This document is submitted as a draft for review by the West Virginia Division of Energy in advance of submission as a report of findings related to the potential of regions of West Virginia for the location of a coal-to-liquids production plant or geologic storage of CO2 in deep saline aquifers in Devonian or Silurian sandstones.

Research Support Program for the West Virginia Division of Energy

Final Report
(Phase 2)

Submitted to the

West Virginia Division of Energy

By

The West Virginia University Board of Governors

On Behalf of West Virginia University

And Its National Research Center for Coal & Energy

Project Dates: July 1, 2009 – December 31, 2011

Project Manager: Douglas Patchen
Principal Investigator: Richard Bajura
Tim Carr, Co-Investigator
West Virginia University

and

West Virginia Geological and Economic Survey, Team Member
Michael Hohn, Co-Investigator

Contact Information
National Research Center for Coal & Energy
304/293-6034
Richard.Bajura@mail.wvu.edu

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Research Support Program for the West Virginia Division of Energy
Phase 2 Cost Extension: July 1, 2009 – December 31, 2011

Executive Summary

Scope of Report

West Virginia University's National Research Center for Coal and Energy (WVU NRCCE) received a cost extension to the program initiated in October, 2007 to provide program support to the West Virginia Division of Energy (WVDOE). This Phase 2 cost extension focused on two major work areas:

- Evaluating the value-added economic potential of carbon sequestration sites near the State border; and,
- Evaluating the storage potential of deep saline aquifers in Devonian and Silurian sandstones. Remaining funds from Phase 1, estimated at $50,351, were reprogrammed to reduce the overall cost of the effort, for which $157,024 in new funding was received.

Oil Recovery Potential

The Jacksonburg-Stringtown oil field, located primarily in Wetzel and Tyler counties, had an estimated 88,500,000 barrels of original oil in place in the Upper Devonian Gordon sandstone, of which approximately 20,000,000 barrels were produced during primary recovery (Ameri et al., 2002). If minimum miscibility pressure (MMP) could be achieved in the Jacksonburg-Stringtown oil field, an additional recovery of 8% to 16% of the original oil in place could be expected, which would be 7.1 to 14.2 million barrels. Other fields in northeast West Virginia provide similar opportunities for CO_2 -enhanced oil recovery (CO2-EOR) (Kinder Morgan, 2001).

An oil sample was obtained for MMP slim tube analysis. Results indicate that the MMP is 941 pounds per square inch (psi) at 80^{o}F (Appendix A), well below expected hydrostatic pressure for the reservoir (~1200 psi). This result indicates that if an anthropogenic CO_2 source can be located, the Jacksonburg-Stringtown oil field has significant potential for miscible CO2-EOR associated with value-added geologic storage.

Aquifer Characteristics

The Oriskany Sandstone is an extensive saline aquifer from which large quantities of hydrocarbons have been produced from structural and combination stratigraphic-structural traps with a salt water drive. The Oriskany also is used extensively for storage of natural gas. Thirty two (32) Oriskany gas storage fields have a combined storage capacity approaching 1 trillion cubic feet (TCF), more capability to store and deliver than storage fields in any other formation within the northern Appalachian basin (American Gas Association, 2001). Many of these storage fields have been in operation since the 1950's, attesting to the ability of these fields and seals to maintain long-term containment (American Gas Association, 2001). This further indicates that, at the local level, the Oriskany has the necessary volume, porosity and containment characteristics for geologic storage of CO_2. Long-term lateral containment of large-scale CO_2 injection appears to be associated in the Oriskany with convergent flow located in the eastern Appalachian basin.

Storage capacity for the Oriskany Formation was estimated by the equation:

$$G_{CO2}=Ah_g\Phi_{tot}\rho E$$

where

- G_{CO2} is the estimate of total saline formation storage capacity in kilograms,
- A is the area of basin greater than 800 meters in depth,
- h_g is the average thickness of formation at depths greater than 800 meters,
- ϕ_{tot} is the average formation-scale porosity for thickness h_g (8.08%),
- ρ is the density of CO_2 at pressure and temperature that represents storage conditions for saline formation averaged over h_g (800 kg/m^3 at P = 18.01 MPa and T = 43.29 °C), and,
- E is the storage efficiency factor that reflects a fraction of total pore volume filled by CO_2 (USDOE estimations of E are a low of 0.01 and a high of 0.04).

Carbon Storage Potential

Oriskany isopach and porosity grids were generated using a minimum curvature method and a 10,000 meter by 10,000 meter grid size. These grids were then used to perform a grid-to-grid calculation to estimate the available volume within the potential CO_2 sequestration area. Grid-to-grid calculations were then performed using the constants for density of supercritical CO_2 (800 kg/m^3) and the storage efficiency factors (0.01 and 0.04). The result is a storage resource estimate of 1.246 to 4.983 gigatonnes of CO_2 in the Oriskany. Maps and data are available through http://www.wvcarb.org/.

Carbon storage analysis for the Silurian Tuscarora and Newburg sandstones used the formula above and porosity values interpreted from well logs. Petra Software™ was used to import scanned well log images which were then correlated to identify the tops and bottoms of the formations of interest. Once the intervals were identified, specific curves were digitized, including Gamma Ray (GR), Neutron Porosity (NPHI) and Density Porosity (DPHI). In cases where NPHI and DPHI curves were both available, they were used to create an Average Porosity (PHIA).

Average porosity of the Tuscarora Sandstone in eight wells in the study area is 4.9%. Average temperature and pressure values were based on log analysis of the Kanawha 5903 well (temperature at depth = 111° F (43.9° C), pressure at depth = 862 psi (Jarrell et al., 2002)). The estimated storage capacity of the Tuscarora Sandstone ranges between 102 million tonnes at an efficiency factor of 0.01 and 408 tonnes at an efficiency factor of 0.04.

In the Newburg sandstone study, once PHIA values were normalized, storage capacities were estimated for the total study area and for reduced areas representing subsets of the well data based on presence of a specified minimum porosity. Four porosity cutoff values were considered: 3%, 5%, 7%, and 10%, with well control and study area size decreasing, respectively. Average temperature and pressure were based on log analysis and completion records of wells in the Rocky Fork Field (temperature at depth = 112.5° F (44.7° C), pressure at depth = 2500 psi). The most conservative estimate of the storage potential of the Newburg sandstone included only the area where wells in the Newburg include an interval of at least 10% porosity; calculated storage capacity ranged from 4.2 tonnes (0.01 efficiency factor) to 16.9 tonnes. Calculated storage capacity in the Newburg over the total area ranges from 16.4 million tonnes (0.01 efficiency) to 65.81 million tonnes (0.04 efficiency).

Relevance to U.S. Department of Energy Programs

The Secretary of Energy of the U.S. Department of Energy has requested that the National Coal Council (NCC) undertake a study about the use of enhanced oil recovery (EOR) technologies for the increased production of petroleum and the side benefits of retaining CO2 used for the EOR operations to remain in the ground. The report is due for completion in the latter half of calendar year 2012. We recommend that the results of the present study be used to estimate the potential for increased recovery of petroleum and the storage of CO2 in West Virginia. The modeling used to estimate West Virginia reserves and potential should also be examined for application to other areas in the Mid-West basin.

Table of Contents

Section Page

INTRODUCTION

West Virginia University (WVU), in cooperation with the West Virginia Geological and Economic Survey (WVGES), initiated work in October, 2007 to provide program support to the West Virginia Division of Energy (WVDOE) in the following topical areas:

1. Task 1: Sites for Coal-to-Liquids Plants (Carr/Patchen)
2. Task 2: Value-Added Carbon Capture and Storage (Carr/Patchen)
3. Task 3: Constraints on Increased Natural Gas Production (Avary)
4. Task 4: Water for Energy (Donovan/Ziemkiewicz)
5. Task 5: Fossil Energy Technology Program Support (Bajura/Wafle/Patchen)

In February 2009, WVU delivered to WVDOE a report (Phase 1 report) on the above five tasks in which potential follow-on, Phase 2 activities were identified. In conducting these tasks, the research team considered only sites whose overall reference area was in West Virginia, as outlined in the scope of work. However, this approach placed restrictions on evaluation criteria and the conclusions reached in the report because sites near the border could not be fully considered. The scope of work of the initial study also focused on value-added options (enhanced coal bed methane, enhanced oil recovery) for carbon storage, whereas the greatest carbon sequestration potential in West Virginia is in deep saline reservoirs.

The goals of the Phase 2 study were to expand the site selection criteria to fully evaluate the potential of reservoirs that extend into adjacent states, and to include consideration of deep saline reservoirs, specifically the Lower Devonian Oriskany Sandstone and the Silurian Newburg sandstone and Tuscarora Sandstone.

Four research tasks, with multiple subtasks, were created and completed to meet these goals.

In addition to the work plan described below, team members actively participated in other statewide activities. For example, Katharine Avary attended meetings of the Geology and Technology Subcommittee of the West Virginia Carbon Capture and Storage (WV CCS) Committee, during which the Geology & Technology Committee’s draft report was reviewed. She also served as a source for background information for an article on Carbon Capture and Storage (CCS) in the summer 2010 issue of "Views and Visions," published by Bowles, Rice, McDavid, Graff and Love, LLP.

WORK PLAN - PHASE 2

Phase 2 consisted of four major work tasks, including a task to accomplish program management and project integration. These tasks are described below.

Task 6: Evaluation of Value-Added Carbon Storage Applications

Task Manager:	Tim Carr, WVU Department of Geology and Geography (WVUDGG)
Participants:	WVGES, WVU WV GIS Technical Center (WVGISTC), NRCCE

Under Tasks 1 and 2 in Phase 1, we presented data for potential Coal-to-Liquid (CTL) sites and Carbon Storage Sites (CSS) for value-added carbon storage options, including enhanced oil and natural gas recovery and coal bed methane production with carbon sequestration. These data were tempered by constraints that did not allow consideration of site characteristics outside the state border. In actual applications, carbon storage plumes may spread in all directions in the subsurface, depending on the local pressure gradient, so a full circle around a potential site must be considered. Extending a site option to include the portion of a reservoir that underlies another state will require cooperation of all affected states in moving forward with any actual storage project.

The purpose of Task 6 was to consider potential CSS sites that lie close to the WV state border and evaluate their potential without regard to state boundaries. This task built on the data base already present in the WVCarb website identified in the Phase 1 final report.

The work included:

- Evaluation of oil and natural gas sites near the state border for possible enhanced oil / natural gas recovery, value-added storage options
- Evaluation of potential storage sites in unmineable coal seams with enhanced coal bed methane production
- Including the new data in the WVCarb data base
- Preparation of a final report to supplement the draft report prepared in Phase 1

Task 7: Model Development and Analysis of Oriskany Sandstone

Task Manager:	Tim Carr (WVUDGG)
Participants:	WVGES, WVGISTC, NRCCE

WVUDGG and WVGISTC developed a data base which contains some, but not all, of the relevant data needed to map the Oriskany Sandstone. A model for characterizing the region was partially completed at the outset of the project; and additional work was completed to generalize the model for application to all deep saline layers of interest. The work included:

- Developing a model for evaluation of deep saline aquifers, generalized for application to all regions of interest; including characterization parameters and capability for estimating carbon storage potential (volume and cost considerations)
- Completing data acquisition of the Oriskany Sandstone throughout the state and entering the data into the WVCarb data base
- Contributing information about the Oriskany Sandstone for a final report on deep saline aquifers as a combined report on Tasks 7 and 8

Task 8: Evaluation of Newburg and Tuscarora Sandstones

Task Manager: Mike Hohn (WVGES)
Participants: WVUDGG, WVGISTC, NRCCE

This task was led by WVGES, who generated a new data set as opposed to finalizing an existing data set already started by WVUGDD and WVGISTC. The model developed under Task 7 was used to guide the construction of the data set and the evaluation of the sequestration potential of these reservoirs.

The scope of work was similar to Task 7 and is summarized as follows:

- Acquisition of data for the Newburg and Tuscarora while applying the model and data set construction parameters outlined in Task 7
- Entering the data in the WVCarb data base
- Contributing information about these sandstones to a final report on deep saline aquifers as a combined report on Tasks 7 and 8

Task 9: Project Coordination

Task Manager: Douglas Patchen (NRCCE)
Participants: WVUDGG, WVGISTC, NRCCE

Project coordination activities were completed at the NRCCE by Douglas Patchen following his retirement from the WVGES. NRCCE asked him to assume a part-time assignment with the NRCCE to serve as task manager for coordination of the activity, a role he served in Phase 1.

RESULTS – PHASE 2

Task 6: Evaluation of Value-Added Carbon Storage Applications

6.1 INTRODUCTION

Capturing and storing carbon dioxide (CO_2) from power plants and industrial processes involves significant capital and operating costs. In limited cases, captured CO_2 could have considerable value. For example, it may be sold to oil producers for use in CO_2 -enhanced oil recovery (CO2-EOR). In some mature oil fields, producers can recover significantly more of the oil in place by injecting CO_2 into a well. CO2-EOR has been used in the United States for more than 30 years, providing experience in transporting and injecting CO_2 as well as increasing petroleum production (NETL, 2010a).

In 2009, CO2-EOR operators injected nearly 50 million metric tons of CO_2 into operating domestic oil wells, most of which was obtained from natural sources. However, the limited supply of natural CO_2 has provided enough incentive for a few facilities to capture anthropogenic CO_2 (NETL, 2010b). This activity also has financed the construction of several pipelines to transport CO_2 to oil fields. There is potential for more early adopters of carbon capture and storage (CCS) to market CO_2 to EOR operators.

In West Virginia, the deployment of CCS in power generation, coal to liquids (CTL) and other industrial facilities that emit significant volumes of CO_2 could be stimulated by using the captured CO_2 to produce more oil through the application of CO2-EOR technology. Based on very early work there appears to be significant potential for CO2-EOR in West Virginia (Pease and Watts, 1979). Increasing West Virginia and domestic oil production through CO2-EOR using anthropogenic sources could offset the cost of CCS, and could contribute to lower crude oil imports, enhanced domestic energy security, and significant state and national economic and environmental benefits.

It has been estimated that the productive use of this captured CO_2 for EOR could increase domestic oil production by 3.0 to 3.6 million barrels per day by 2030 (ARI, 2010). This could increase Lower-48 production from 54% to 65% by 2030 (EIA, 2011). The reduction of oil imports that could result from this increased domestic production would represent 33-40% of net crude oil imports in 2009 and 36-43% of net crude oil imports projected in 2030 (EIA, 2011).

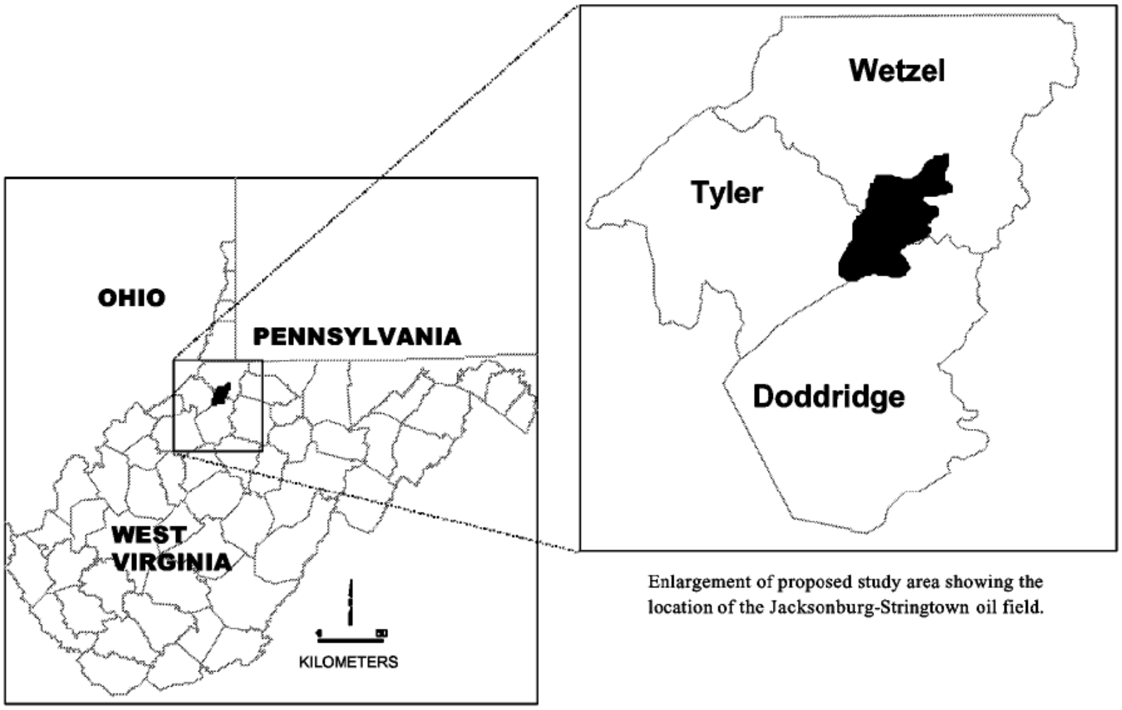
Typically, a reservoir that has undergone a successful waterflood is a prime candidate for a CO_2 flood, provided that: the minimum miscibility pressure (MMP) can be reached; there is a substantial volume of residual crude oil remaining; and the ability of the CO_2 to contact the crude oil is not hindered by geological complexity. When a waterflood is used to push oil through a reservoir, a significant residue is left behind. With CO_2 flooding, CO_2 and oil mix above a pressure known as the minimum miscibility pressure (MMP). At or above the MMP, CO_2 is miscible and acts as a solvent, cleanly sweeping the reservoir, leaving a small residue behind. At pressures below the MMP, CO_2 is immiscible and can assist oil production by swelling the oil and reducing its viscosity. The primary determinates of MMP are crude oil composition (primarily gravity and viscosity) and reservoir conditions (operating pressure and temperature, which is related primarily to depth).

6.2 METHODOLOGY AND CONCLUSIONS

The Jacksonburg-Stringtown oil field, located primarily in Wetzel and Tyler counties, had an estimated 88,500,000 barrels of oil in place in the Upper Devonian Gordon sandstone interval, of which approximately 20,000,000 barrels were produced during primary recovery (Figure 6.1; Ameri et al., 2002). A pilot waterflood began in 1981 and was successful enough to warrant development of a full-scale waterflood beginning in 1990 that reached field-scale in 2000 over the western parts of the field (Figure 6.2). The positive response on oil production can be viewed in county production data for Tyler County beginning in the early 90’s (Figure 6.3), and progressing with the spread of waterflood operations to the north into Wetzel County during the early 2000’s (Figure 6.4). If MMP could be achieved in the Jacksonburg-Stringtown oil field an additional recovery of 8% to 16% of the original oil in place, which would be 7.1 to 14.2 million barrels, could be expected. Other fields in northwestern West Virginia provide similar opportunities for CO2-EOR (Kinder Morgan, 2001).

