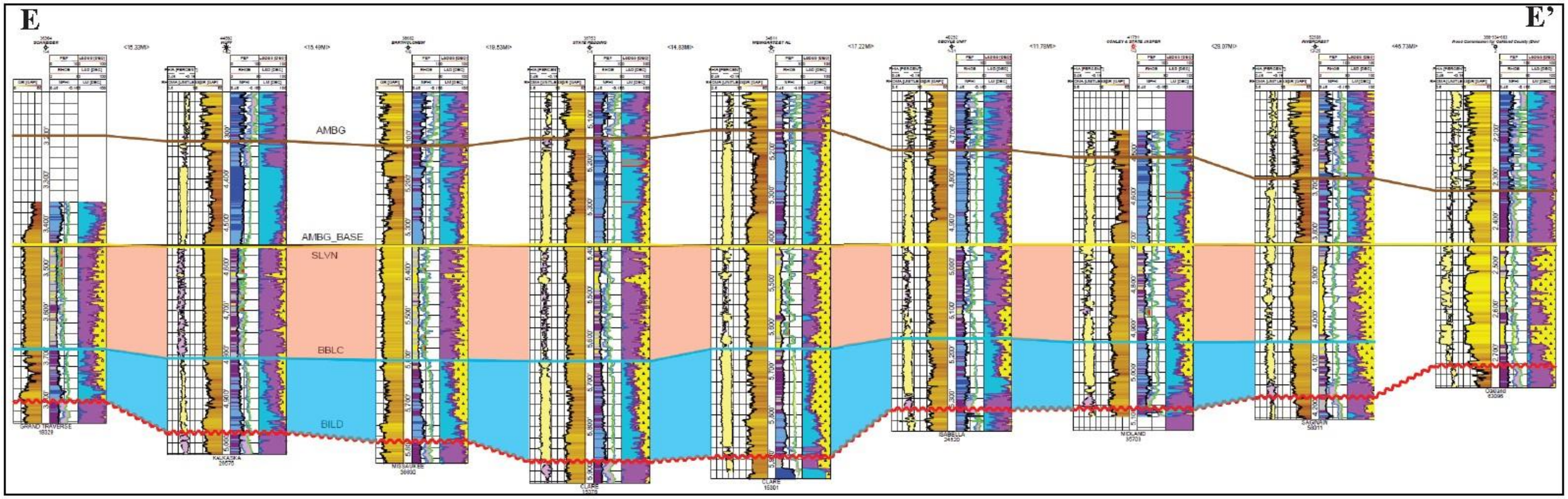
AMBG_BASE
SLVN
DDLC
BILD
MANISTEE
KALKASKA
KALKASKA
CRAWFORD
MONTMORENCY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STATE REDDING
CONLEY & STATE JASPER
AMBG
AMBG_BASE
SLVN
BBLC
BILD
GRAND TRAVERSE
KALKASKA
MISSAUKEE
CLARE
CLARE
ISABELLA
MIDLAND
SAGINAW
OAKLAND

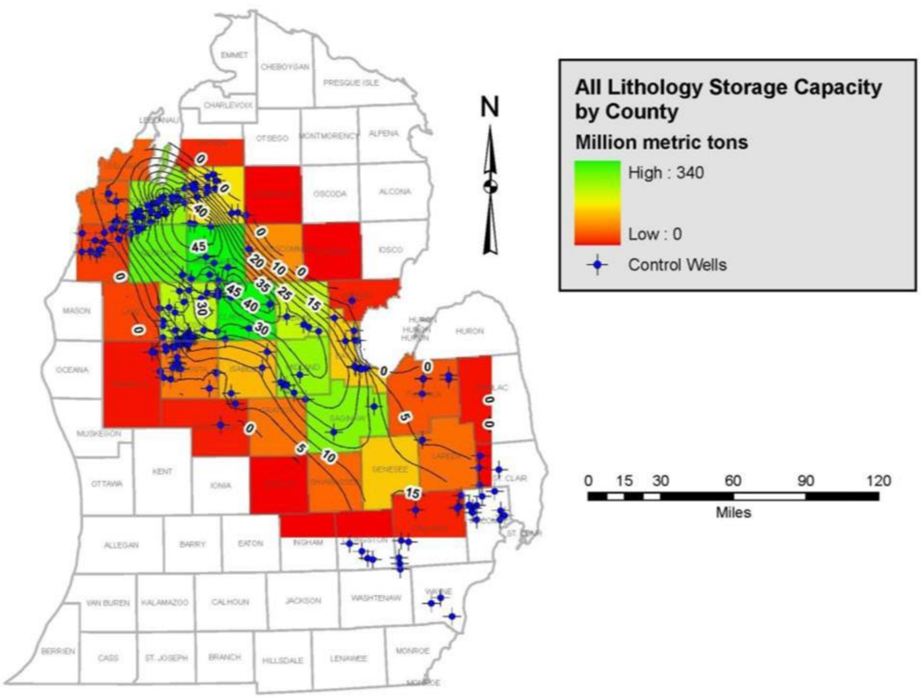


Figure 27a. Sandstone, mix and tripolitic chert lithology (conventional and unconventional reservoirs) CO2 storage capacity by county map, assuming 4% efficiency. Composite net porosity contours of sandstone, mix and tripolitic chert lithologies are superimposed on the map.

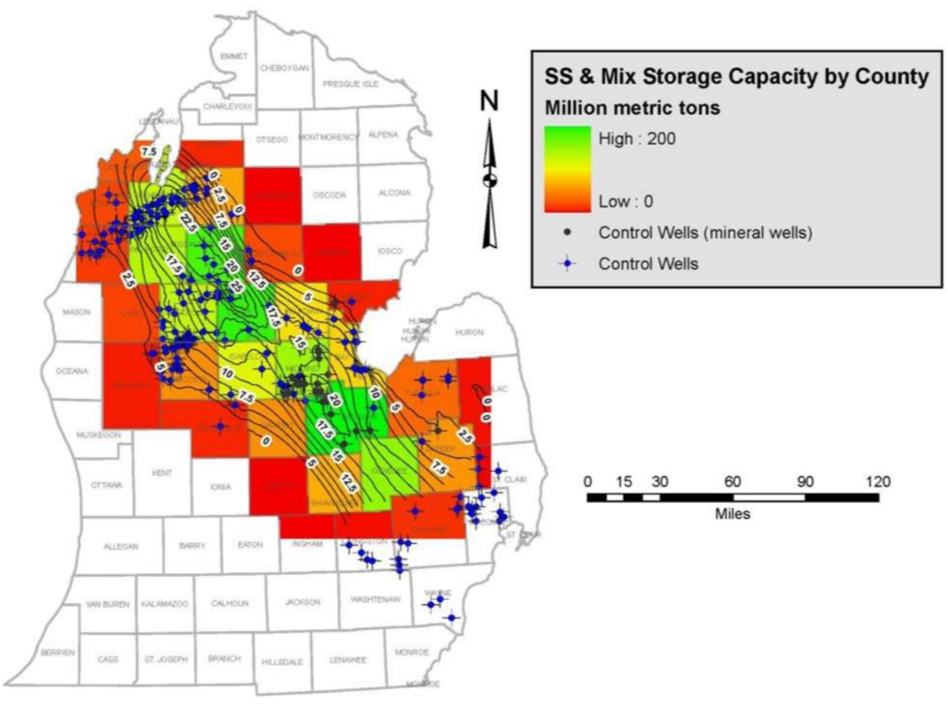


Figure 27b. Sandstone and mix lithologies (conventional reservoirs only) CO2 storage capacity by county map, assuming 4% efficiency. Composite net porosity contours of sandstone and mix lithology are superimposed on the map.