An oil sample was obtained for MMP slim tube analysis from the East Resources L. J. Fluharty 3 (API 4710300911) at the very northern edge of the field (Figure 6.2). The oil had a gravity of 46.5 at reservoir conditions. Results indicate that the MMP is 941 pounds per square inch (psi) at 80^{o}F (Appendix A). The MMP is well below expected hydrostatic reservoir pressure for the reservoir of ~1200 psi. This result indicates that if an anthropogenic CO_2 source can be located, the Jacksonburg-Stringtown oil field has a significant potential for miscible CO2-EOR associated with value-added geologic storage.

This information is being used for screening economics and reservoir simulation as part of an MS thesis at West Virginia University. Results will be distributed to the public upon completion.



Enlargement of proposed study area showing the location of the Jacksonburg-Stringtown oil field.

Figure 6.1 - Location of the Jacksonburg-Stringtown oil field in northwestern West Virginia (figure from Ameri et al., 2002). Similar fields exist throughout northwestern West Virginia.

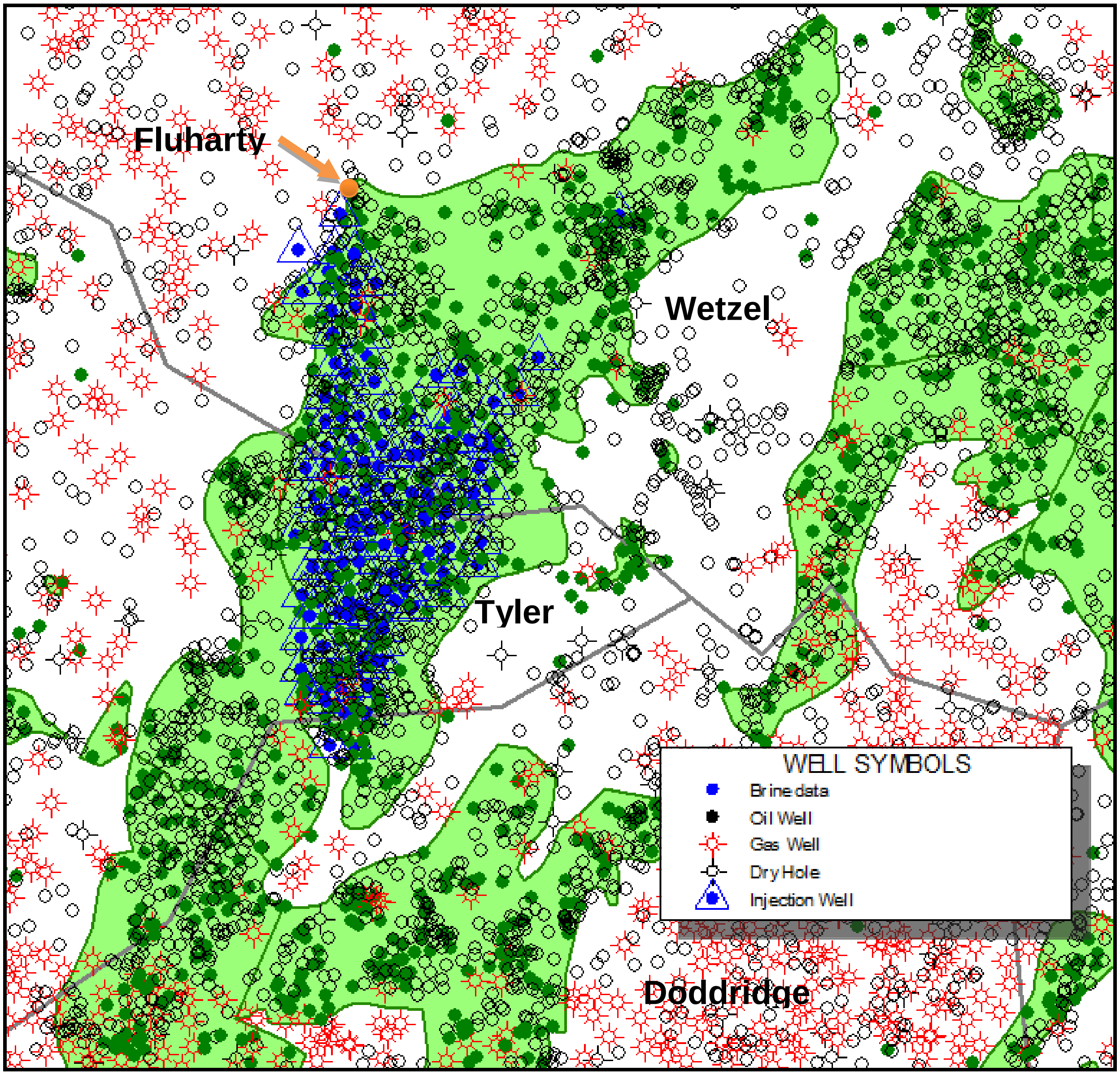


Figure 6.2 - Image showing oil (green) and gas (red) wells in the area of the Jacksonburg-Stringtown oil field across eastern Tyler and southern Wetzel counties. The numerous oil fields in the area are highlighted in green. Injection wells for the waterflood area of the Jacksonburg-Stringtown oil field are shown as blue triangles. An oil sample was obtained from the East Resources L. J. Fluharty 3 (API 4710300911) at the very northern edge of the field and is highlighted in orange.

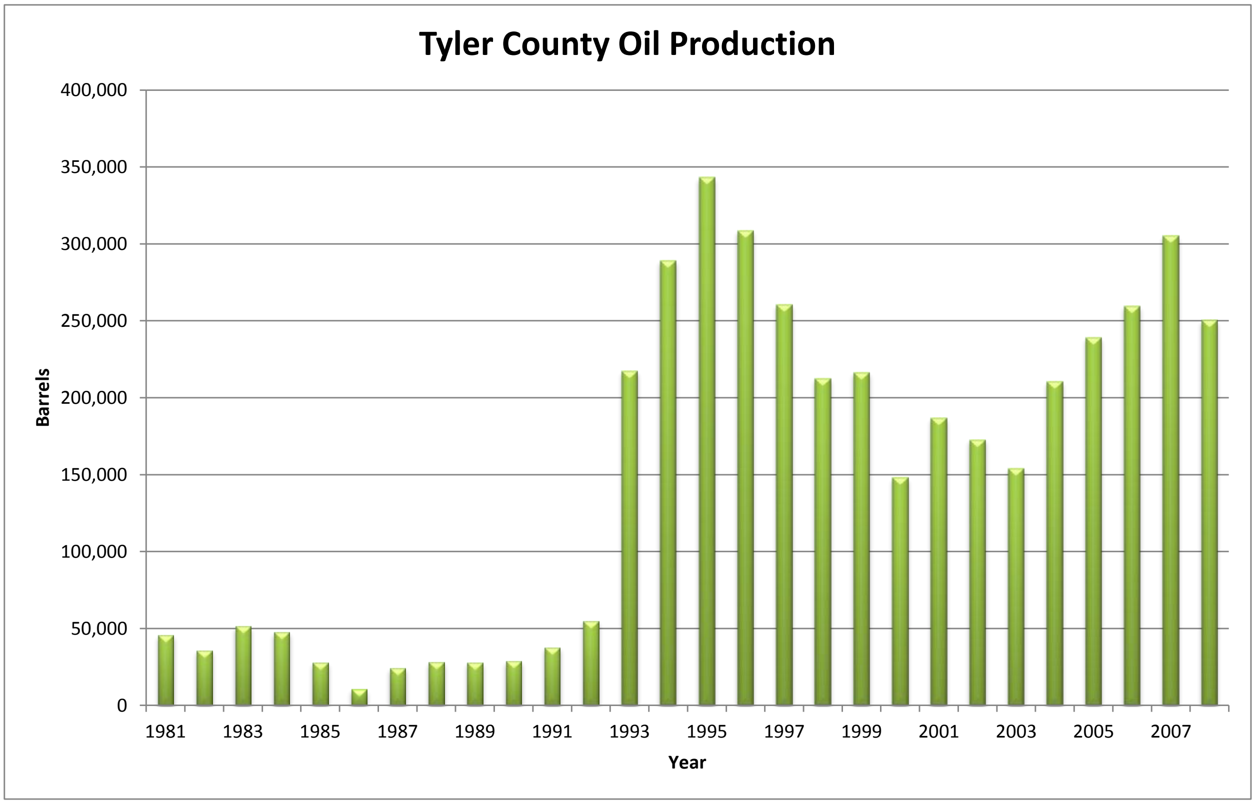


Figure 6.3 –Plot of Tyler County, West Virginia annual oil production showing the effect on increased oil production from the waterflood in the southern parts of the Jacksonburg-Stringtown oil field, which began in 1990-91.

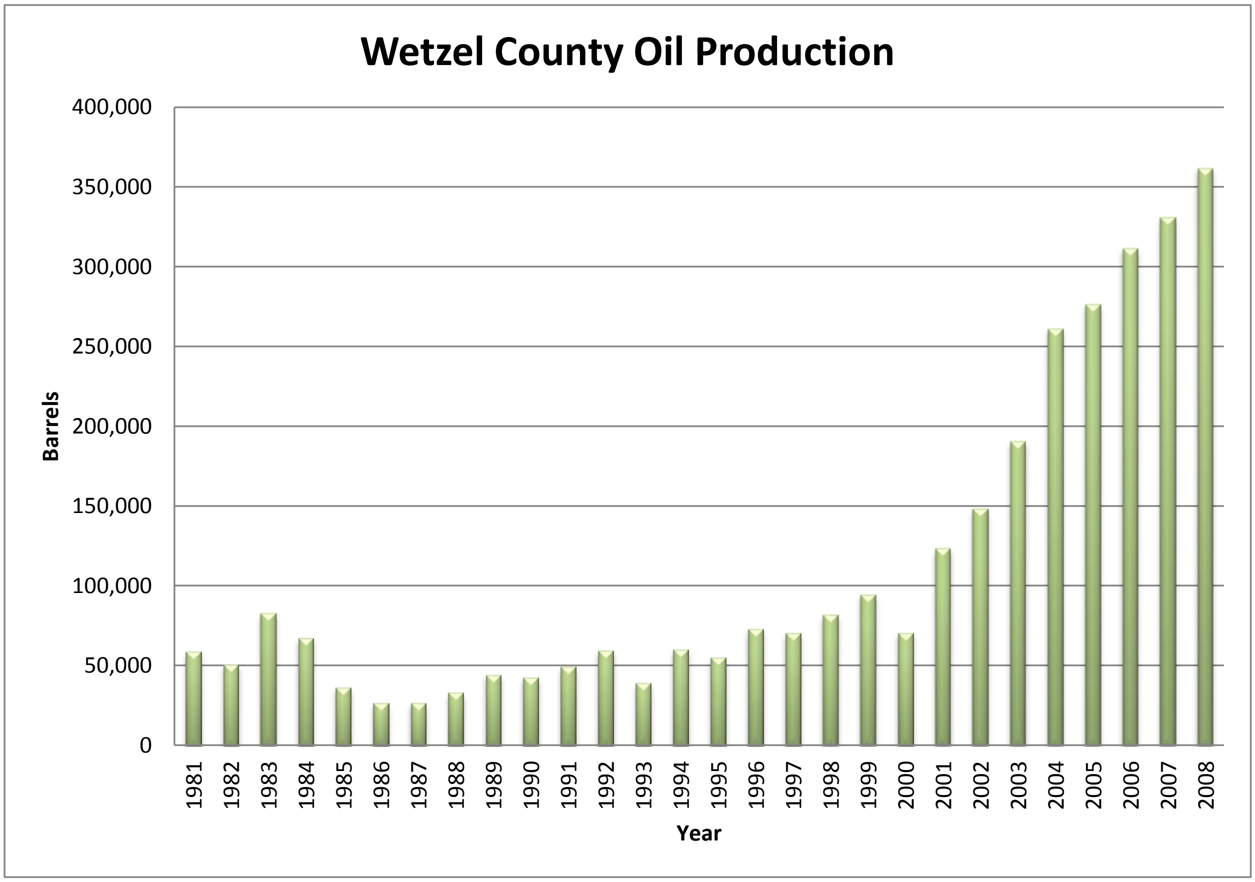


Figure 6.4 –Plot of Wetzel County, West Virginia annual oil production showing the effect on increased oil production from the extension of the waterflood to the northern parts of the Jacksonburg-Stringtown oil field, which began in 2000.

Task 7: Model Development and Analysis of Oriskany Sandstone[1]

7.1 SUMMARY

Data for the Oriskany Sandstone were used to generate isopach, porosity, pressure, temperature and salinity grids across West Virginia and adjoining areas of the Appalachian basin. Grids were then used to perform a grid-to-grid calculation to estimate the available volume within the potential CO_2 sequestration area. Calculations were performed using the constants for density of supercritical CO_2 (800 kg/m^3) and the storage efficiency factors (0.01 and 0.04). The result is a storage resource estimate for the Oriskany Sandstone of 1.246 to 4.983 gigatonnes of CO_2. Data are available through http://www.wvcarb.org/.

7.2 INTRODUCTION

The Oriskany Sandstone of the Appalachian basin is a widely distributed, saline aquifer which has produced large quantities of hydrocarbons (primarily natural gas). Currently, the Oriskany is host to numerous gas storage fields and has the potential for large-scale geologic storage of CO_2. Published and unpublished data of rock characteristics, pressure, temperature, and formation water geochemistry, along with new brine samples, were integrated within a geographical information system to better understand the regional-scale hydrogeological regime and the regional geologic CO_2 storage potential. The Oriskany is generally underpressured, which would aid in storage of CO_2 by lowering injection and displacement pressures. The geothermal gradient for the Appalachian basin, approximately 20°C/km, is lower than what is expected for cratonic rocks, decreasing the pressure at which CO_2 would be in a supercritical state. The up-dip flow of the Oriskany Sandstone formation waters is generally controlled by outcrops at high elevation to the east and at low subsurface elevation to the west, and opposed by increased salinity-induced buoyancy forces down-dip. The flow pattern is substantiated by the salinity distributions, with relatively lower salinity at recharge to the east due to mixing with fresh meteoric water and higher salinity at depth. The brine geochemistry, temperature, pressure and hydrologic flow conditions could lower the relative speed and risk of CO_2 migration and improve the potential for long-term entrapment of CO_2 in the Oriskany Sandstone.

The ideal saline aquifer for geologic storage of CO_2 is comprised of porous rock saturated with brine at sufficient depth to maintain CO_2 in a supercritical condition. It must be capped by one or more regionally extensive impermeable rock formations that enable trapping of injected CO_2 over long periods of time. In addition, areas of converging fluid flow can aid in long-term lateral containment of injected CO_2 (Bachu et al., 2007; Bachu, 2008). A saline aquifer assessed for storage is defined as a porous and permeable body of rock containing water with total dissolved solids (TDS) greater than 10,000 ppm, which

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[1] This write-up is a summary of material generated as partial fulfillment of a MS Thesis by Ms. Jamie Skeen. This thesis was supported in part by funding from the West Virginia Division of Energy.

can store large volumes of CO_2. A saline aquifer can include more than one, named, regionally-extensive, geologic formation or be defined as only part of one formation (Bachu et al., 2007).

The storage capacity for CO_2 is a geological resource whose availability can be expressed using the resources and reserves concept just as other energy or mineral commodities such as oil and gas, copper, or gold are classified (CSLF, 2005; Bachu et al., 2007). A resource is a commodity whose quantities are estimated to exist at a given time and can be currently or potentially extracted. It can be either in-place or inferred. A reserve is a commodity whose quantities are known to exist and can be economically recoverable with current technologies and economic conditions (Frailey et al., 2006; Bachu et al., 2007).

During this study, we provided improved geospatial data to better evaluate the Oriskany Sandstone as a regional geologic storage resource and to influence future site screening. Site specific evaluations are beyond the scope of this effort and require additional geologic, geophysical, cultural and economic data.

More accurate estimates of porosity, salinity and flow potential of formation water could allow a better estimation of CO_2 storage capacity in West Virginia and the surrounding areas of the Appalachian basin, as well as indicating possible migration directions and information on hydrocarbon accumulation (Bachu, 1995b; Anfort et al., 2001; Carr et al., 2005). With the use of both new and existing data, the Oriskany Sandstone was analyzed throughout the Appalachian basin in terms of the parameters that influence storage resource volume, injectivity and long-term containment. The often significant differences (i.e. depth, thickness, salinity, pressure, temperature and porosity) that exist across the extent of the Oriskany Sandstone have been taken into account. The salinity, large-scale potential flow of the formation water and basin-scale storage resource volume of the Oriskany Sandstone were estimated, mapped and loaded into an online map server.

Since the 1930's, the Oriskany has become one of the most important formations for gas exploration and gas storage in the Appalachian basin. As a result, the Oriskany has been the subject of numerous studies related to structure, stratigraphy, petrology, petrophysics and other topics (Diecchio et al., 1984; Diecchio, 1985). The Oriskany is typically a fossiliferous quartzarenite cemented with locally-variable amounts of quartz or calcite. It can be traced continuously through New York, Pennsylvania, Ohio, Maryland, West Virginia, Virginia and Kentucky (Diecchio, 1985; Bruner and Smosna, 2008). The Oriskany typically unconformably overlies strata of the Helderberg Limestone or equivalents, and is overlain by Onondaga Limestone, Huntersville Chert or Needmore Shale (Figure 7.1), which vary from limestone to chert to shale and are locally sandy (Diecchio, 1985). Because the Oriskany is a major, deep-gas producer within the basin, data such as pressure, temperature, porosity, permeability and brine composition are available (Diecchio et al., 1984). The data indicate that the Oriskany may be a potential target for geologic storage of CO_2. Both intergranular and fracture porosity exist within the Oriskany, and overlying, thick, low-permeability zones within the Appalachian basin provide the potential for vertical containment (Diecchio, et al., 1984; Gupta et al., 2005).

7.3 PREVIOUS WORK

The Oriskany Sandstone was analyzed recently by the USDOE to determine its CO_2 sequestration reservoir potential (Soong et al., 2004a, 2004b; Dilmore et al., 2008). These studies of the solubility and displacement volumes for CO_2 sequestration potential were based upon brine samples taken from a single well in Indiana County, Pennsylvania that were assumed to be representative of Oriskany Formation brine chemistry basin wide (Dilmore et al., 2008). Due to varying depth, thickness, porosity, temperature, pressure and brine composition, additional analyses over a more extensive area are needed in order to properly characterize the Oriskany saline aquifer. Each of these variables independently has the potential to affect the volume and long-term retention of CO_2 that could be injected and stored.