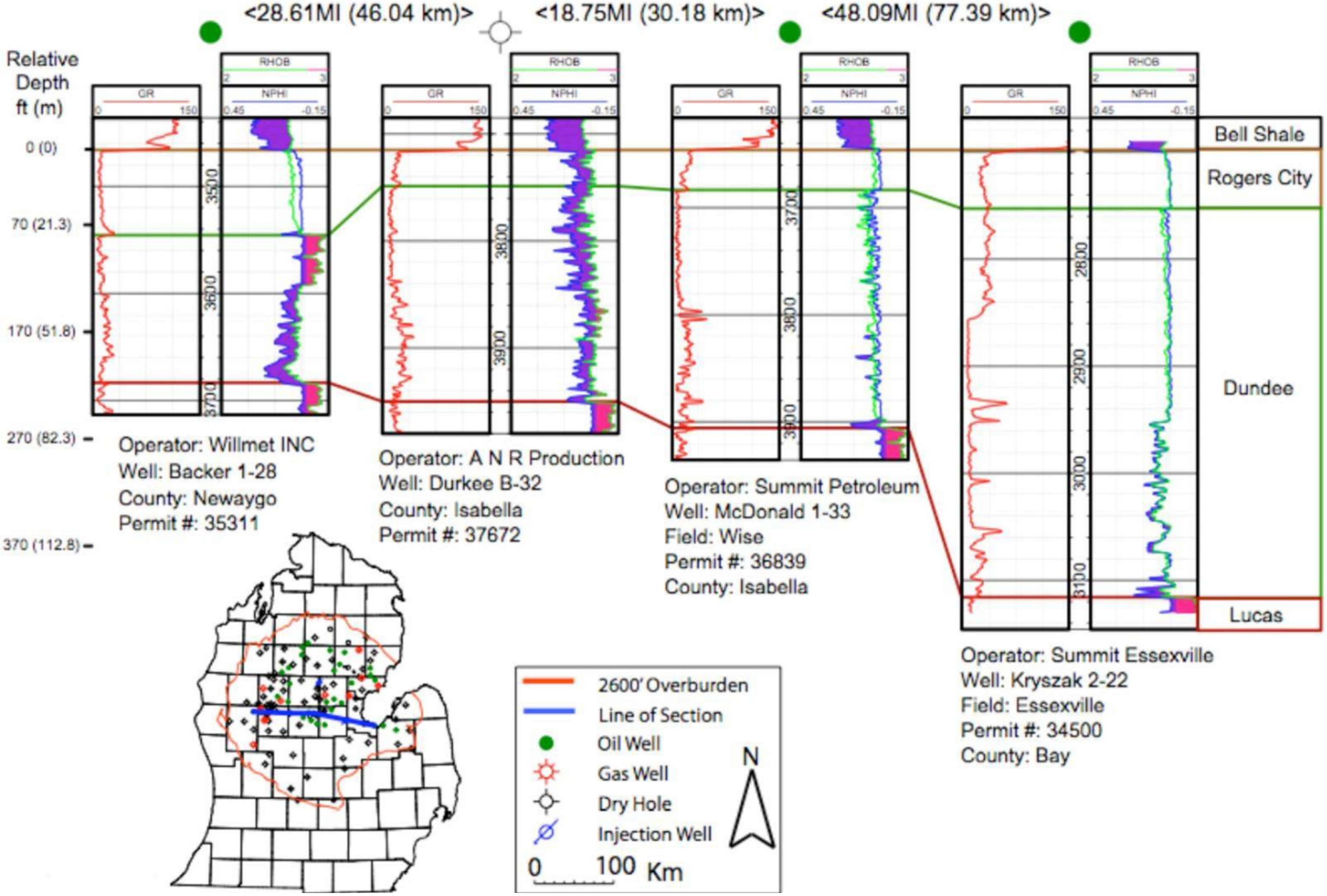


Figure 28. Regional cross section showing variability in lithology and thickness in the Rogers City and Dundee. Both units, but especially the Dundee, thicken toward the east. The Rogers City thins in the central part of the basin. Dolomite (shaded dark) is quite variable, while anhydrite (shaded light) in the Dundee is only present in the western part of the basin. GR = gamma ray; RHOB = bulk density; NPHI = neutron porosity.