At standard atmospheric conditions CO_2 is a stable gas that is slightly denser than air. For temperatures greater than 31.1 °C and pressures greater than 7.38 MPa, CO_2 is a supercritical fluid. In its supercritical state, CO_2 has the high-density characteristics of a liquid, yet behaves like a gas by filling all the available volume (Bachu and Stewart, 2002; Bachu 2008). In order for the injected CO_2 to remain in a supercritical phase, the Oriskany Sandstone must be 800 meters or greater in depth. Maintaining this supercritical phase is important because the injected CO_2 occupies several orders of magnitude less volume than in its gaseous phase. These deep depths will also reduce the relative buoyancy of the CO_2 and help to insure an adequate thickness of confining layers is present above the Oriskany to act as an impermeable seal.

Estimating the porosity and thickness of the Oriskany provides a means to calculate the reservoir's potential volume that can be used to store CO_2 when the depth criterion is taken into consideration. The average porosity value controls the maximum possible space that the sequestered CO_2 can occupy. The brine composition of the aqueous fluids within this porosity is critical for determining the volume of CO_2 trapped through dissolution into the formation water and precipitated as mineral components. The solubility of CO_2 in the formation water decreases with increasing water salinity (Brennan and Burruss, 2006).

7.4 METHODOLOGY

The geology, stratigraphy and geometry of the Oriskany were described to understand the flow regime and estimate the storage volume. Well data were processed using a subsurface geologic information system to generate structure contour maps, isopach maps and grids for calculating CO_2 storage volume. The porosity of basin rocks is a hydraulic property that has control on the subsurface fluid flow (Bachu and Undershultz, 1992). Core- and well-scale porosity were used to estimate the basin (regional) scale porosity of the Oriskany. The well-scale porosity is the vertical arithmetic average of the core-scale values weighted by the thickness of the unit sampled. The basin (regional) scale estimates were obtained from the large-scale, spatially averaged well-scale porosity. Knowledge of sedimentary basin geology, lithology and hydrostratigraphy is important in understanding the flow of formation waters (Bachu and Undershultz, 1995; Bachu, 1997). Fluid flow is driven by fluid pressure gradients, which may be influenced to greater or lesser degrees by compaction, topographic variations in water column height, pressure loss to flow and spatial variations in temperature, pressure, elevation, density and fluid composition (Bachu, 1995a). Spatial variations in temperature, pressure, density and TDS concentrations were mapped across the basin. All data used are available through http://www.wvcarb.org/.

7.5 GENERAL CHARACTERISTICS OF ORISKINAY SANDSTONE

The Oriskany Sandstone dips toward the center of the Appalachian basin along a northeast-southwest trend (Figure 7.2). At the center of the study area, it reaches a maximum depth ≤ 2,000 meters mean sea level (MSL). It shallows toward outcrop areas to the east (along the Allegheny Front and Eastern Overthrust Belt) and in the subsurface to the west. The area within the known outcrop belt could not be accurately represented with the limited data and therefore was not contoured. A map of depth to the Oriskany was constructed to map areas suitable for supercritical CO_2 injection. The Oriskany reaches maximum depths of over 2,500 meters in the center of the Appalachian basin (Figure 7.3). The potential CO_2 sequestration area was mapped along the 800 meter depth contour (Figure 7.4). The area was not mapped into locations were depth data were lacking. The delineated area is 139,000 km^2 (± 1,000 km^2).

The thickness of the Oriskany varies across the Appalachian basin from zero to a thickness ≥ 75 meters (Figure 7.5). In the “no-sand area” in the northern Appalachian basin, the Oriskany is thin or absent due to erosion or non-deposition (Diecchio, 1985). The Oriskany is typically thickest in the High Plateau and Eastern Overthrust Belt regions, but thins and pinches out to the west, northwest and south, where it is generally ≤ 10 meters thick.

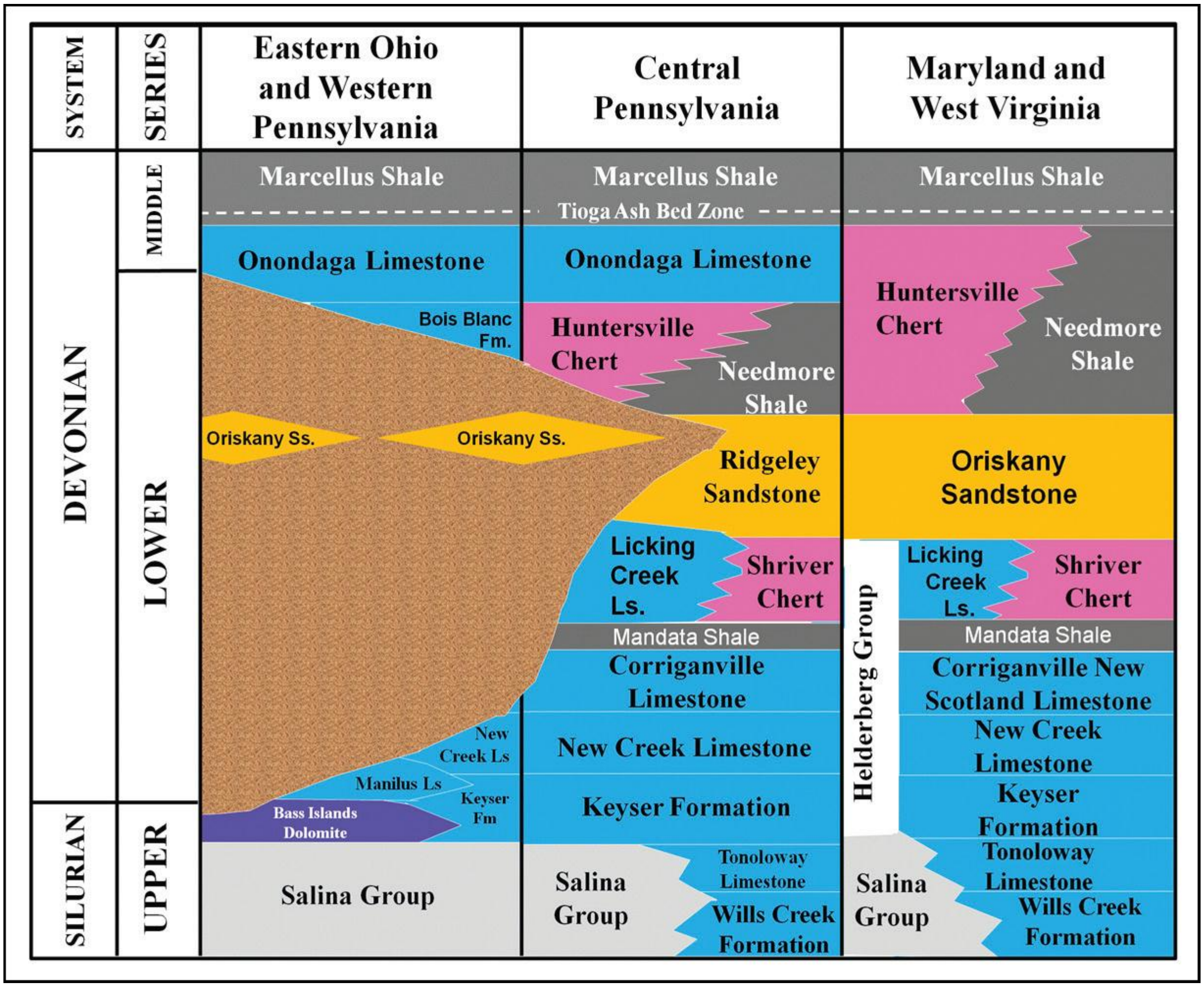


Figure 7.1 - Stratigraphic column of Lower Devonian of Maryland, Ohio, Pennsylvania and West Virginia. Based on stratigraphic column of Pennsylvania Geological and Topographic Survey

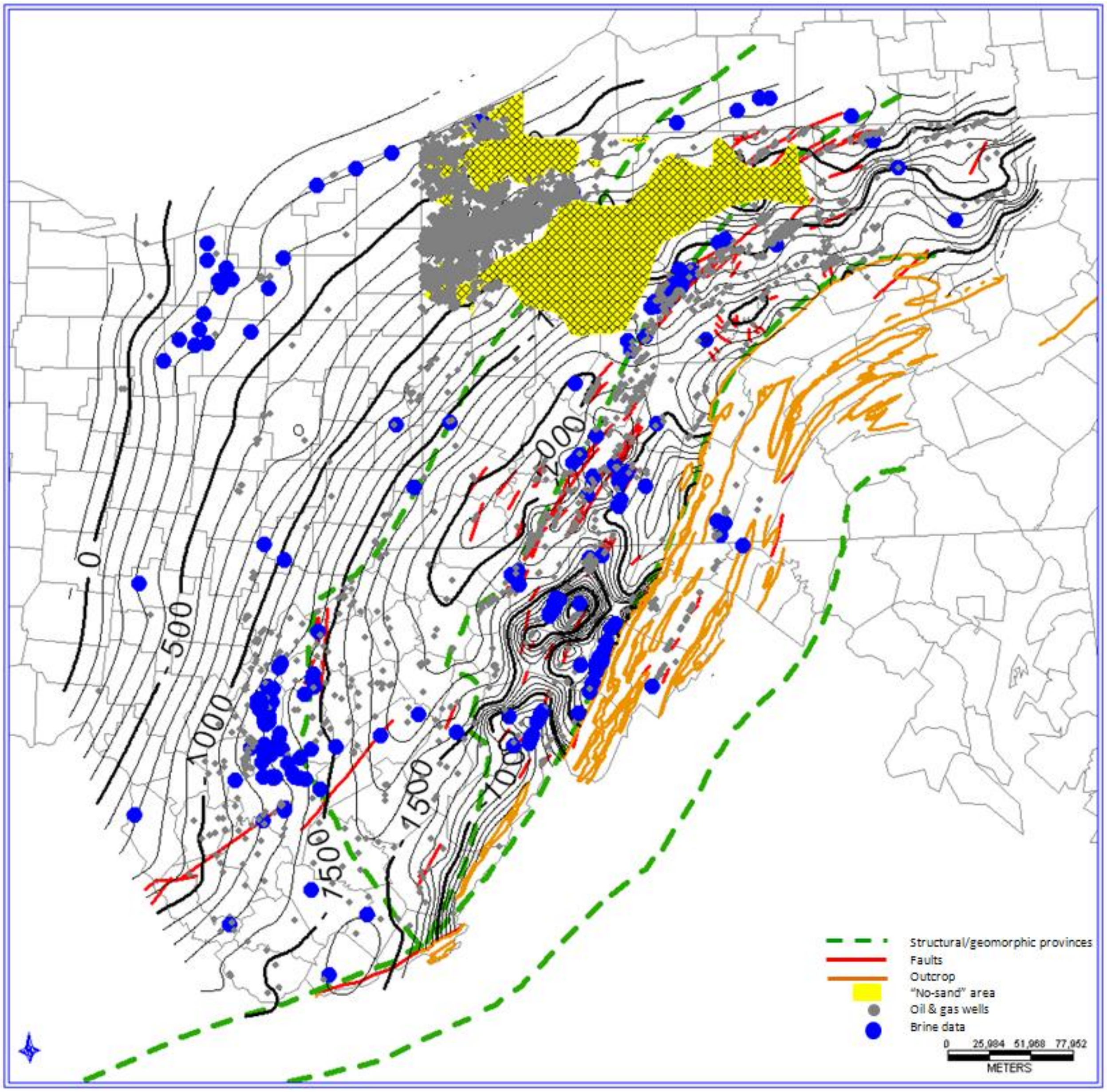


Figure 7.2 - Structure on the top of the Oriskany Sandstone. Contour interval is 100 meters.

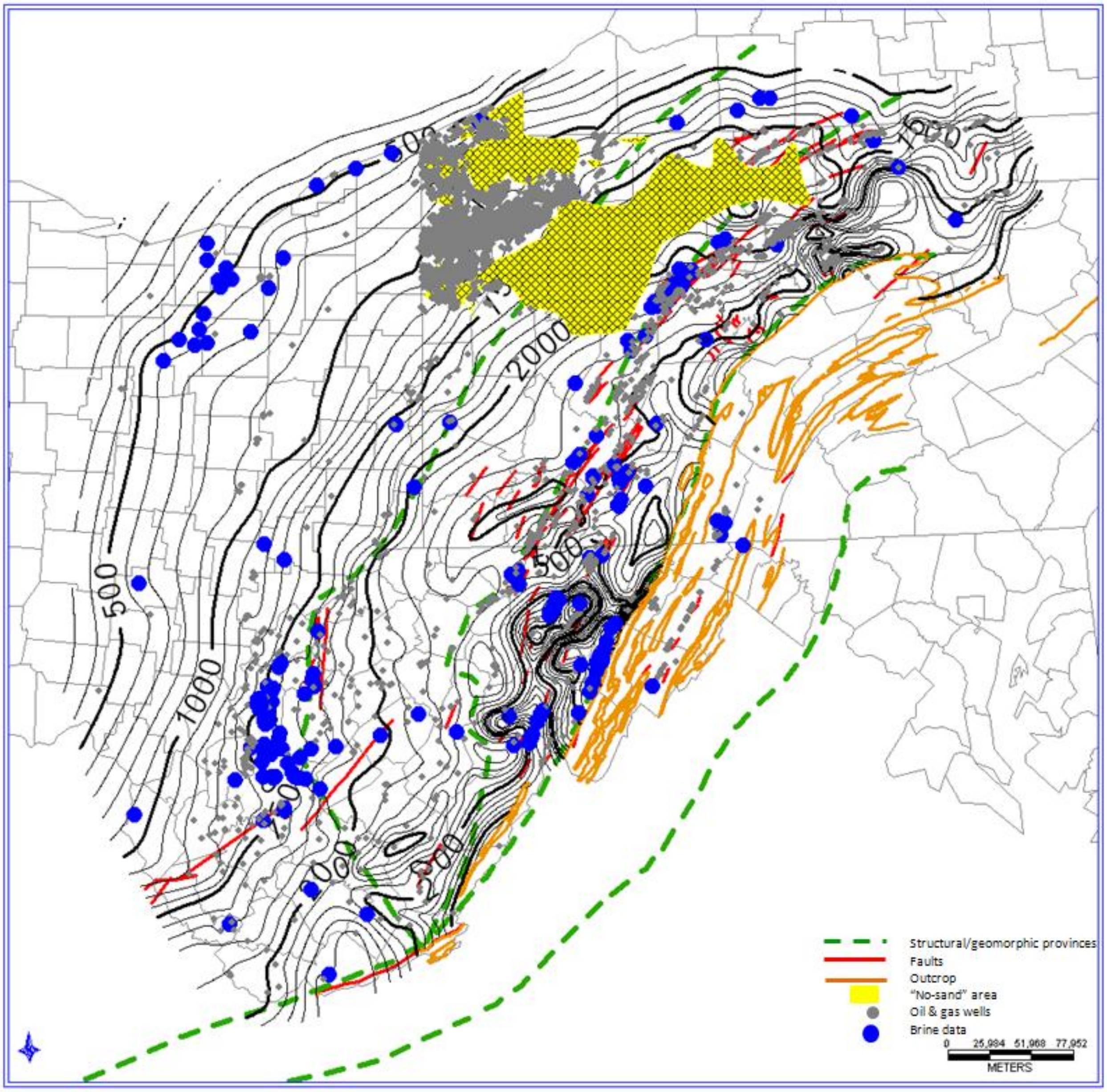


Figure 7.3 - Depth to top of Oriskany Sandstone. Contour interval is 100 meters. Areas within the known outcrop belt to the east were not contoured due to lack of sufficient data to accurately depict the complex structure.

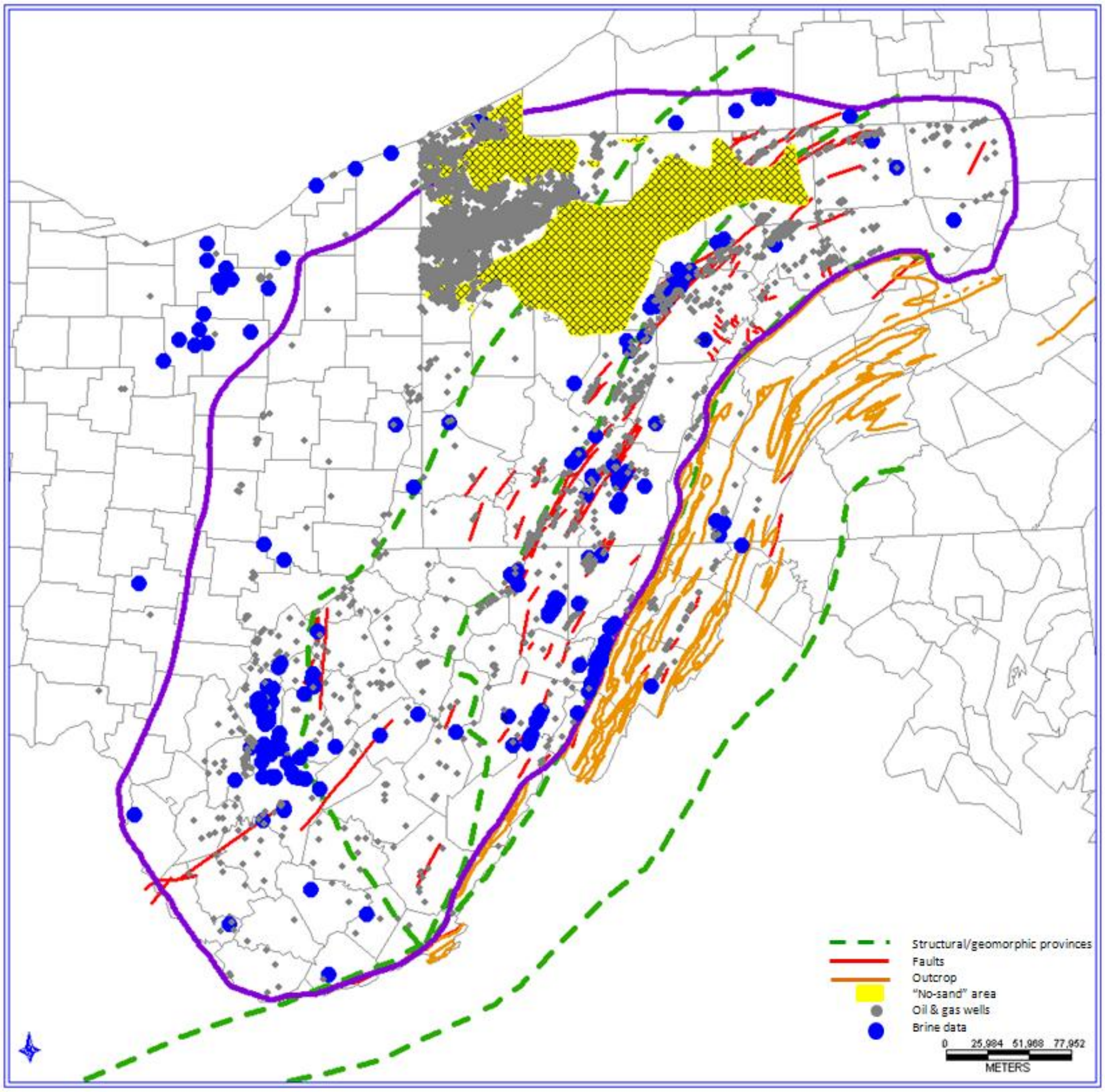


Figure 7.4 - Oriskany Sandstone potential sequestration area. The purple line indicates the study area that meets the depth greater than 800 meters criteria for supercritical CO_2 storage and avoids areas of known outcrop belts.