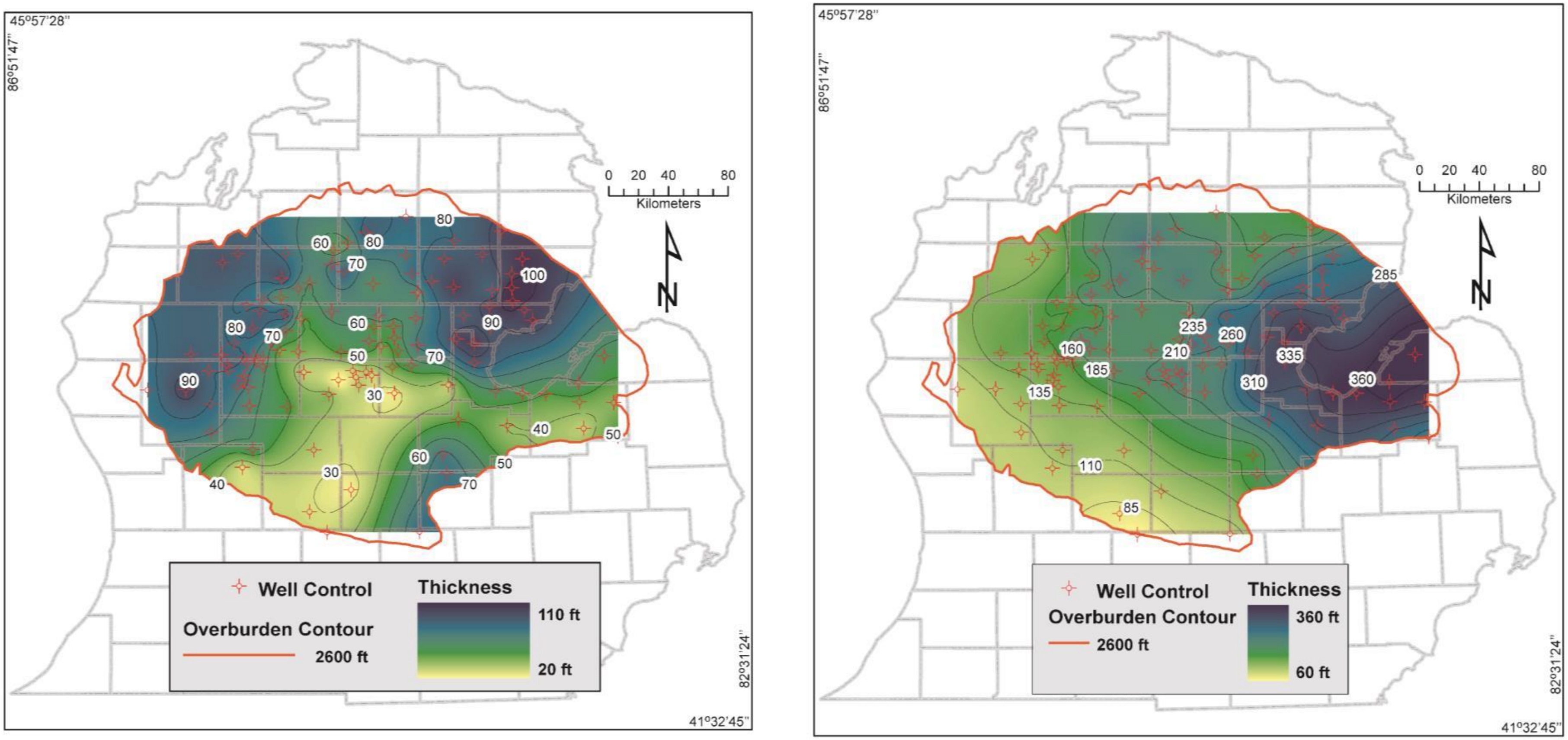


Figure 29. Isopach maps. (A) Isopach map of the Dundee. The Dundee thickens eastward toward the Middle Devonian depocenter, where its maximum thickness is greater than 350 ft (107 m). (B) Isopach map of the Rogers City. Thickness trends in the Rogers City are more variable than in the Dundee, and the Rogers City is commonly much thinner than the Dundee. The Rogers City is thinner in the central part of the basin compared to similar thicknesses in the eastern and western parts of the basin. Solid red lines in both figures indicates the 2600 ft overburden thickness (drillers depth) contour line.

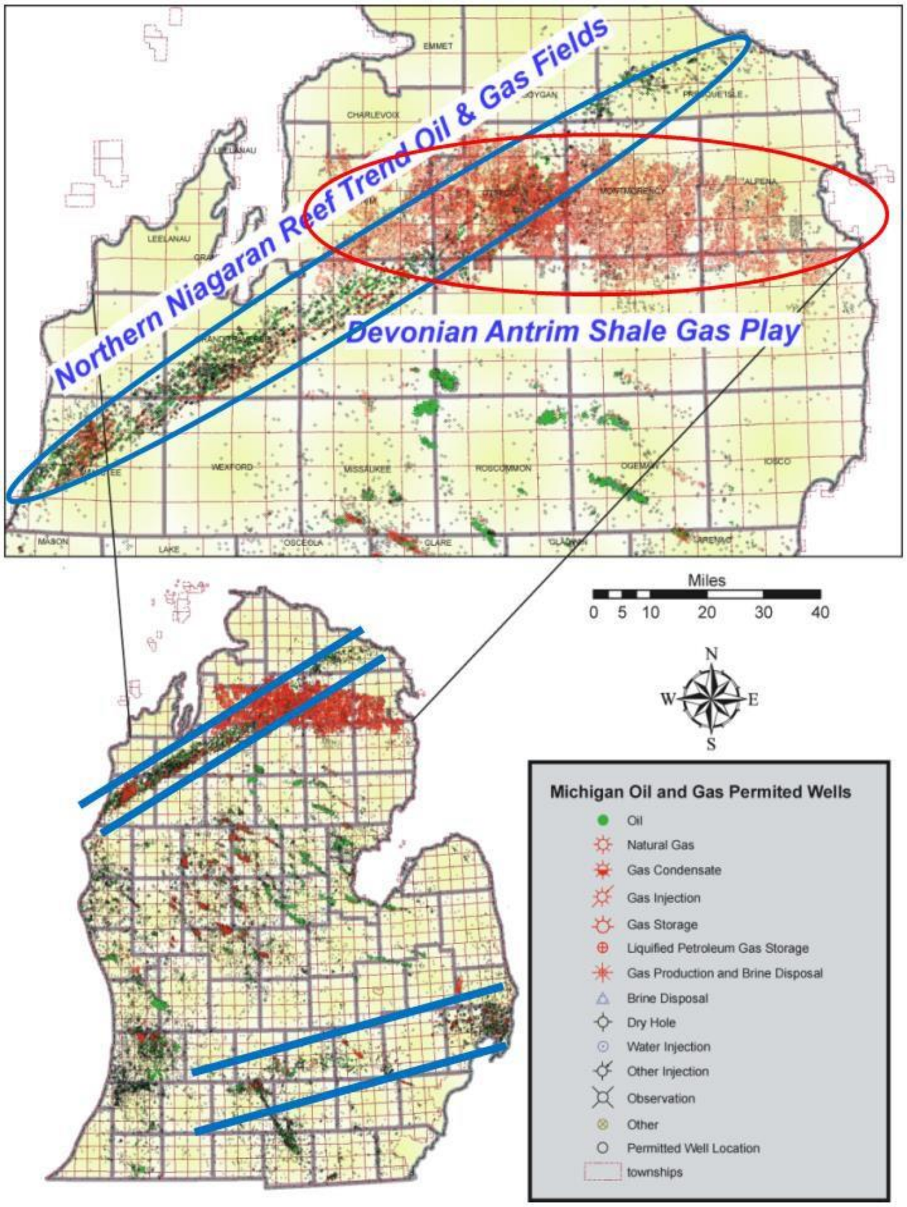
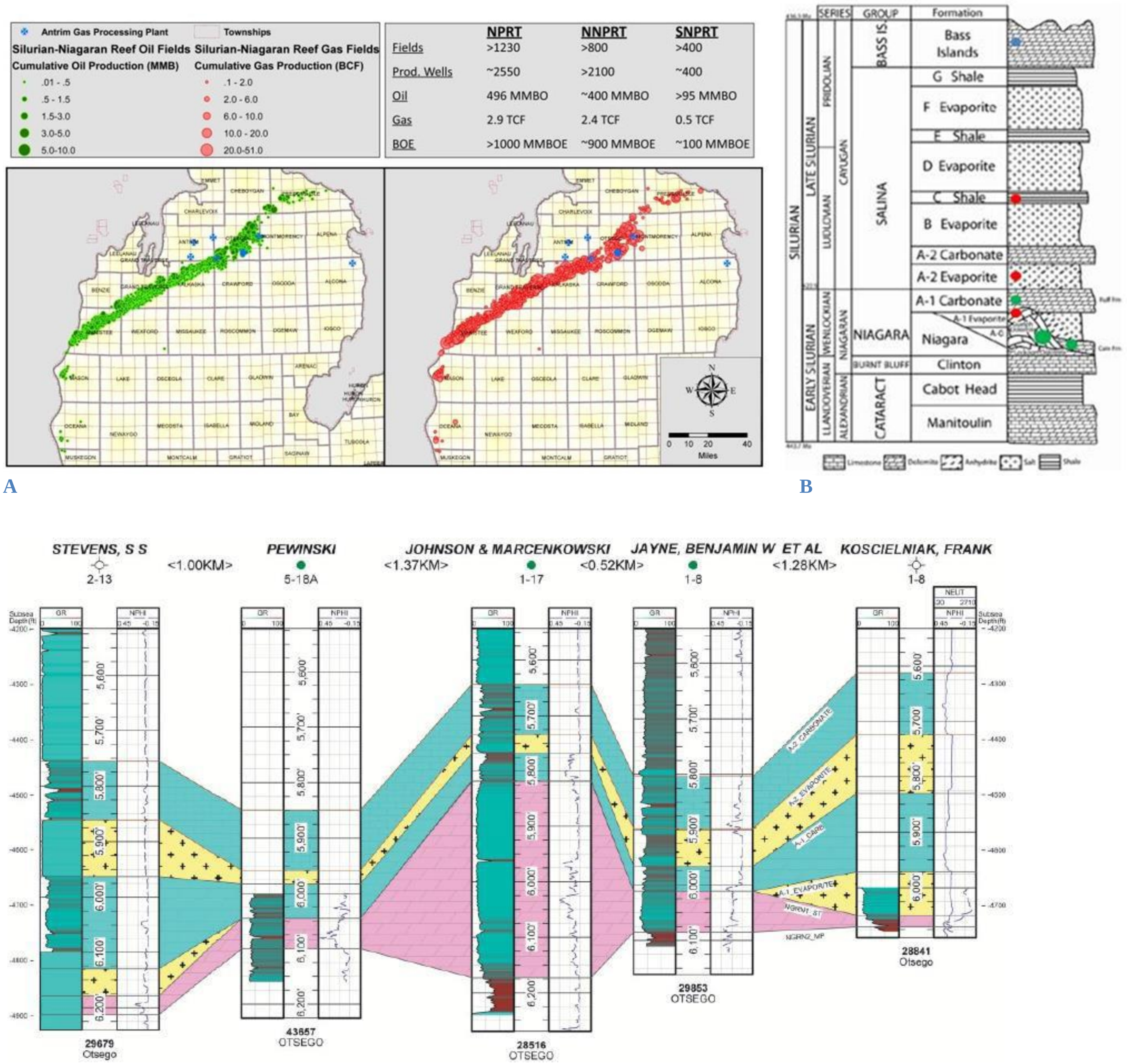
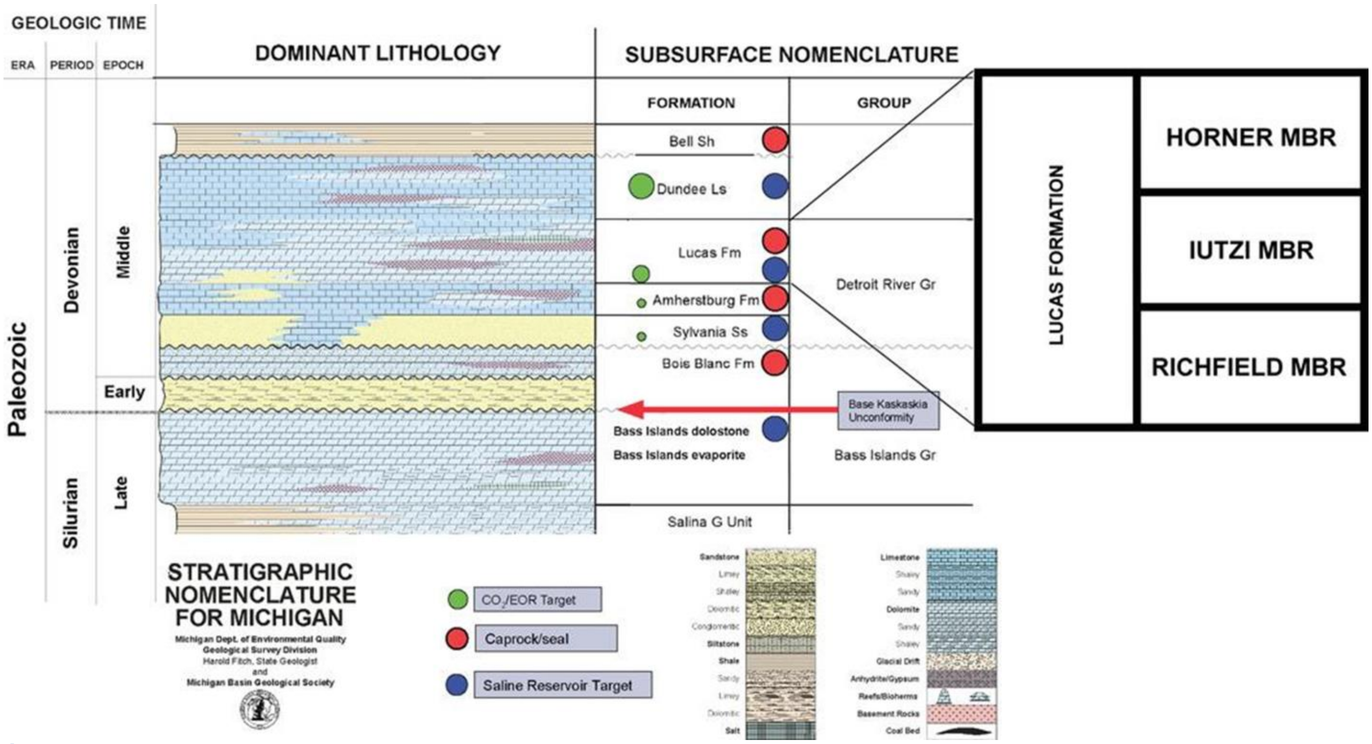


Figure 30. Map of Oil and Gas wells in Michigan with map symbol legend. Blue lines in the state map indicate the southern and Northern NPR trend oil fields; the blue ellipse in the inset is the NNPRT. The red oval is the major area of Antrim Shale gas production in Lower Michigan.

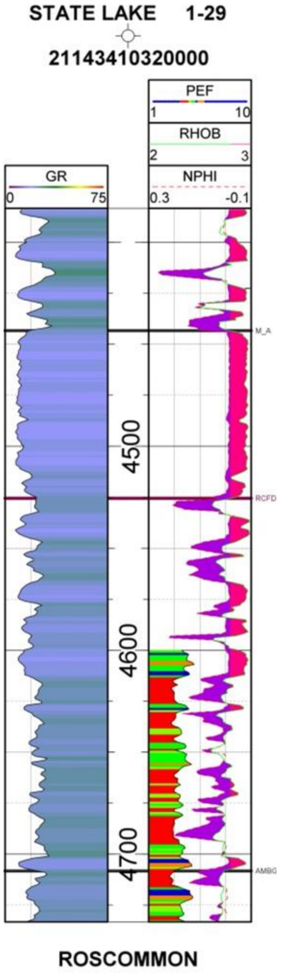


	NPRT	NNPRT	SNPRT
Fields	>1230	>800	>400
Prod. Wells	~2550	>2100	~400
Oil	496 MMBO	~400 MMBO	>95 MMBO
Gas	2.9 TCF	2.4 TCF	0.5 TCF
BOE	>1000 MMBOE	~900 MMBOE	~100 MMBOE

Figure 31 . (A) NNPRT oil and gas fields and NPRT production. BOE is barrels of oil equivalent. (B) Subsurface Silurian stratigraphy in the Michigan basin. Green dots are CO2/EOR opportunities; blue dots are saline reservoirs and red dots are regional confining layers. (C) Structural, wire-line log cross section and interpreted stratigraphy through the Chester 18 oil field in Otsego CO., MI, the largest NPRT oil field, and one of the most successful water-flood projects with over 20 years of secondary recovery data. The field encompasses about 212 ha (675 acres) and has a maximum lateral extent of less than 3 km (1.9 miles). NGRN1-ST (pink brick pattern) is the Guelph or Brown Niagaran producing unit