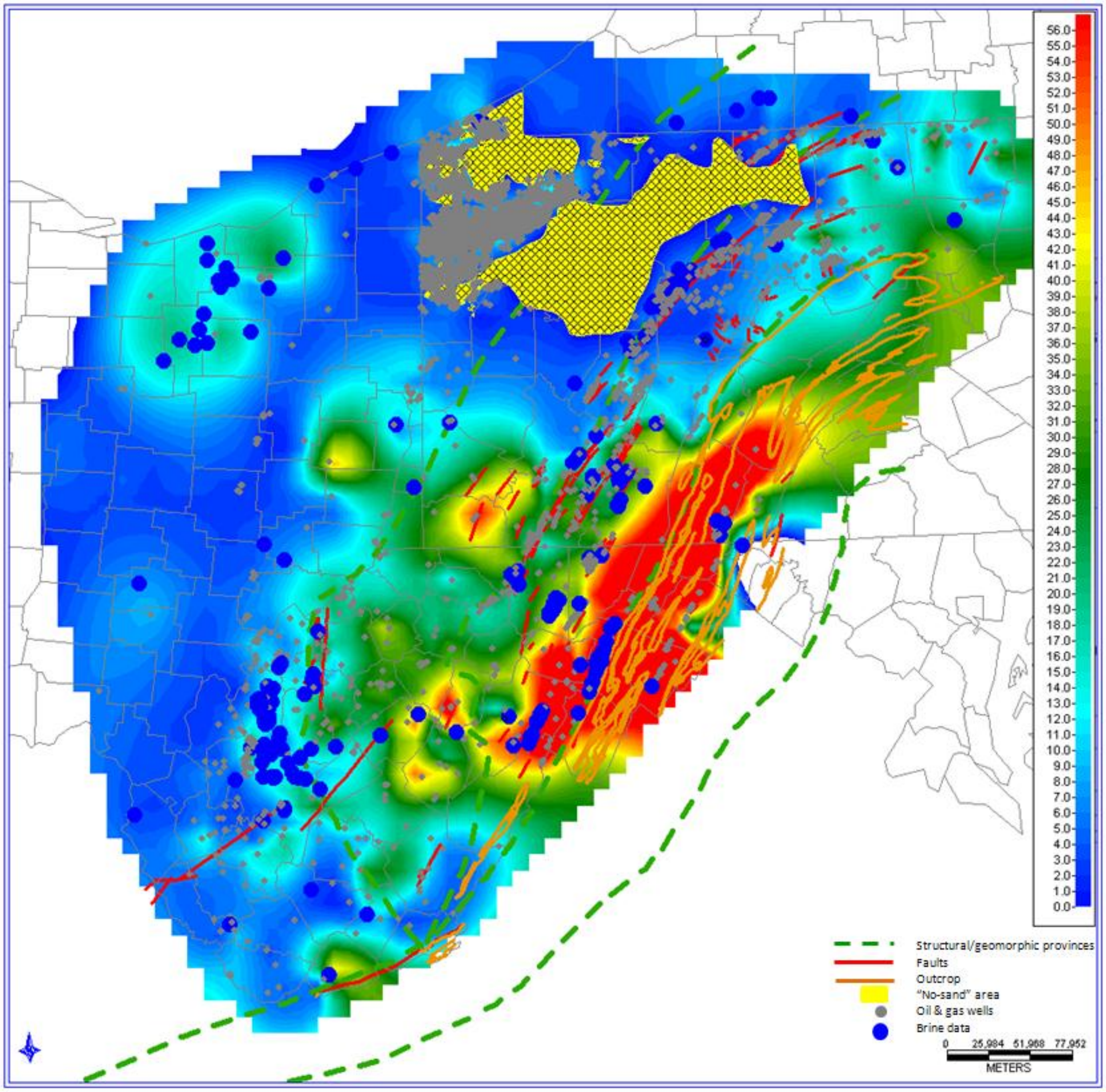


Figure 7.5 - Oriskany Sandstone thickness estimate. The average thickness is 16 meters. Contour interval is 1 meter. “No-sand areas” are indicated by yellow cross-hatched.

7.6 RESERVOIR AND ROCK PROPERTIES

Core data were used to estimate the porosity of the Oriskany. The data were largely restricted to areas of existing oil and gas wells, requiring extrapolation across data gaps to map the study area. The core-scale porosity measurements were scaled up to well scale and then to basin scale using the method described by Bachu and Underschultz (1992, 1993). The method states that the formation-scale porosity index (Φ) of the unit is the arithmetic average of the core-scale values weighted by the thickness of the unit. Well-scale porosity values were then used to estimate the potential CO_2 storage volume.

It should be noted that reported core-porosity data represent volume-averaged values corresponding to the physical size of the sample (i.e., core plug). Therefore, they do not reflect larger-scale, secondary porosity elements such as vugs and fractures (Bachu and Undershultz, 1992).

Porosity estimates were collected from published studies, as well as from producing or potential oil and gas wells (Headlee and Joseph, 1945; Herald, et al., 1962; Harper and Patchen, 1996; New York Geological Survey, pers. comm.; and Texas Keystone, pers. comm.). These data consisted of porosity values for counties and individual oil and gas fields. These porosity values were assigned to the wells located within the counties or fields resulting in a total of 894 well values. Using the method of Bachu and Undershultz (1992, 1993) a mean porosity of 8.08% was estimated and a map was interpolated using the minimum curvature method (Figure 7.6). The Low Plateau and High Plateau of the central Appalachian basin contain the area with the lowest porosity values.

Bottom-hole temperatures (BHTs) are recorded during logging of the borehole and commonly are not at equilibrium with formation temperature and require correction. Temperatures from shallow boreholes are generally too high, and temperatures from deep boreholes are too low. One method to correct for these erroneous BHTs is to plot the values versus depth, with the mean surface temperature (12° C for the Appalachian basin) providing an intercept (Forster et al., 1999). Figure 7.7 shows a plot of Oriskany bottom-hole temperature versus depth for 57 wells. By comparing the regression equation between the uncorrected and corrected intercepts a correction factor can be generated.

Under hydrostatic conditions, pressure increases with depth at the rate of 9.74 kPa/m for fresh water, and approximately 10.71 kPa/m for brine with 145,000 mg/L TDS. Recorded pressure, like temperature, is related to both depth and burial history (Carr et al., 2005). Measured pressure values may be influenced by drawdown from nearby wells, but these data were still retained because local production is thought to have little influence on regional-scale pressure features (Bachu and Undershultz, 1995). Final shut-in pressure versus depth for 225 wells in the Oriskany is shown in Figure 7.8. The hydrostatic gradient for fresh water and brine are plotted over these data to test hypotheses that the Oriskany is either overpressured or underpressured (Figure 7.8). The data indicate that the Oriskany is underpressured.

Existing brine geochemical data were gathered from published and unpublished state and federal geological surveys, as well as local oil and gas companies. The data were checked for quality assurance based on the method described by Hitchon and Brulotte (1994). An additional ten brine samples were collected from existing oil and gas wells distributed throughout the Appalachian basin, with an attempt made to collect new samples from areas of data gaps. The location of these brine samples depended on the participation and cooperation of local oil and gas companies. The brine samples were collected according to United States Geological Survey (USGS) standards in 500 mL, high-density polyethylene bottles that were labeled with well location, formation sampled, depth and date.

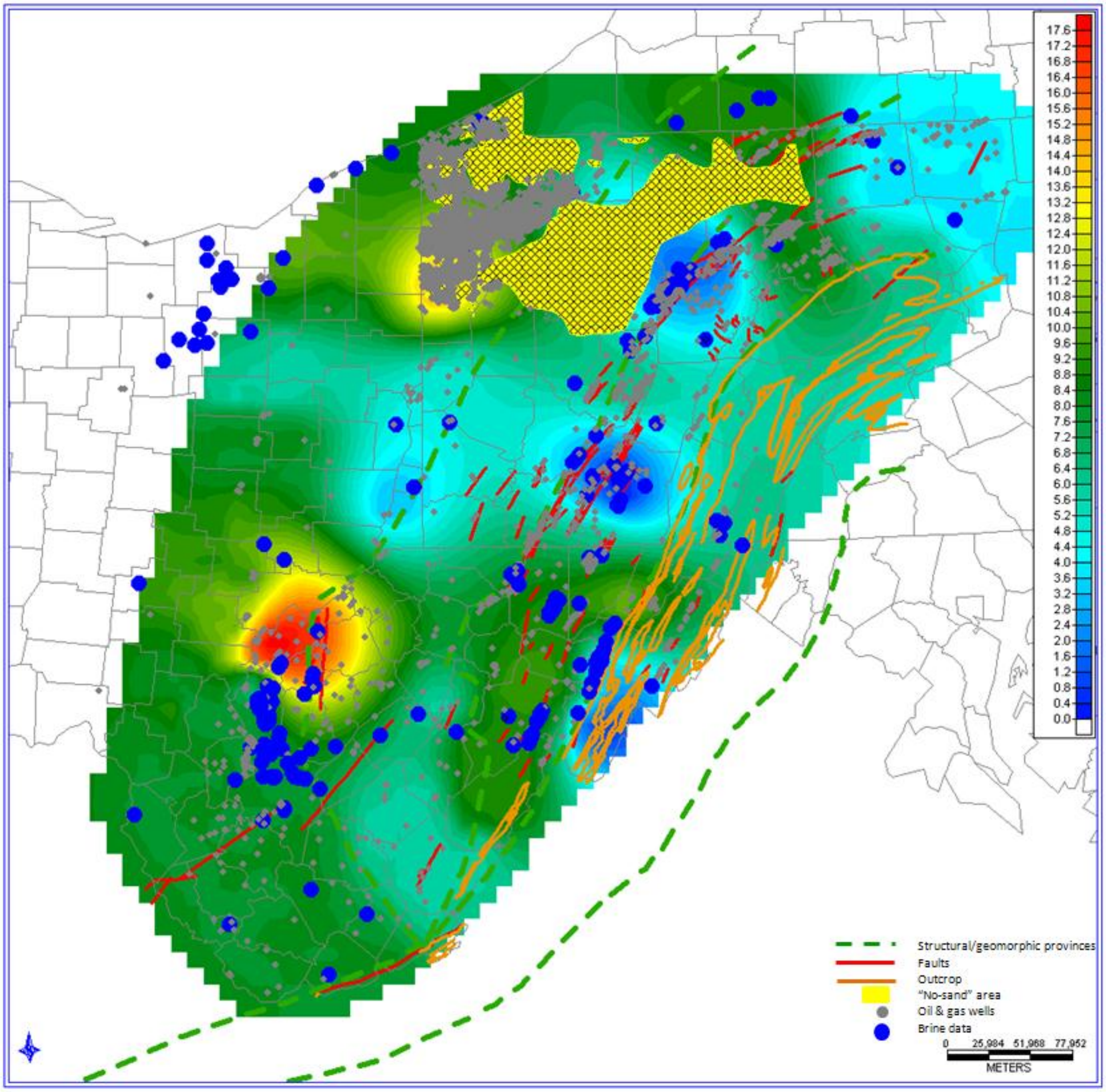


Figure 7.6 - Oriskany Sandstone porosity map. Contour interval is 0.2 porosity units.

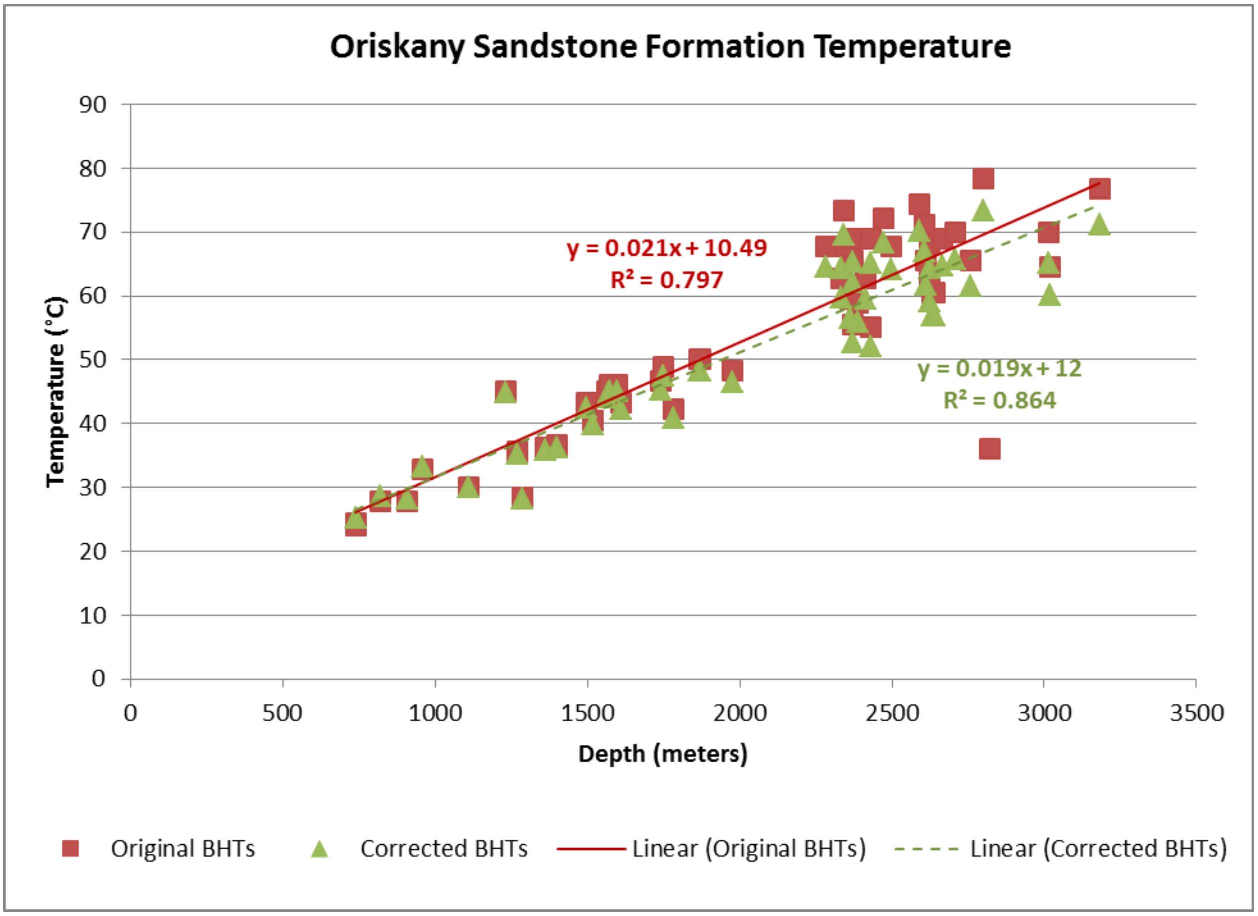


Figure 7.7 - Oriskany Sandstone formation temperature (°C) plotted against depth (m). Data are from 57 wells.

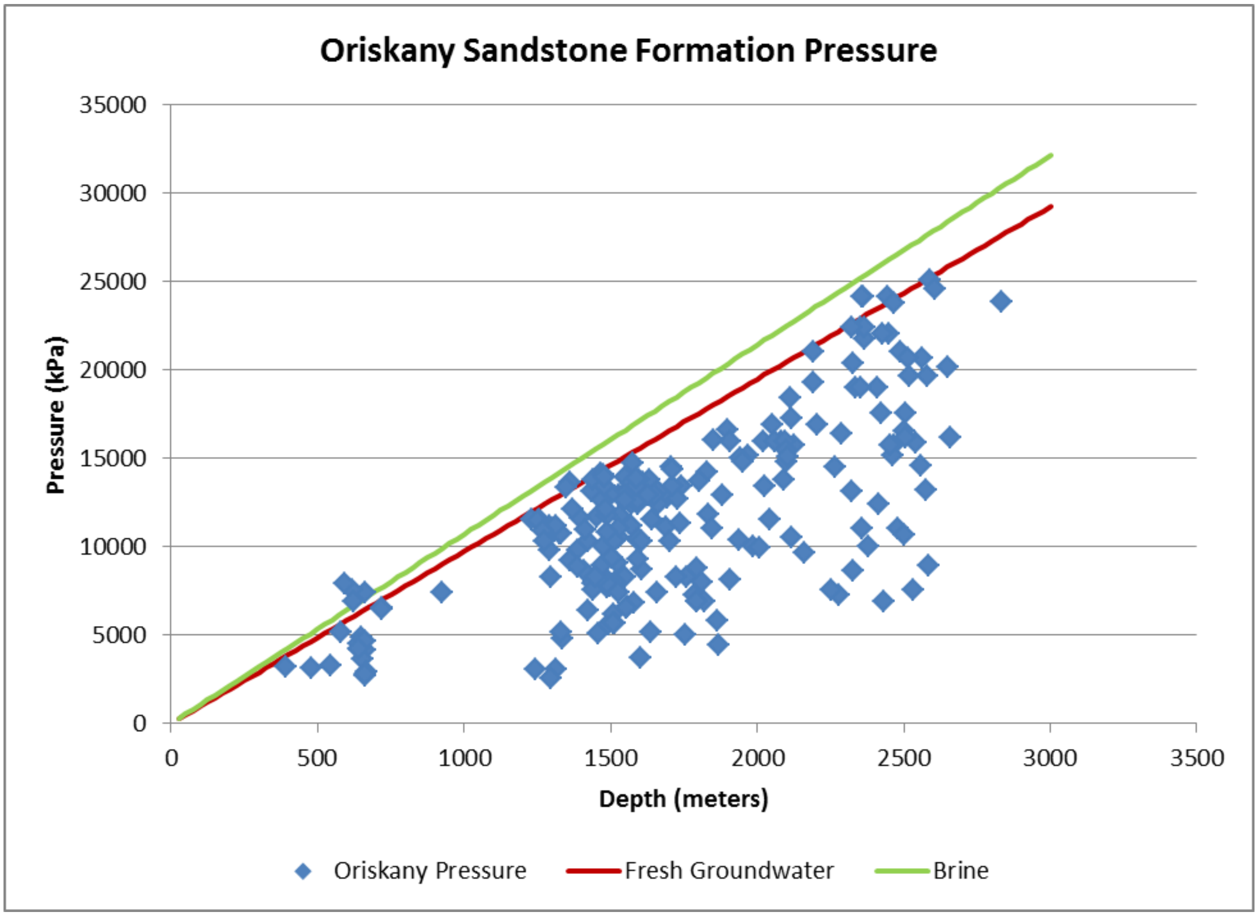


Figure 7.8 - Oriskany Sandstone formation pressure (kPa) plotted against depth (m). Red line indicate the idealized pressure gradient for fresh groundwater (TDS <10,000 mg/L). Green line indicate the idealized pressure gradient for brine (TDS=145,000 mg/L). Data are from 225 wells.