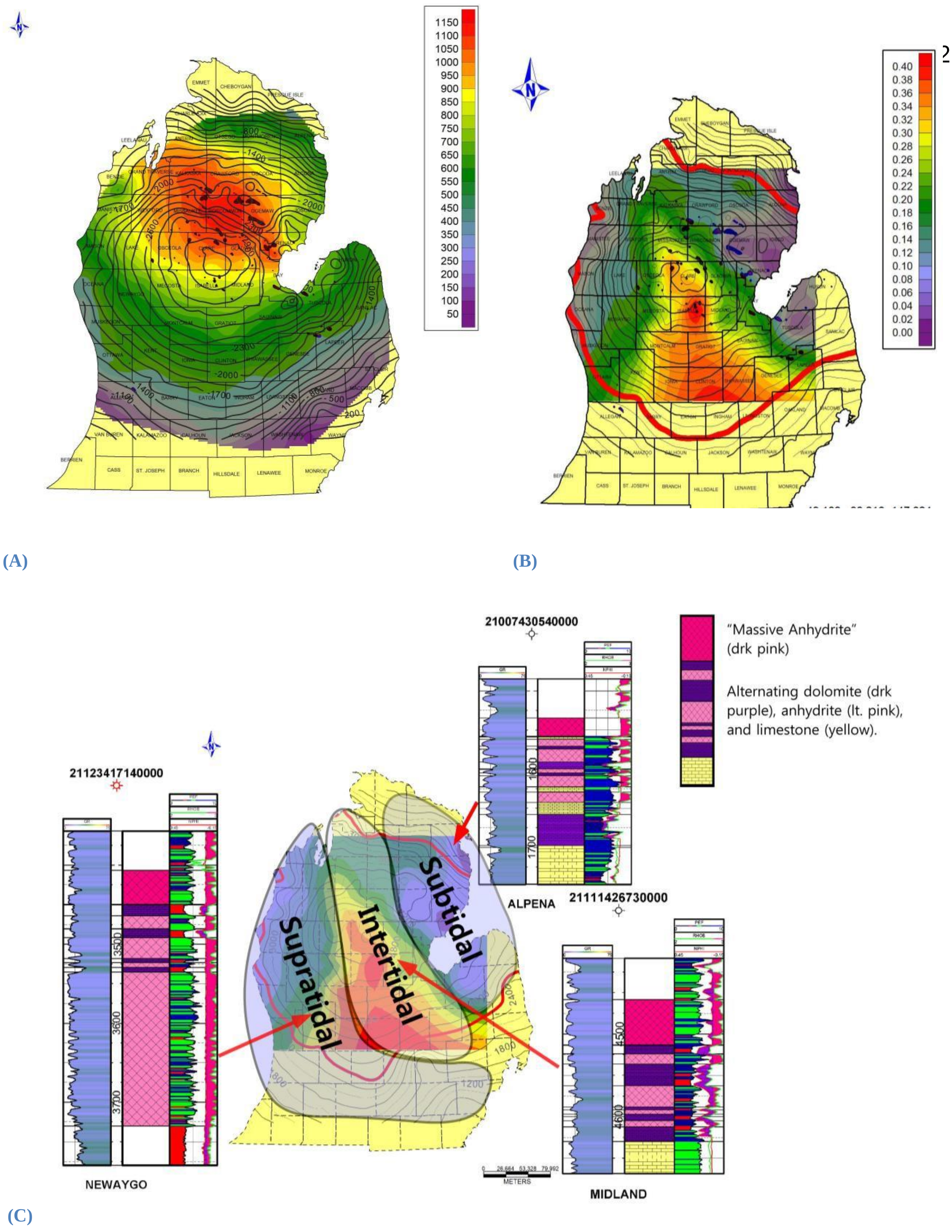


A



B

Figure 32. (A)Middle Devonian, Lucas Formation stratigraphy in the Michigan basin. (B) Type well log section for the Richfield Member in the East Norwich Field, Roscommon County, Michigan. M_A=Informal massive anhydrite of the Iutzi Member; RCFD=Top Richfield Member; AMBG=Top Amherstberg formation. Wire line log display shows: (1) color gradient for natural gamma-ray log response (GR; track 1); (2) bulk density (RHOB) log cutoff at 2.8 g/cc, shaded pink and interpreted as anhydrite (track 2); (3) “quick look” neutron porosity (NPHI)-RHOB log separation, shaded purple and interpreted as dolostone (track 2); and (4) color-coded photoelectric effect (PEF) log curve (track 2), interpreted as red=dolostone and blue-green-orange= limestone/anhydrite.



(A)

(B)

(C)

Figure 33. (A) Driller's depth contour map on the top Lucas Formation with superimposed isopach grid and legend. The red contour represents the minimum depth for effective storage of CO2 (2,600 ft [792 m] measured depth). (B) Map of Richfield Member driller's depth contours and grid showing the ratio of gross thickness of dolomite to gross thickness of other non-reservoir facies (anhydrite and limestone). The red contour represents the minimum depth for effective storage of CO2 (2,600 ft [792 m] measured depth). (C) Interpreted paleogeography in the Richfield member of the Lucas Formation on the basis of lithology interpreted from well logs (symbols as in Figure 28). Important Richfield oil fields are shown in dark polygons in (A) and (B).