7.7 FLUID FLOW ANALYSIS

Darcy’s law describes fluid flow in a porous medium. When it is written in terms of hydraulic head rather than pressure, it shows that the flow of formation water is driven by hydraulic gradients, density differences, and variations in temperature and chemical concentrations (Bachu, 1995b). For sedimentary basin-scale flow systems, temperature and chemical concentration differences are generally thought to be unimportant by comparison with hydraulic- (topographic) and buoyancy-driving mechanisms (Bachu, 1995a, 1995b). Buoyancy, due to density differences, can potentially play an important role by opposing and retarding the flow of formation waters driven by hydraulic-head gradients (Bachu, 1995b).

In order to analyze the flow pattern, the formation pressures were used to calculate equivalent freshwater hydraulic head, H_o:

(1)

where p is formation pressure, $\rho_o = 1000$ kg/m^3 (density of freshwater), g is the gravitational constant 9.80665 m/s^2, and z is elevation relative to sea level (Bachu and Undershultz, 1993, 1995; Anfort et al., 2001). Formation waters in sedimentary basins become less dense as temperature increases, but denser as salinity increases. Therefore, density variations have the potential to introduce error in freshwater hydraulic head estimates (Bachu and Undershultz, 1993, 1995). An indication of the magnitude of this introduced error is given by the dimensionless driving force ratio (DFR) defined (Davies, 1987; Bachu, 1995) as:

(2)

where $|\Delta E|$ is the magnitude of the aquifer slope, $|\Delta H_o|_h$ is the magnitude of the horizontal component of the freshwater hydraulic-head gradient, $\Delta\rho$ is the difference between formation-water and freshwater densities. If the DFR value is greater than 0.5, neglecting buoyancy effects will introduce significant errors in flow analysis using an equivalent head concept (Davies, 1987). However, according to Aufont, et al., (2001), the presence and direction of flow will be correct but the magnitude will be less than indicated. This is due to hydraulic gradients and buoyancy acting in opposite directions along dip. The values for H_o thus calculated were mapped using the minimum curvature parameters and the resulting gradients were used to estimate the flow direction and strength.

Figure 7.7 shows correcting for erroneous BHTs in the Oriskany to a zero-depth intercept of 12 °C (average surface temperature) to yield a linear geothermal gradient by regression of:

$$T = 0.0195 \times d + 12 \quad (3)$$

where T is in degrees Celsius and d is in meters. This is approximately 20°C/km, low for cratonic rocks, typically 25 to 30 °C/km. Hitchon (1984) attributes low geothermal gradients to topographically-controlled hydrodynamic flow. The newly calculated geothermal gradient values were used to generate a map of subsurface temperature of the Oriskany using the minimum curvature method (Figure 7.9). The resulting grid will be used in estimating the storage capacity of the Oriskany.

Final shut-in pressure recorded from gas wells of the Oriskany (based on n = 225 wells) is significantly below the expected hydrostatic gradient for fresh groundwater. Pressure plotted against depth indicates that the Oriskany is underpressured (Figure 7.8). This underpressure below hydrostatic for either fresh or average-salinity water (lines on Figure 7.8) may be due to drawdown from nearby wells and/or lack of sufficient shut-in time to reach pressure equilibrium. A few cases (< 5%) of overpressure were observed, but the Oriskany reservoirs at a regional scale appear to be underpressured. Abnormally low reservoir pressures can be caused by gaseous diffusion and gas shrinkage in reservoirs that have been uplifted or otherwise cooled. The High Plateau of the central Appalachian basin is the area with the highest pressure values. The newly calculated pressure gradient values were used to generate a map of subsurface pressure of the Oriskany using the minimum curvature method (Figure 7.10). The resulting grid will be used in estimating the storage capacity of the Oriskany.

Oriskany brine geochemical data were compiled from numerous published and unpublished sources. Additional brine samples were collected from ten existing oil and gas wells and storage fields distributed throughout the Appalachian basin. Across the study area, the TDS ranges from fresh (TDS < 10,000 mg/L) to brine (TDS > 300,000 mg/L) (Figure 7.11). The brines are concentrated in the structural lows at the center of the basin, while the relatively low TDS concentrations are associated with the outcrop areas to the east and southeast.

Formation pressure was used to calculate equivalent freshwater hydraulic head H_o (Formula 1). Use of freshwater hydraulic heads in the flow analysis of variable-density formation waters may introduce significant errors, depending on the interaction between the potential and buoyancy forces driving the flow (Bachu and Undershultz, 1993, 1995). Density values were calculated from salinity, temperature, and pressure using the relationships published by Gill (1982). Across the extent of the Oriskany the density ranges from approximately fresh water (1,030 kg/m^3) to a density of 1,300 kg/m^3. The formation water with the highest density is concentrated in the Oriskany structural lows at the center of the basin. The formation water with the lowest density is associated with the outcrop area to the east and the subcrop or pinch-out area to the west (Figure 7.12).

An indication of the significance of this introduced error is given by the dimensionless driving force ratio (DFR) (Formula 2). If the DFR value is greater than 0.5, neglecting buoyancy effects will introduce significant errors in flow analysis (Davies, 1987). Within the Oriskany the values were generally much less than 0.5, with the exception of two areas located in south-central Pennsylvania. Hydraulic heads (Figure 7.13) range from over

1,000 m in the deeper part of the basin to less than 250 m at the potential recharge area to east and the potential discharge area to the west.

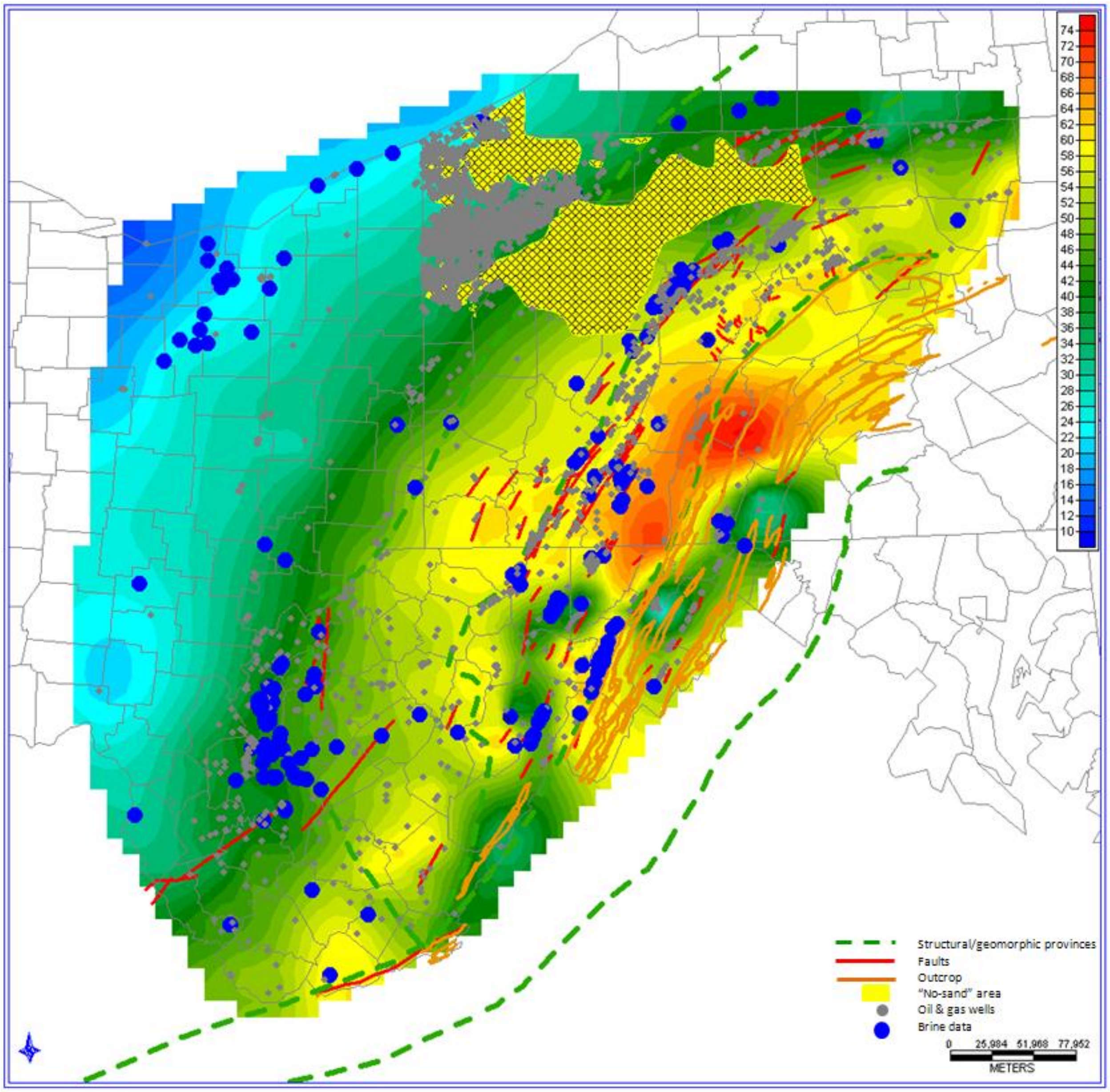


Figure 7.9 - Oriskany Sandstone formation temperature (°C) using the newly calculated gradient. Contour interval is 2° C.

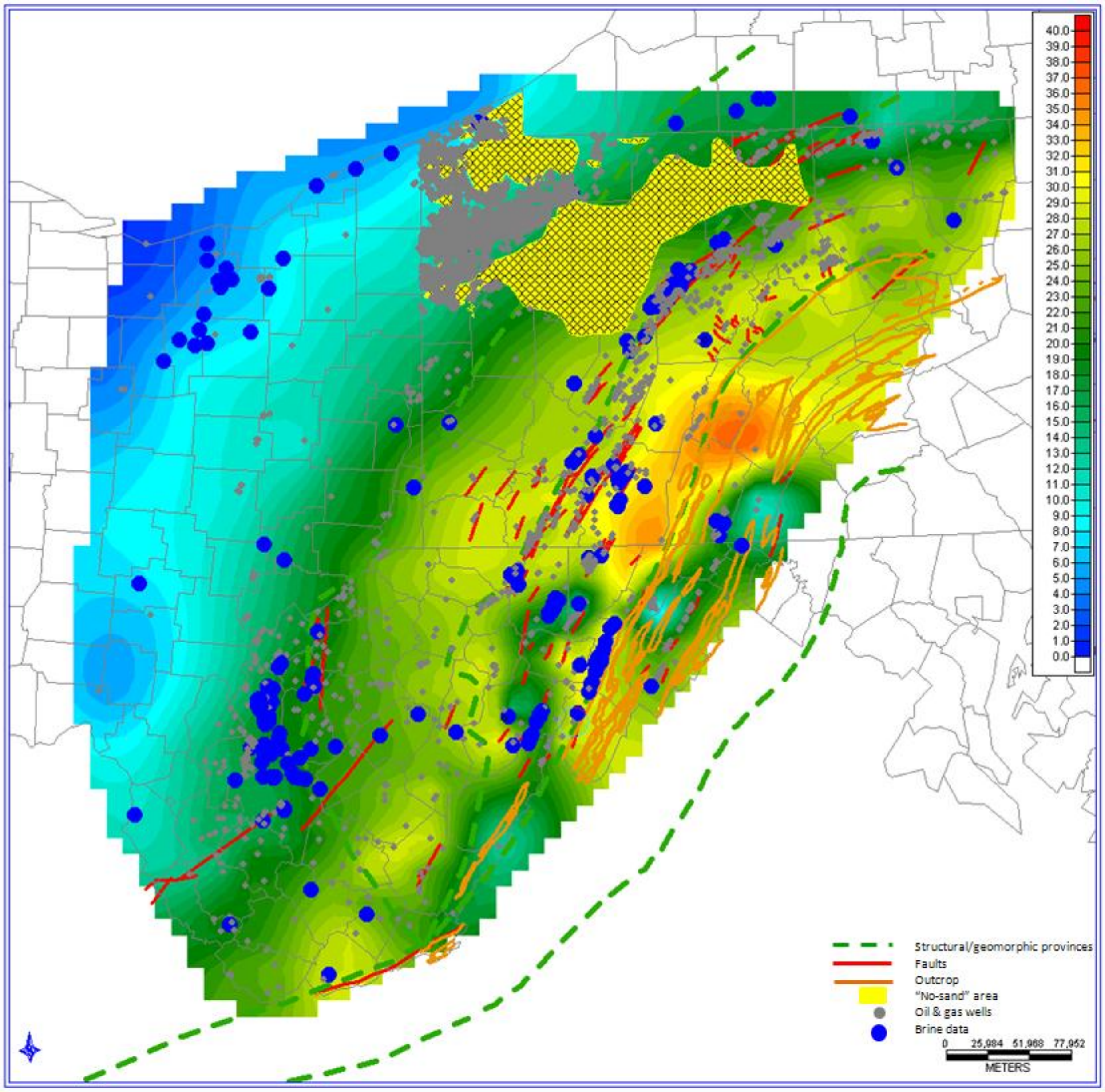


Figure 7.10- Oriskany Sandstone formation pressure (kPa) at top of structure using the newly calculated pressure gradient. Contour interval is 1 kPa.

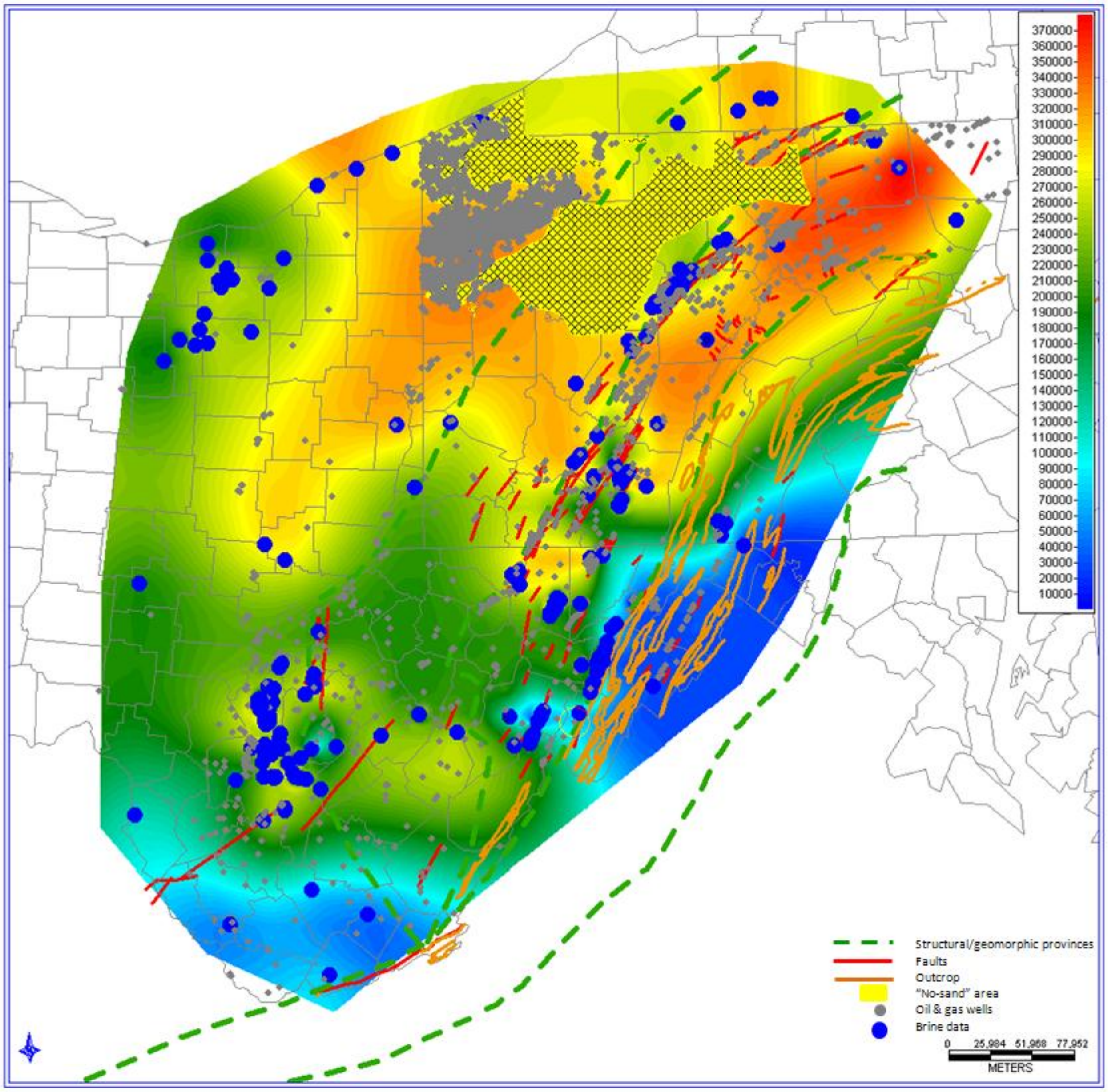


Figure 7.11 - Oriskany Sandstone TDS (mg/L) map. Contour interval is 5,000 mg/L.