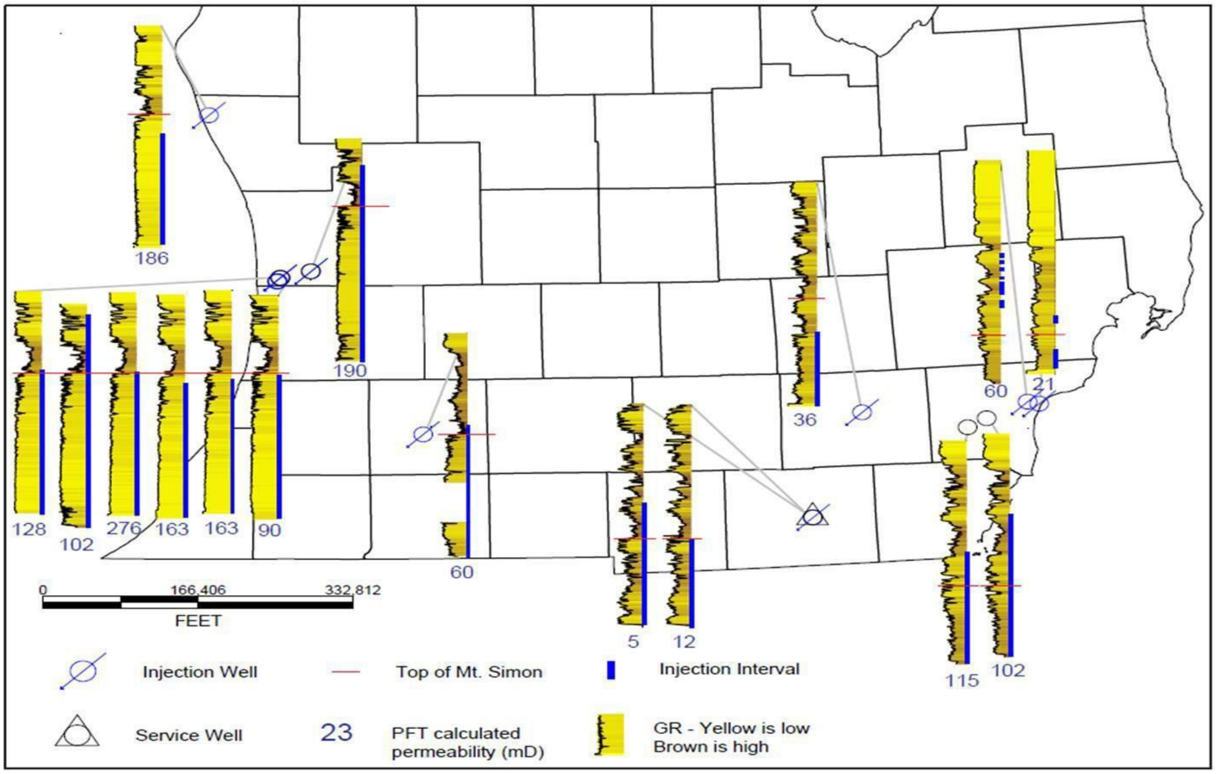


Figure 34. Distribution of pressure fall-off tests in the Mount Simon Sandstone (and related strata) in deep waste injection wells in southern Lower Michigan. This map documents the distribution of pressure fall-off test data and calculated reservoir permeability. Hydraulic conductivity for the Mount Simon in the west is higher than the hydraulic conductivity for the Mount Simon in the east. Furthermore data in the east suggests that the Knox sequence (formations above the Mount Simon) may have comparable injection potential compared to the Mount Simon Sandstone

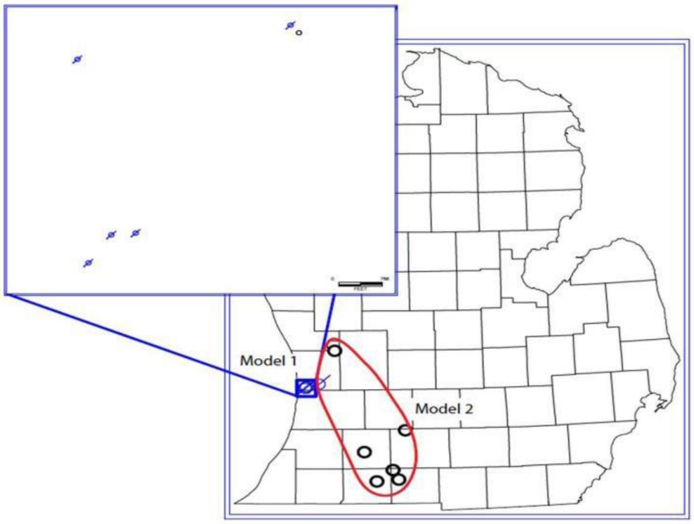


Figure 35. (A) Location map for two static geological models in the Mount Simon Sandstone in southwest Lower Michigan. The map illustrates the locations of the wells used in two static geologic models; model 1 is small spatial scale and model 2 is regional scale

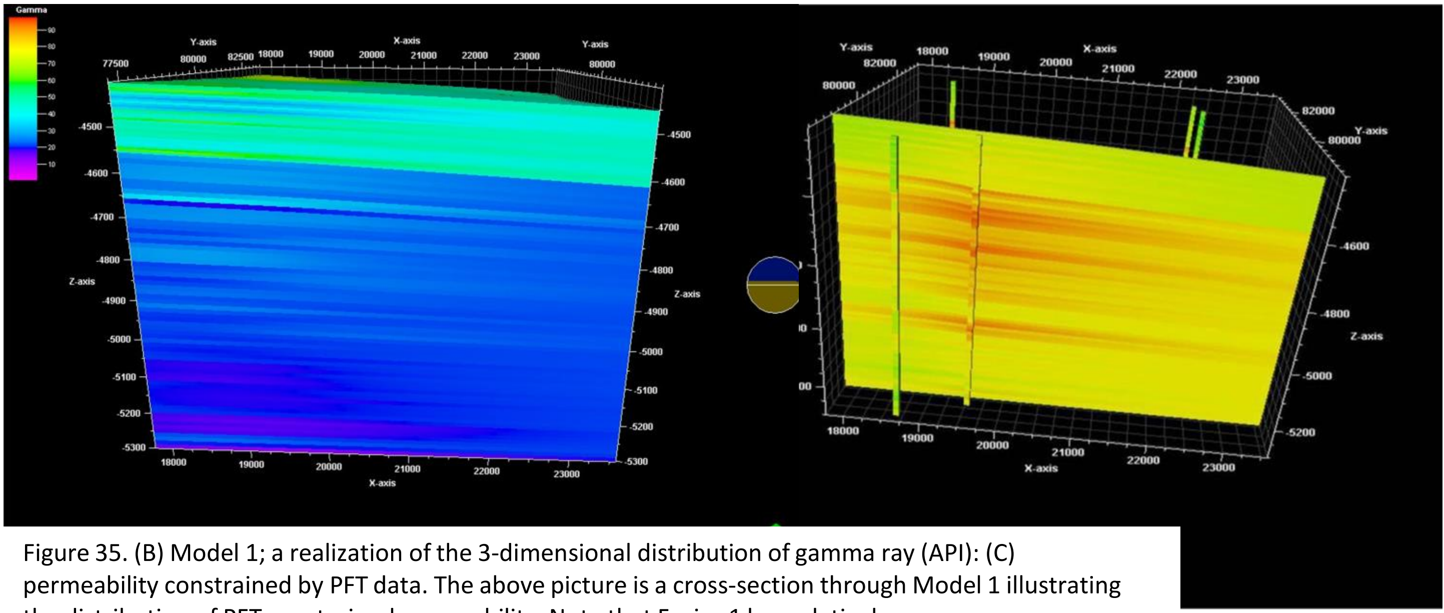


Figure 35. (B) Model 1; a realization of the 3-dimensional distribution of gamma ray (API): (C) permeability constrained by PFT data. The above picture is a cross-section through Model 1 illustrating the distribution of PFT constrained permeability. Note that Facies 1 has relatively