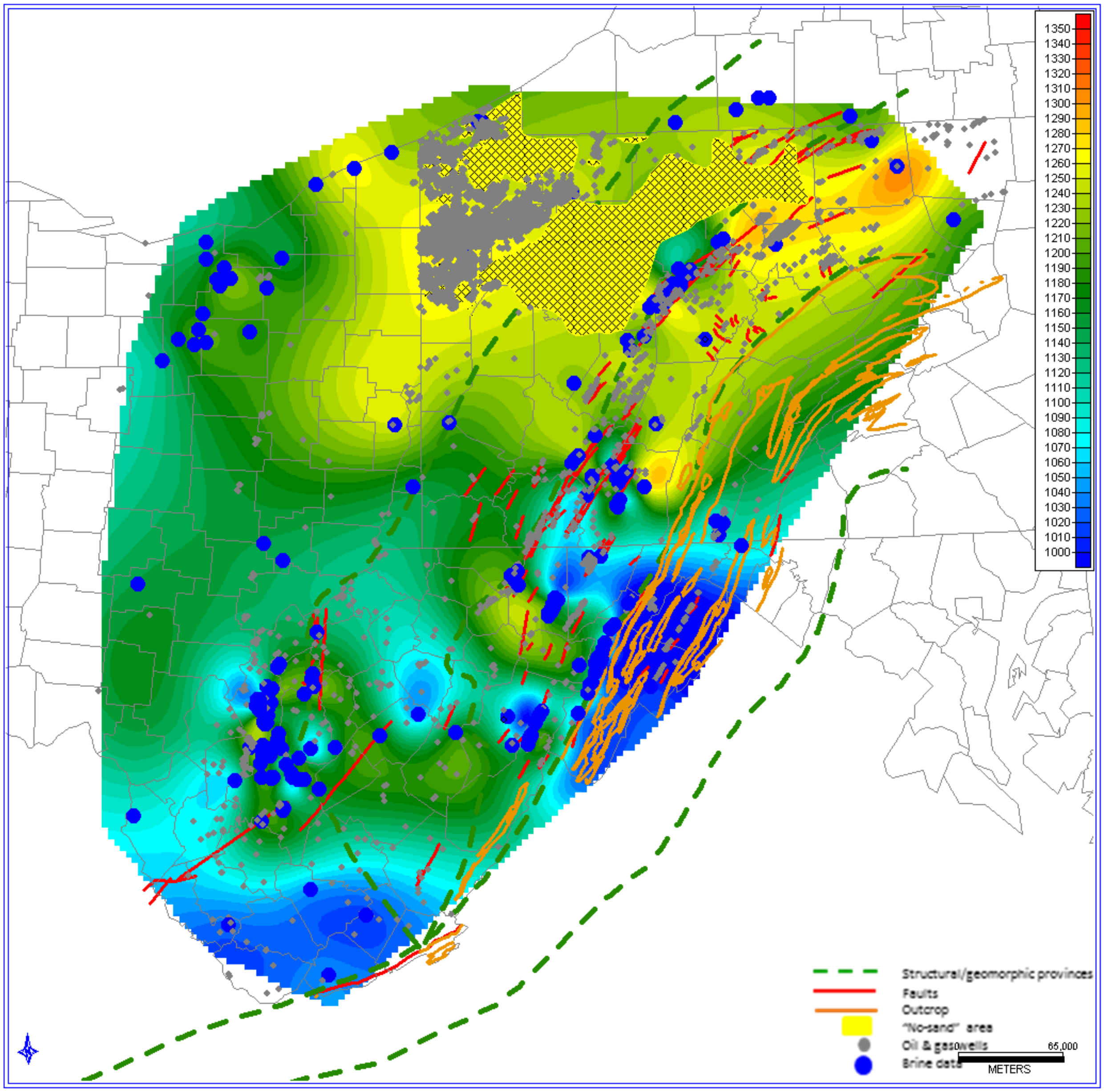


Figure 7.12 - Oriskany Sandstone formation water density map. Contour interval is 10 kg/m^3.

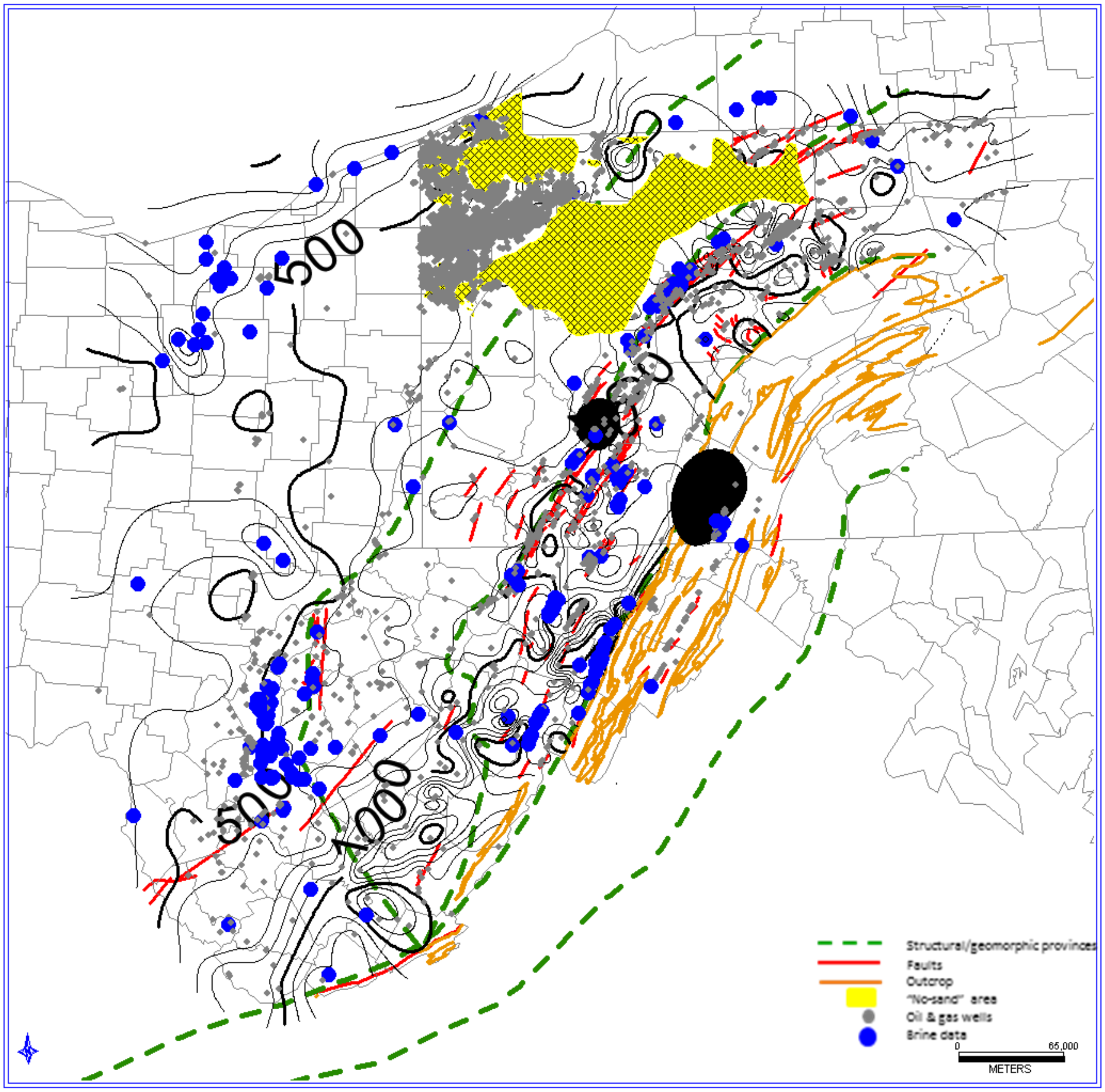


Figure 7.13 - Oriskany Sandstone equivalent hydraulic head contours with areas indicated in black in which DFR values exceed 0.5. Contour interval is 500 meters.

7.8 RESULTS

The Oriskany dips toward the center of the basin, a trend that is consistent with the preserved northeast-southwest central axis. The Oriskany shallows toward the outcrop area to the east along the Allegheny Front and Eastern Overthrust Belt and toward the west. The Oriskany is typically thickest, over 75 meters, in the Eastern Overthrust Belt and the High Plateau and thins, to a thickness less than 10 meters, toward the northwest, west and south. Using the depth and isopach data, the volume estimate of 2,188 km^3 (± 1 km^3) will be used to calculate a total Oriskany CO_2 storage capacity

The average 8.08% porosity value calculated for this study is consistent with the value calculated by Dilmore and others (2008) for the USDOE. This value indicates that the Oriskany has the potential to provide adequate porosity for the injection of supercritical CO_2 (Bachu, et al., 2007). The areas of the Appalachian basin that had the lowest estimated porosity values were the areas of greatest depth (>2,000 m MSL).

The temperature data were corrected for erroneous BHTs that are often encountered during drilling, and are, therefore, directly related to depth. There was no indication that any temperature anomalies existed in the Oriskany before processing. The geothermal gradient for the Oriskany Sandstone (~20°C) is lower than expected for cratonic rocks (25-30°C) (Hitchon, 1984). The pressure values indicate that the Oriskany is underpressured. This underpressure is an indication of the integrity and longevity of the overlying confining layer which will serve as a vertical seal for sequestered CO_2 (Puckette and Al-Shaieb, 2003). There is some indication that drawdown from nearby wells and insufficient shut-in time may have an effect on some wells within the Oriskany study area. The High Plateau of the central Appalachian basin is the area with the highest pressure values, which is consistent with the suggestion of Russell (1972) that correlates high pressure values not only with depth but also deformation.

The TDS concentrations of the Oriskany formation fluids range from freshwater to dense brine. The brine samples were characterized by large differences between the reported TDS concentrations from neighboring wells within the same gas field. The cause of these differences may be related to areal, vertical and temporal variability, errors introduced from sampling procedures, or to varying methods of chemical analysis (Jorgensen, et al., 1993). The dense brines were concentrated in the Oriskany structural lows in the center of the basin and to the north. The relatively lower TDS concentrations are at the outcrop area to the east and the subcrop area to the west. This trend would seem to indicate that any mixing of formation water with meteoric water occurs only along the outcrop and subcrop margins or along fault traces. The distribution of freshwater hydraulic head shows the expected trends of northwestward and southeastward flow from the basin center toward the western subcrop area and the eastern outcrop area and further substantiates the previous assumption.

The Oriskany Sandstone of the Appalachian basin is a widely distributed saline aquifer which has produced large quantities of hydrocarbons and is used extensively for storage of natural gas. Oriskany gas storage fields have the capability to store/deliver more natural gas than storage fields in any other formations within the northern Appalachian basin (American Gas Association, 2001). At least 32 gas storage fields are found within the Oriskany, with a combined storage capacity approaching 1 trillion cubic feet (TCF). Many of these storage fields have been in operation since the 1950's, attesting to the ability of these fields and seals to maintain long-term containment (American Gas Association, 2001). This indicates that at the local level the Oriskany has the necessary volume, porosity and containment characteristics for geologic storage of CO_2.

Published and unpublished data of rock characteristics, pressure, temperature and formation water geochemistry, and data from new brine samples, were used to map the regional-scale hydrogeological regime and its relation to the migration of hydrocarbons and geologic CO_2 sequestration potential. Basin-scale fluid flow of the Oriskany Sandstone waters is generally controlled by salinity differences and by differences in structural elevation. The flow pattern is substantiated by the salinity distributions and water geochemistry, with relatively lower salinity at recharge to the east and discharge to the west due to mixing with fresh meteoric water and higher salinity between the recharge and discharge zones. The basin-scale flow pattern is also substantiated by the distribution of oil and gas fields that occur in the central Appalachian basin; the major productive gas fields occur at the boundary between lower salinity and are typically absent in areas of higher salinity. It is believed that hydrocarbon distribution is influenced by basinal variations in buoyancy and entrainment by the formation water flow (Hitchon, 1984).

Long-term lateral containment of large-scale CO_2 injection appears to be associated in the Oriskany with convergent flow located in the eastern Appalachian basin. Storage capacity for the saline Oriskany Formation is estimated by the equation:

(4)

G_{CO2} is the estimate of total saline formation storage capacity in kilograms, A is the area of basin greater than 800 meters in depth, h_g is the average thickness of formation at depths greater than 800 meters, ϕ_{tot} is the average formation-scale porosity for thickness h_g (8.08%), ρ is the density of CO_2 at pressure and temperature that represents storage conditions for saline formation averaged over h_g (800 kg/m^3 at P = 18.01 MPa and T = 43.29 °C), and E is the storage efficiency factor that reflects a fraction of total pore volume filled by CO_2 (USDOE estimations of E are a low of 0.01 and a high of 0.04).

Oriskany isopach and porosity grids were generated using a minimum curvature method and a 10,000 by 10,000 meter grid size. These grids were then used to perform a grid-to-grid calculation to estimate the available volume within the potential CO_2 sequestration area (Figure 7.14). Grid-to-grid calculations were then performed using the constants for density of supercritical CO_2 (800 kg/m^3) and the storage efficiency factors (0.01 and 0.04) (Figures 7.15 and 7.16). The result is a storage resource estimate of 1.246 to 4.983 gigatonnes of CO_2. Maps and data are available through http://www.wvcarb.org/.

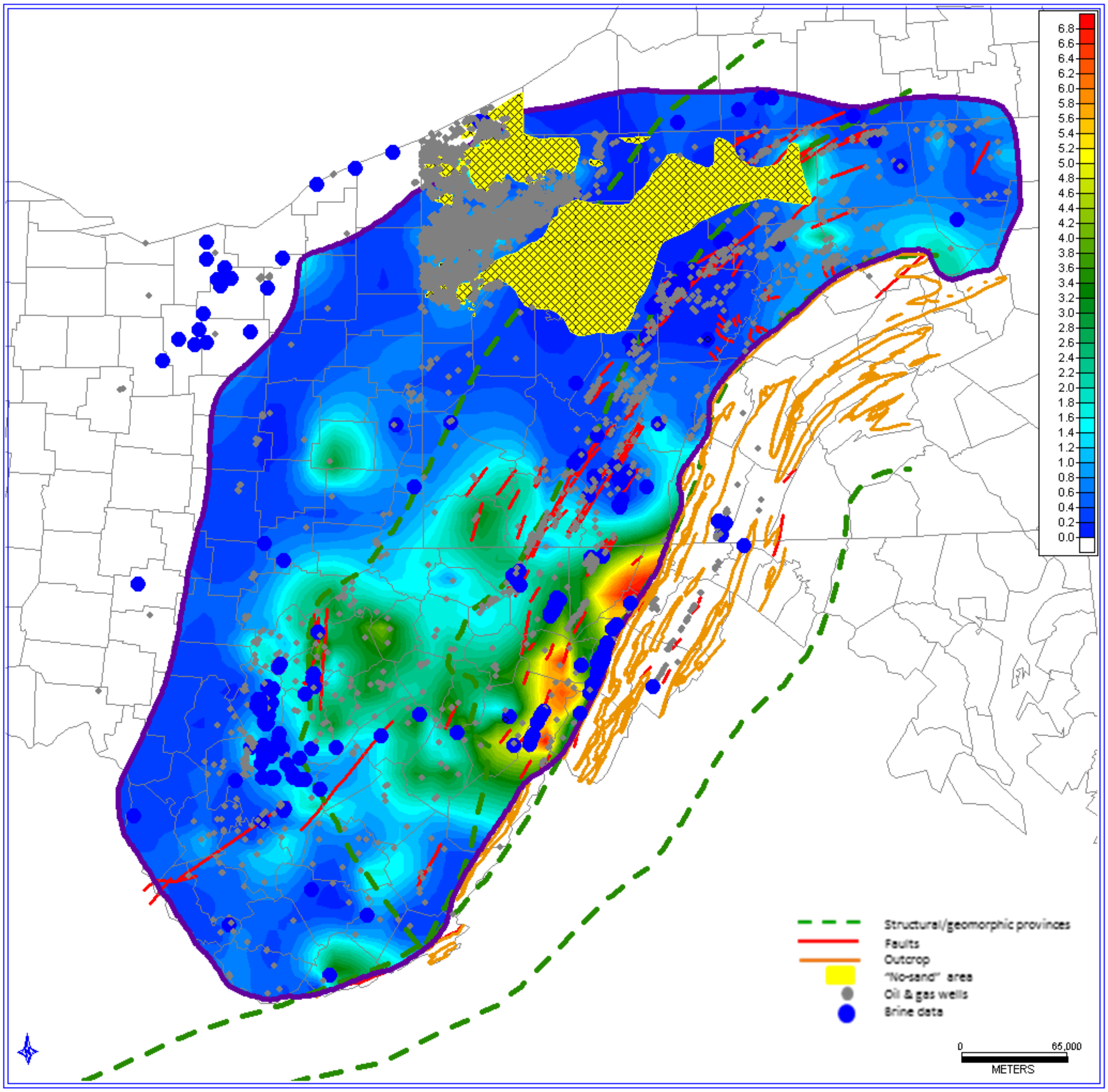


Figure 7.14 - Oriskany Sandstone estimated pore volume map. Contour interval is 0.2 km^3 per 100 km^3.

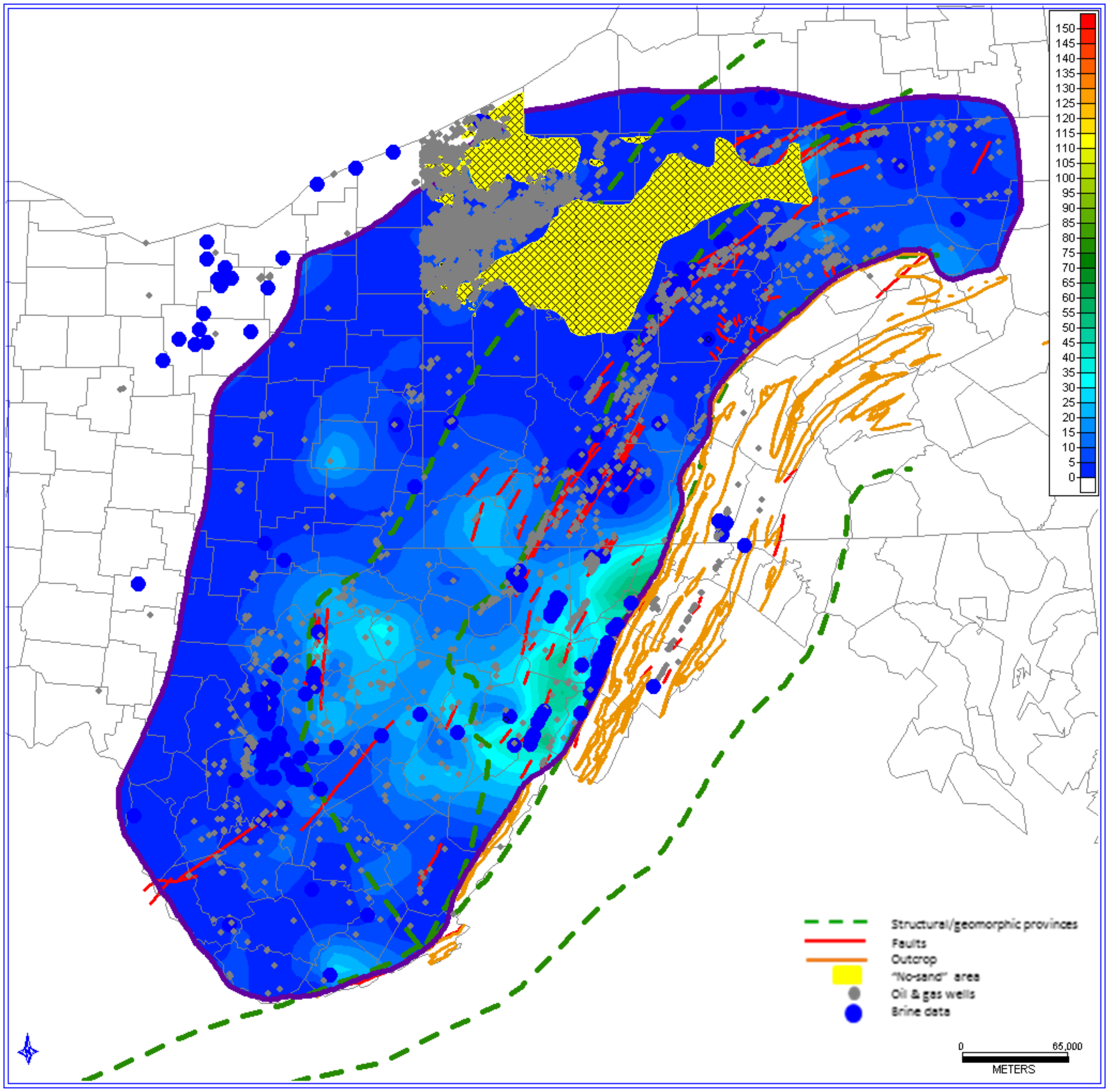


Figure 7.15 - Oriskany Sandstone total storage capacity estimate using the low storage efficiency factor 0.01. Contour interval is 5 kg/m^3.