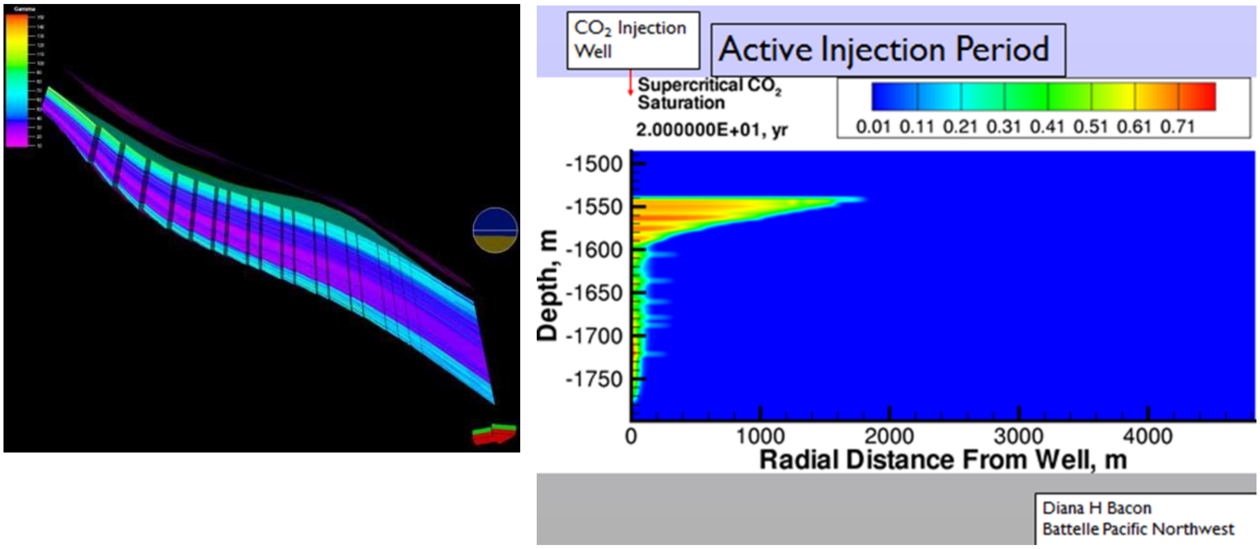
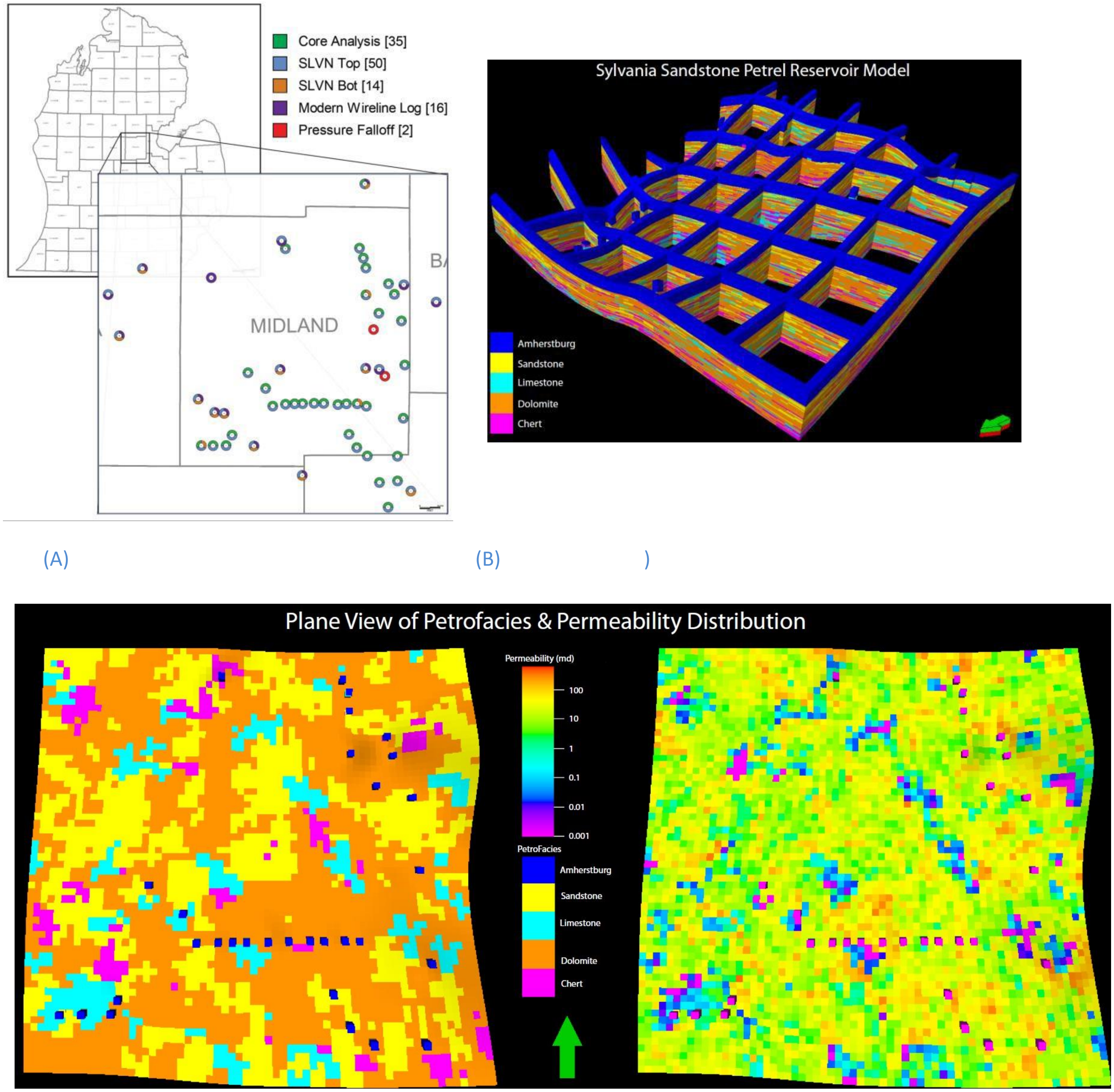


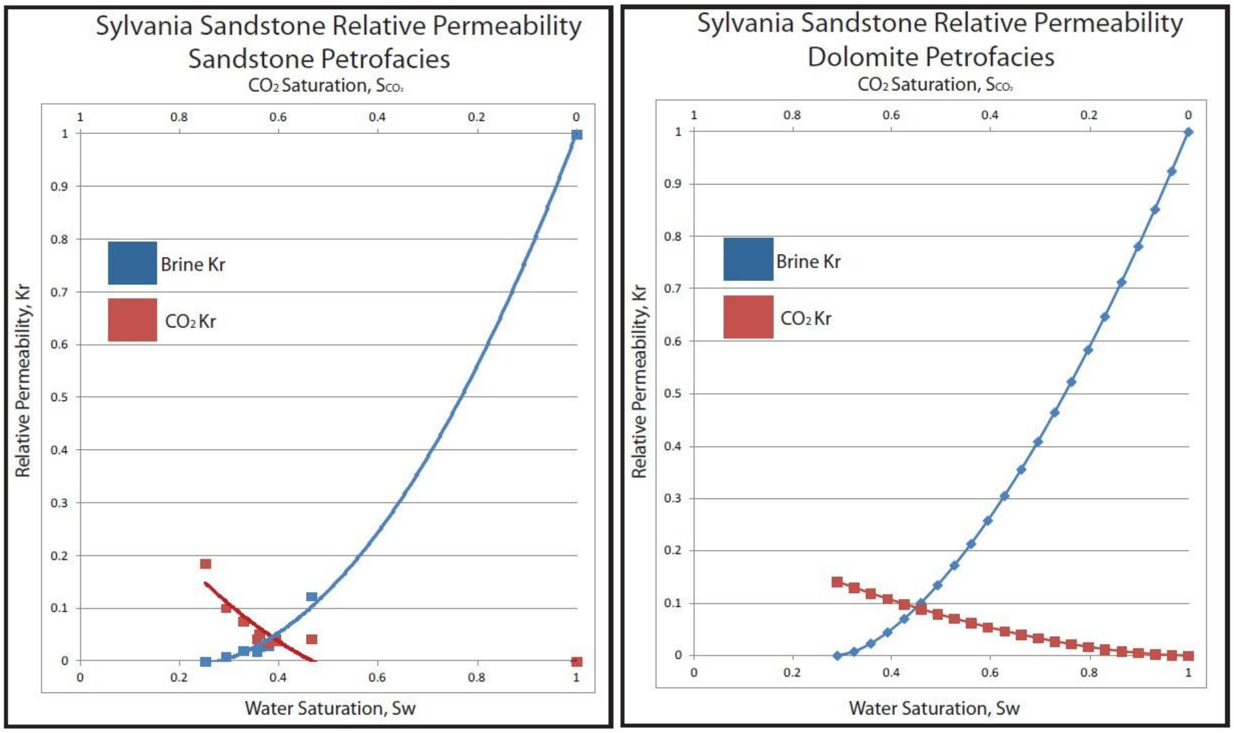
Figure 35. (D) Model 2: gamma ray interpretation. Vertical exaggeration is 100X. This illustrates that there is clear distinction between Facies 1, 2 and 3 when viewing the interpreted GR data. This model is bound by the Precambrian on the bottom and the top of the Eau. (E) Model output for a single well injection simulation showing supercritical CO2 saturation in the Mount Simon Sandstone. The well is one of those used in the satatic model of figure 31(B).



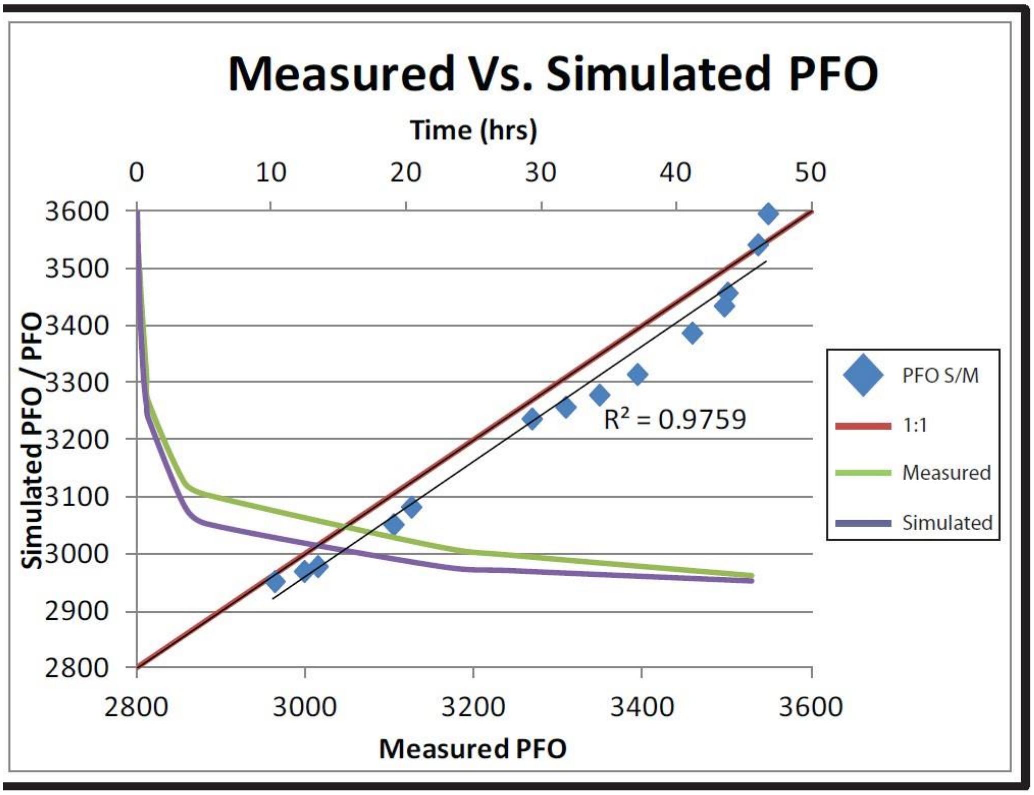
(A) (B))

(C)

Figure 36. (A) Model domain for the Sylvania Sandstone formation in Midland Co., MI. (B) 3D static geological model for the Sylvania Sandstone in Midland Co., MI. (C) Integration of geological and petrophysical (permeability) models for the Sylvania Sandstone. (D) (next page) Laboratory measurements of relative brine-CO2 permeability versus water saturation for the main, conventional reservoir facies of the Sylvania Sandstone. (E) (next page) Measured versus simulated pressure fall-off (history match) in a sample well after multiple realizations of facies and porosity-permeability .distribution.


Sylvania Sandstone Relative Permeability
Sandstone Petrofacies
CO2 Saturation, Sco2
1
0.8
0.6
0.4
0.2
0
Relative Permeability, Kr
Brine Kr
CO2 Kr
Water Saturation, Sw
Sylvania Sandstone Relative Permeability
Dolomite Petrofacies
CO2 Saturation, Sco2
Relative Permeability, Kr
Brine Kr
CO2 Kr
Water Saturation, Sw

(D)


Measured Vs. Simulated PFO
Time (hrs)
0
10
20
30
40
50
3600
3500
3400
3300
3200
3100
3000
2900
2800
Simulated PFO / PFO
R² = 0.9759
PFO S/M
1:1
Measured
Simulated
2800
3000
3200
3400
3600
Measured PFO

(E)

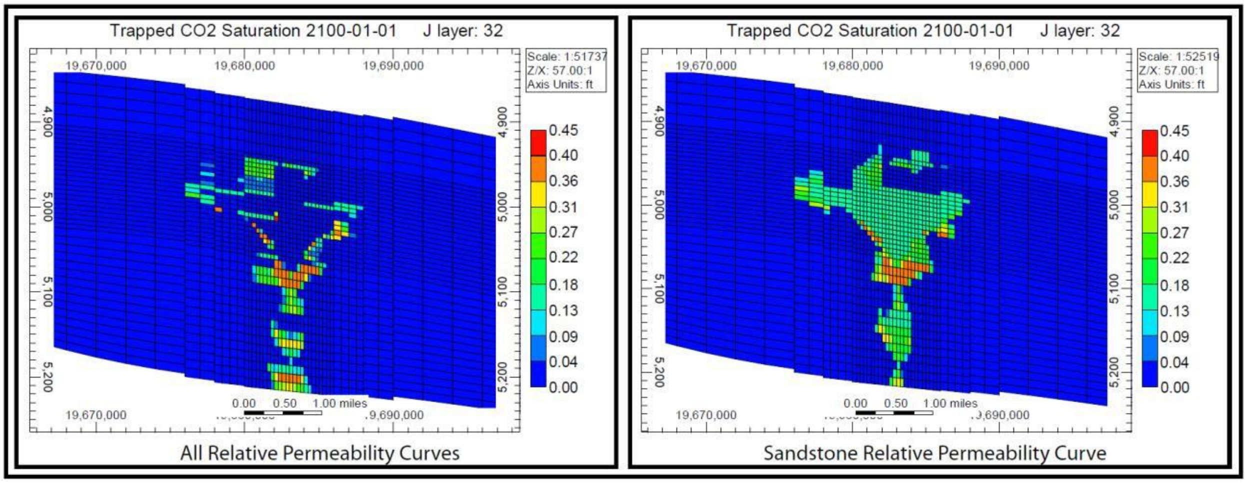


Figure 37. Comparison of two realizations of trapped CO2 concentration after injection in a model well with differing relative permeability (all reservoir facies versus sandstone reservoir facies) in the Sylvania Sandstone in Midland Co., MI

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