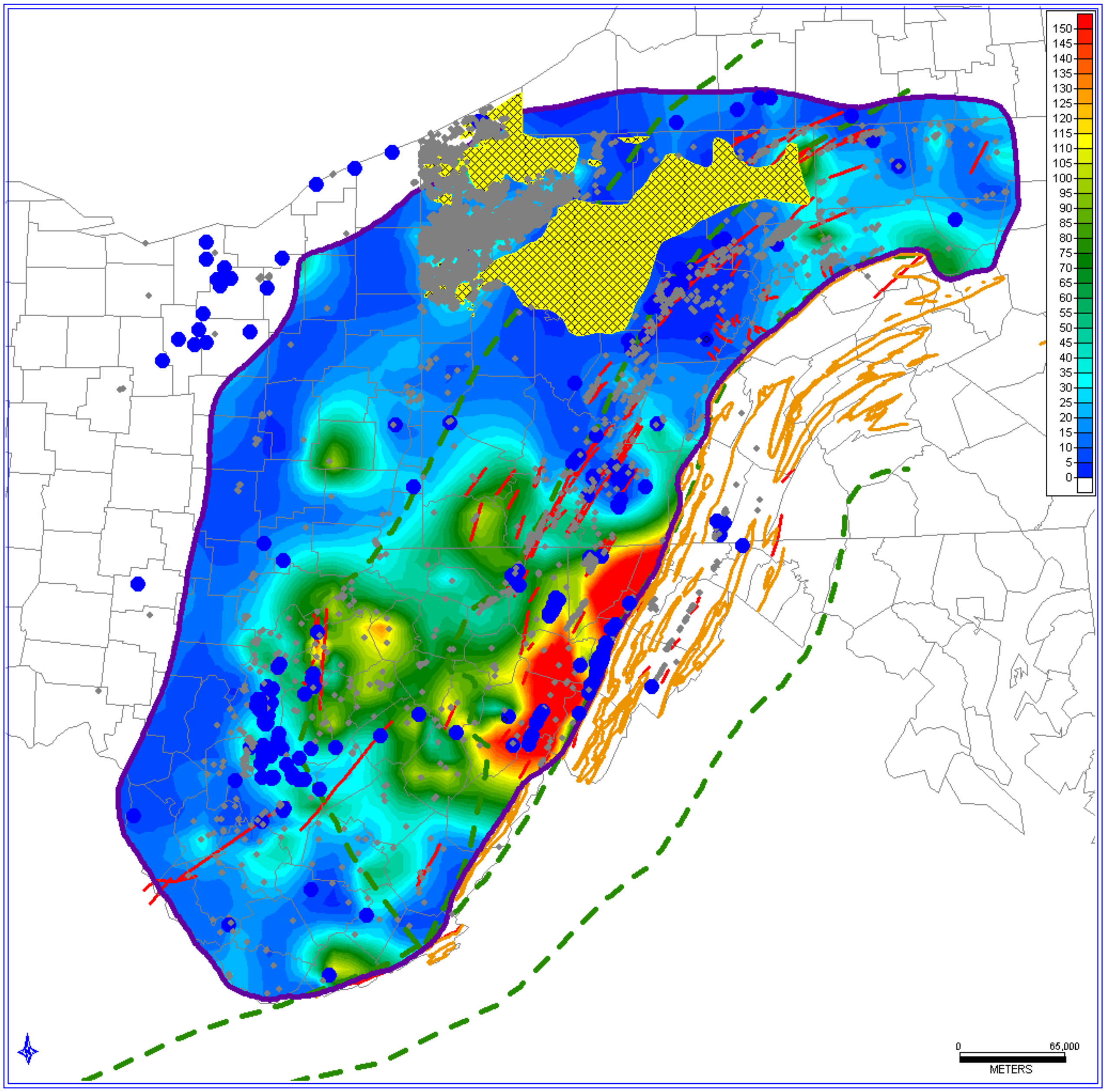


Figure 7.16 - Oriskany Sandstone total storage capacity estimate using the high storage efficiency factor of 0.04. Contour interval is 5 kg/m^3

Task 8: Evaluation of Newburg and Tuscarora Sandstones

8.1 Introduction

In developing a carbon capture and sequestration (CCS) analysis for the Silurian Tuscarora and Newburg Sandstones, porosity values determined from well logs were used to estimate the total saline formation storage capacity in metric tons using equation 4 (section 7.8, above).

Petra Software™ was used to import scanned well log images which were then correlated to identify the tops and bottoms of the formations of interest. Once the intervals were identified, specific curves were digitized including Gamma Ray (GR), Neutron Porosity (NPHI) and Density Porosity (DPHI). NPHI and DPHI curves tend to have scales between -10% and 30%. Since it is physically impossible to have "negative" porosity, these curves were "normalized" to make all negative values equal to "0". In cases where NPHI and DPHI curves were both available, they were used to create an average porosity (PHIA).

Logs from only eight wells were available to be used in the Tuscarora study. Of the eight wells, one well had a DPHI curve only, three wells had NPHI values only and the remaining four wells had both curves and were used to generate PHIA values. It should be noted that DPHI values tend to be much lower than NPHI values. These lower DPHI values will negatively affect the final calculation. In the case of the Newburg analysis, 351 wells compiled from the WVGES database were shown to penetrate the Newburg sandstone. Of those, 103 had sufficient porosity curves that could be used to calculate PHIA values. More data accumulation focusing on the Tuscarora interval would be necessary to calculate a more accurate storage volume potential for that formation.

8.2 Tuscarora Sandstone

The Tuscarora Sandstone lies at the base of the Silurian System in West Virginia (Figure 8.1). It is a quartz-cemented, fine-grained to conglomeratic quartz sandstone occurring as massive beds separated by thin shale beds (Avary, 1996). It underlies much of central Pennsylvania and most of West Virginia, increasing in thickness from less than 100 feet in southwestern West Virginia to over 1,000 feet in northeastern Pennsylvania. It becomes increasingly more shaley from east to west.

Several natural gas fields have been developed in Pennsylvania and West Virginia where the gas was trapped in anticlines; porosity in these fields is enhanced by fractures. Depth to the top of the Tuscarora in West Virginia averages about 7,000 feet. Fields in West Virginia are generally underpressured. Probably the most successful field has been Indian Creek field in Kanawha County despite the presence of large quantities of carbon dioxide, which have been used for enhanced oil recovery in nearby oil fields.

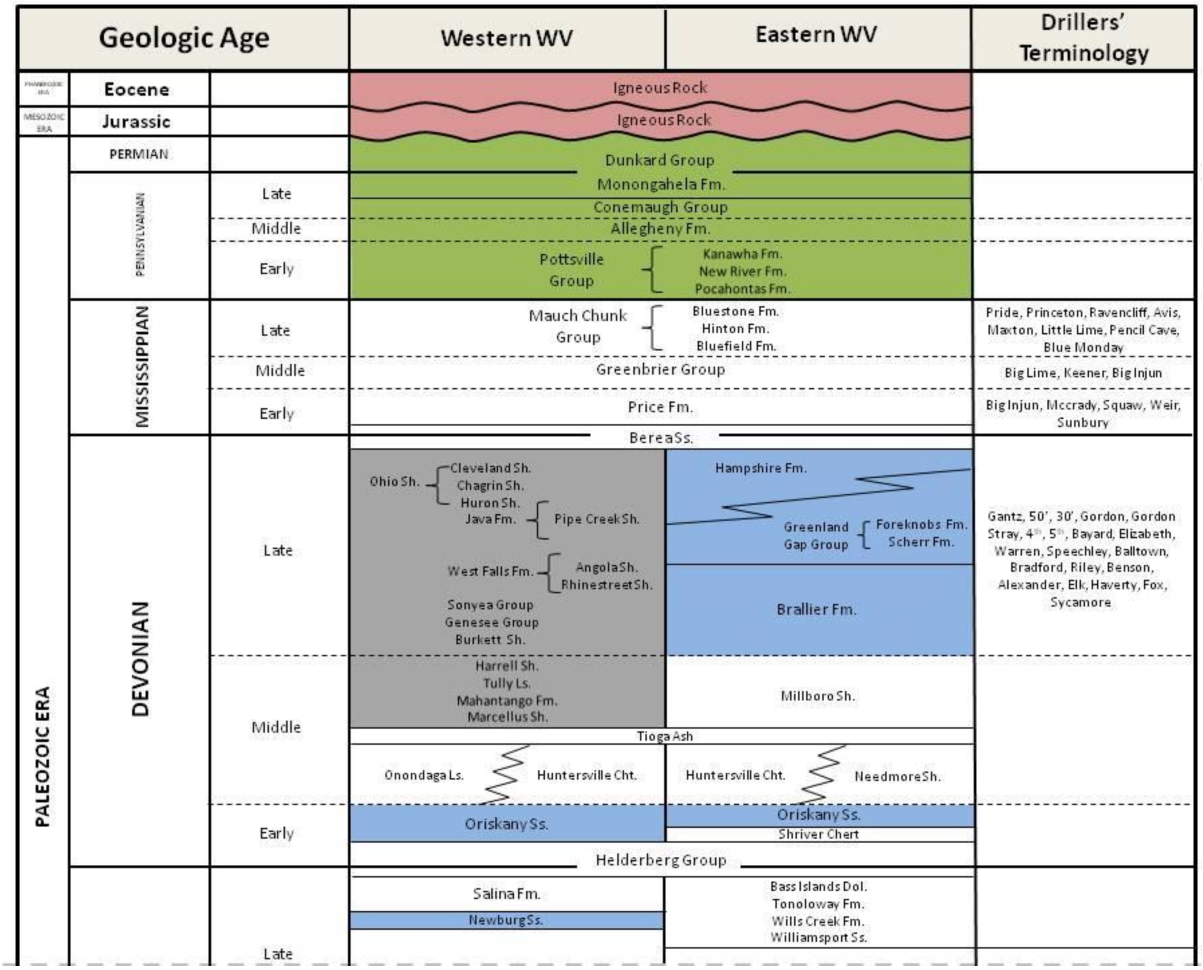
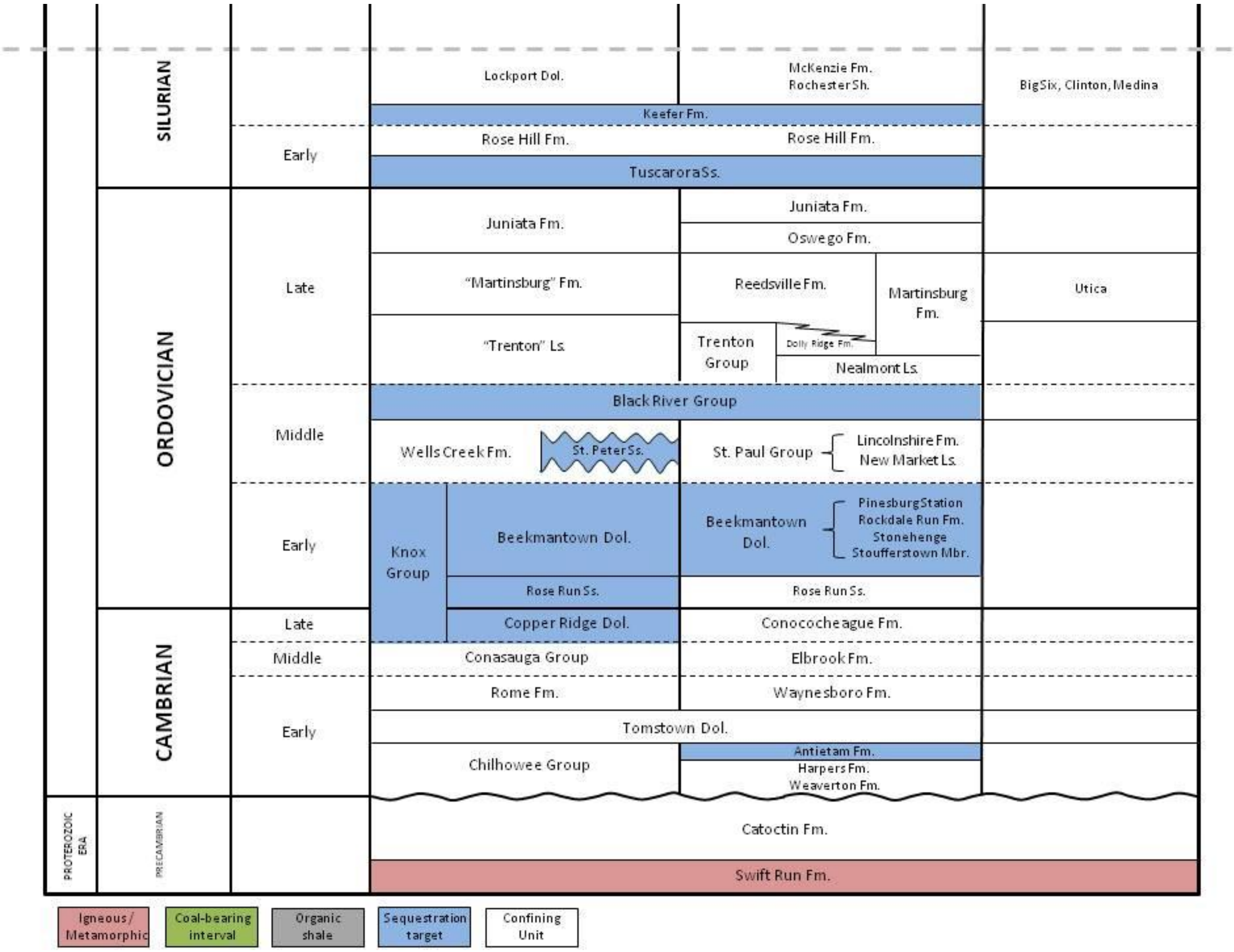


Figure 8.1a. Simplified stratigraphic chart for West Virginia showing units above the Lockport Dolomite (Silurian).



West Virginia Geologic and Economic Survey, Stratigraphy Chart, Updated, May 2011

Figure 8.1.b. Stratigraphic Chart for West Virginia showing units from the Lockport Dolomite to basement rocks.

The Tuscarora Sandstone study area for this analysis lies in western West Virginia, where this sandstone is brittle and well cemented (Figure 8.2). In the initial stages of this study, several maps of the Tuscarora Sandstone were analyzed for a general geologic characterization of the study area, including a structure map and an isopach map (Cardwell, 1976; Avary, 1996) (Figure 8.3a). A depth map also was created using stratigraphic data in the WVGES database which shows the unit well exceeds 2500 feet, the required depth for the sequestration of CO_2 (Figure 8.3b). Also included in the initial analysis were locations of Tuscarora outcrops extracted from the digital version of the 1968 state geologic map (Cardwell et al., 1968); however, these are well east of the final study area. All maps were converted to either shape files or georeferenced raster files.

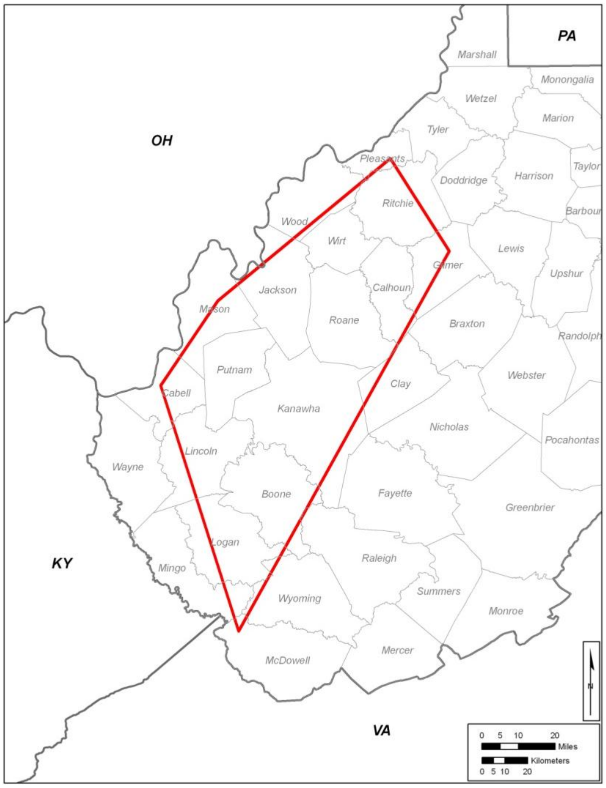
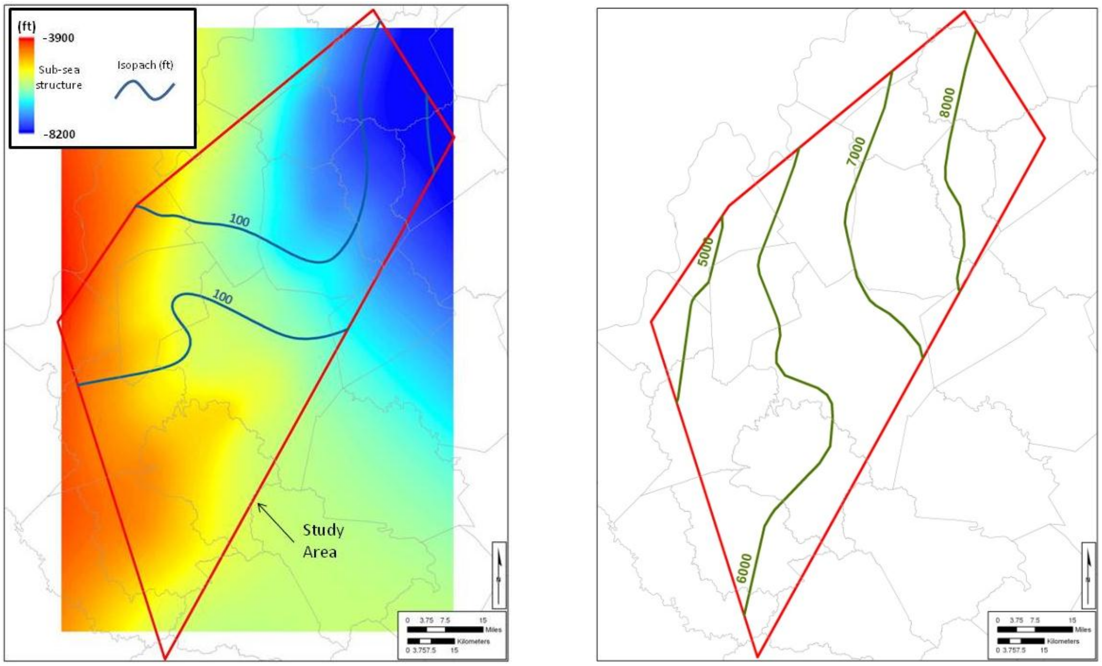


Figure 8.2 – Study area for the Tuscarora Sandstone.



a.

b.

Figure 8.3 - **a.** Tuscarora sub-sea structure and isopach map, **b.** Tuscarora overburden map

Based on calculations from the eight wells in the study area, the Tuscarora interval has an average porosity of 4.9% (Figure 8.4). Average water saturation (S_w) is based on a value obtained from the Indian Creek gas field in Kanawha County, WV (Avary, 1996) whereas temperature and pressure values are based on log analysis of the Kanawha 5903 well. (S_w = 43%, temperature at depth = 111° F (43.9° C), pressure at depth = 862 psi (Jarrell et al., 2002)).

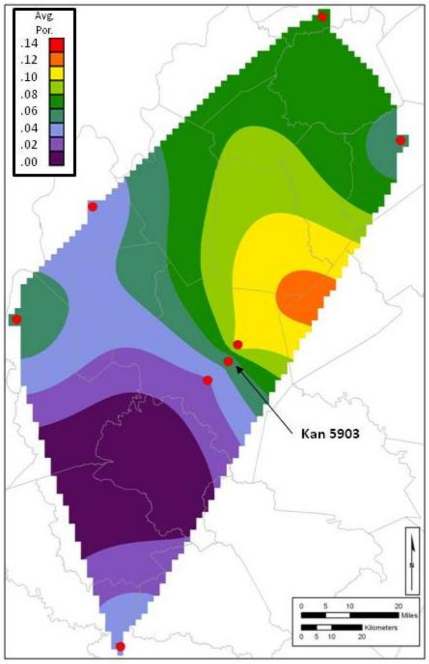


Figure 8.4 - Tuscarora average porosity and well control map

Applying the formula $\mathbf{G_{CO2}=\boldsymbol{A h_g \Phi_{tot} \rho} E}$ where:
A = 129 billion ft^2
$\boldsymbol{h_g}$ = 78.99 ft
$\boldsymbol{\Phi_{tot}}$ = .049
.01 < **E** < .04

$\mathbf{G_{CO2}}$ = 129 billion sq. ft. X 78.99 ft X .049 X 44.89 lbs/ft^3 X (**E**)
= 22.4 trillion pounds of CO_2 / 2200 lbs./tonne= 10.2 billion tonnes X **E**

For an efficiency factor **E** of 0.01: $\mathbf{G_{CO2}}$ = 10.2 billion tonnes X .01 = 102 million tonnes
For an efficiency factor **E** of 0.04: $\mathbf{G_{CO2}}$ = 10.2 billion tonnes X .04 = 408 million tonnes

Tuscarora CO_2 storage potential lies between 102 and 408 million tonnes.

8.3 Newburg Sandstone

The Newburg is a white to gray, very fine to fine-grained sandstone with well-rounded grains (Patchen, 1996.) It ranges in thickness between 0 and 49 feet, although thicknesses greater than 30 feet are rare. In the subsurface, it separates evaporates of the overlying Salina Formation from the underlying Lockport Dolomite of the McKenzie Formation (Figure 8.1a). It produces natural gas in a north-south trend of fields in Kanawha and Jackson counties, West Virginia, and Meigs County, Ohio. West of the productive area, the Newburg sandstone pinches out into shales and carbonates of the Salina Formation. To the east, sparse well control indicates that it correlates with the Crabbottom Sandstone observed in outcrops in Greenbrier and Pocahontas counties, West Virginia.

The pay zone in the Newburg is usually thin, 3 to 10 feet in thickness, near the top of this unit. Average porosity in six fields ranges between 8 and 16%. The Newburg is generally overpressured (Patchen, 1996). Almost everywhere within the geographic area of gas production, the Newburg exceeds 5,000 feet in depth.

The geographic limits of the Upper Silurian Newburg play within the Appalachian basin are based on sandstone thickness and structural features of the interval which generally consist of an upper, clean sandstone with good porosity and reservoir quality and a lower section with poor reservoir quality (Patchen, 1996). This heterogeneity required a more detailed analysis compared to that for the Tuscarora Sandstone. Fortunately, more data were available to support this analysis, comprising a calculation of storage capacity for groups of wells having a specified minimum level of available porosity.

The study area for this analysis lies in central West Virginia (Figure 8.5). GR logs were used to correlate Newburg tops and bottoms and then were used to construct structure and isopach maps (Figure 8.6a, 8.6b). The sub-sea structure map was subtracted from a digital surface contour map acquired from the State Address Mapping Board (SAMB) and used to create a measured depth map that shows the unit well exceeds the required depth limit of 2500 ft (Figure 8.6c). Also included in the initial analysis were outcrop maps of rocks equivalent to the Newburg. These were extracted from the digital version of the 1968 state geologic map (Cardwell et al., 1968). These maps were converted to shape file format.

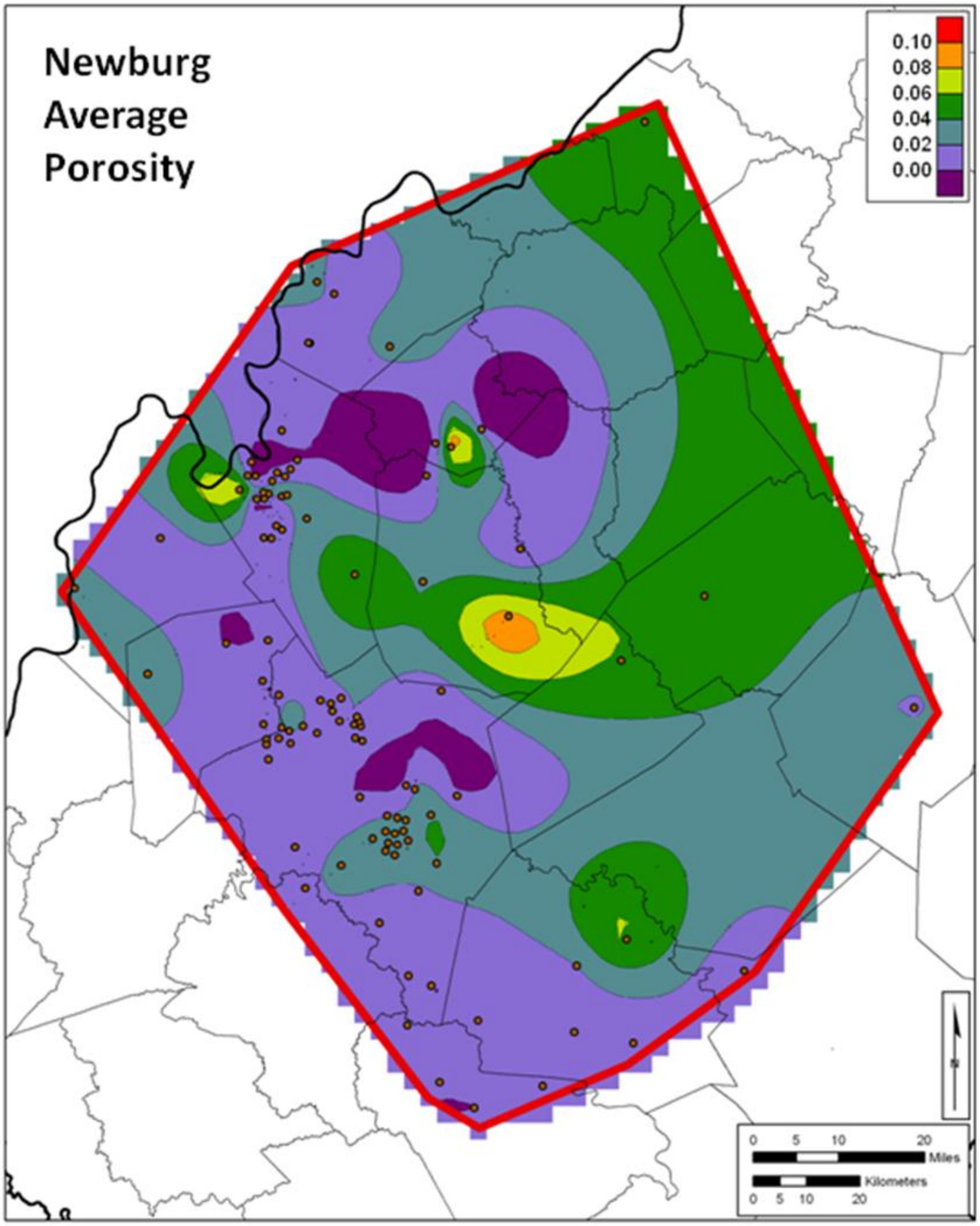


Figure 8.5 – Study area for the Newburg sandstone and normalized mean porosity.

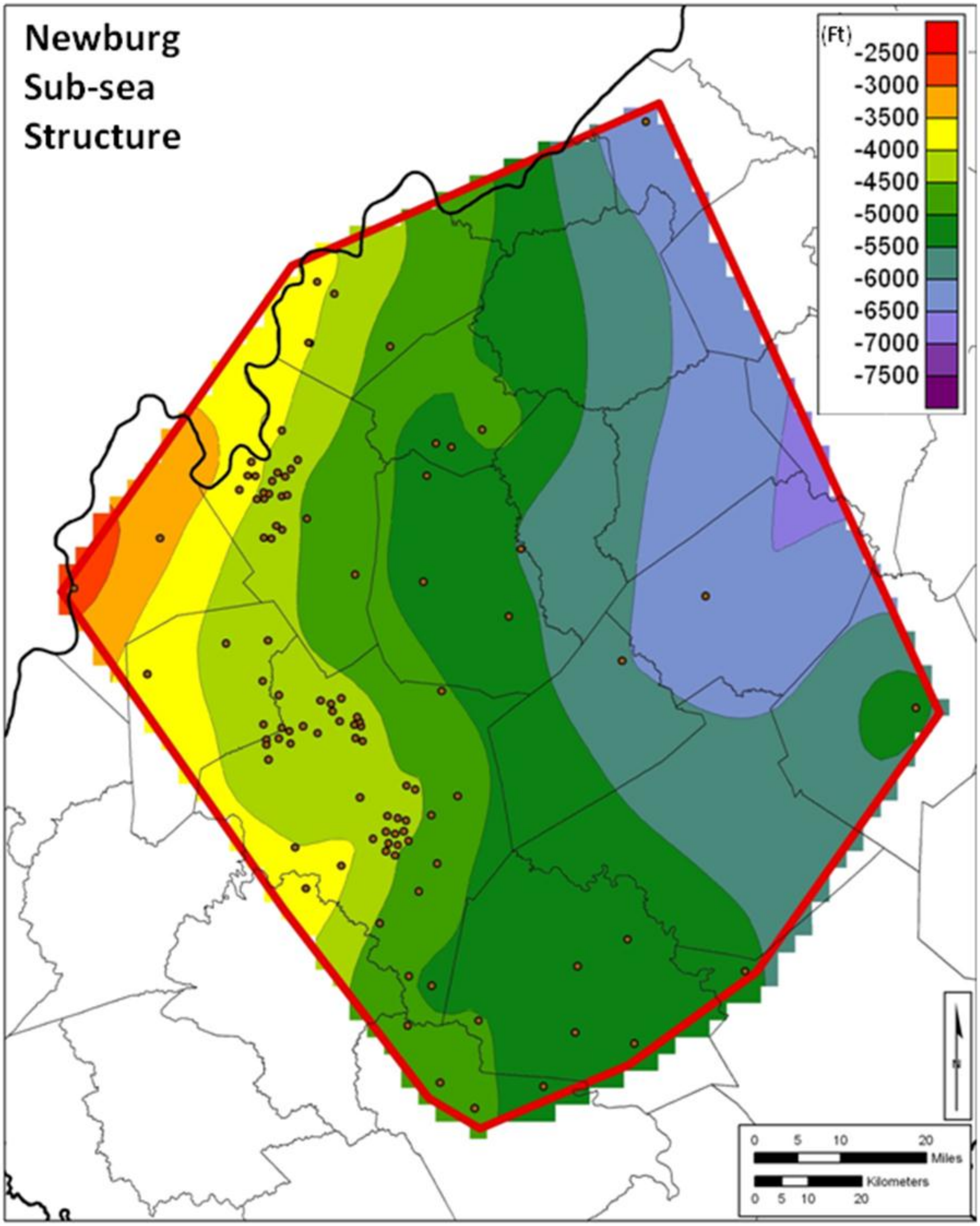


Figure 8.6a. Newburg sandstone structure in feet below sea

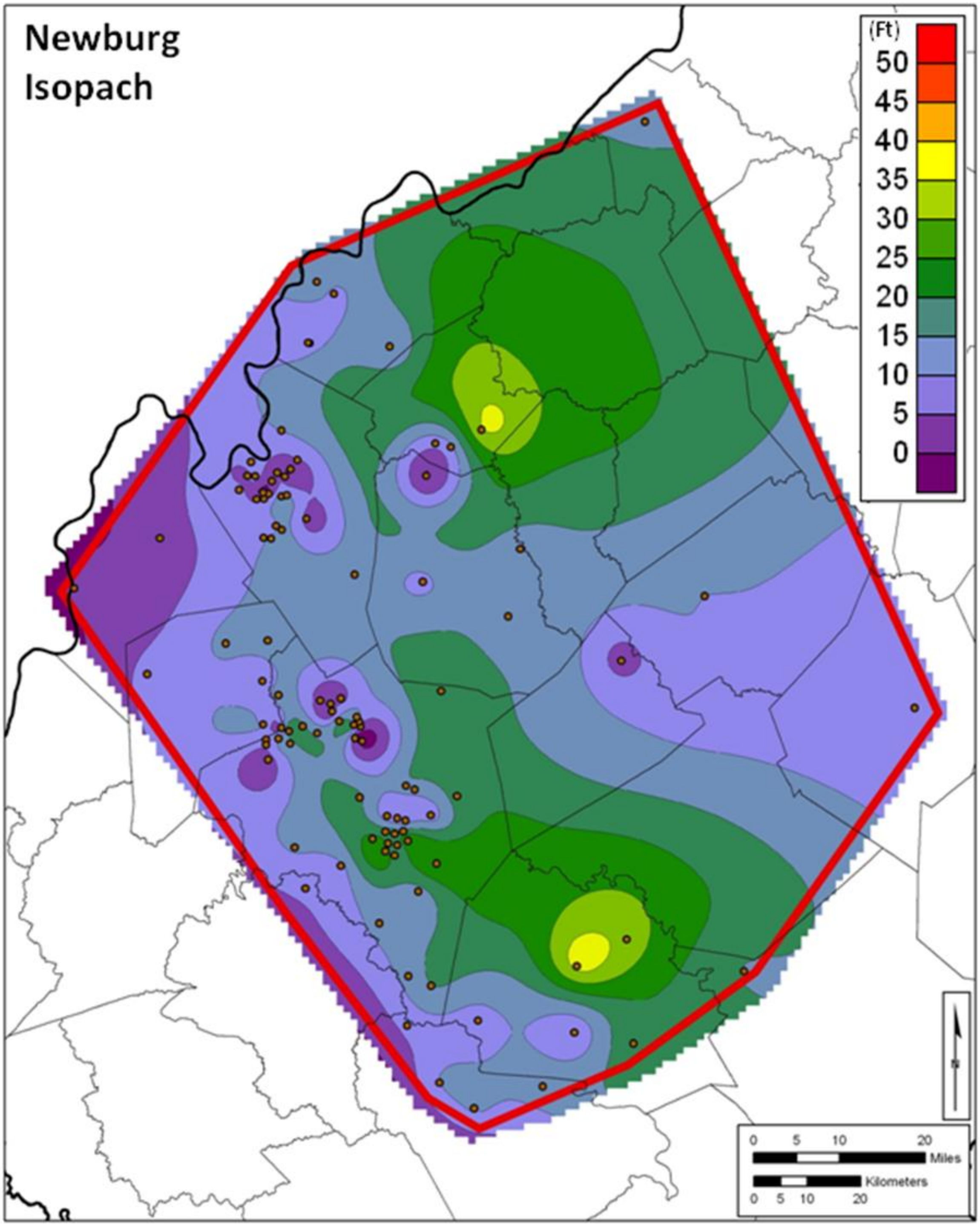


Figure 8.6b. Newburg sandstone thickness in feet.

Once PHIA values were normalized, sequestration capacity was calculated for the overall play area. Average water saturation, temperature and pressure are based on log analysis and completion records of several wells in the in the Rocky Fork field. (S_w = 50%, temperature at depth = 112.5° F (44.7° C), pressure at depth = 2500 psi).

One hundred and two wells were used to estimate storage potential over the total Newburg study area. Applying the formula $\mathbf{G_{CO2}=\boldsymbol{A h_g \Phi_{tot} \rho} E}$ where:

$\mathbf{A}$ = 200 billion ft^2
$\boldsymbol{h_g}$ = 15.2 ft
$\boldsymbol{\Phi_{tot}}$ = .018
.01 < **E** < .04

$\mathbf{G_{CO2}}$ = 200 billion sq. ft. X 15.2 ft X .018 X 49.32 lbs/ft^3 X (**E**)
= 3.6 trillion pounds of CO_2 / 2200 lbs./tonne= 1.23 billion tonnes X **E**

For an efficiency factor **E** of 0.01: $\mathbf{G_{CO2}}$ = 1.23 billion tonnes X .01 = 12.3 million tonnes
For an efficiency factor **E** of 0.04: $\mathbf{G_{CO2}}$ = 1.23 billion tonnes X .04 = 49.1 million tonnes

Calculated Newburg CO_2 storage potential for the total study area lies between 16.4 and 65.8 million tonnes

Capacity also was calculated from subsets of wells to examine the sensitivity of the results to the particular sample of well logs available for analysis. Storage capacity was calculated for areas delineated by wells containing Newburg intervals exhibiting four different porosity cutoff values: 3%, 5%, 7% and 10%.

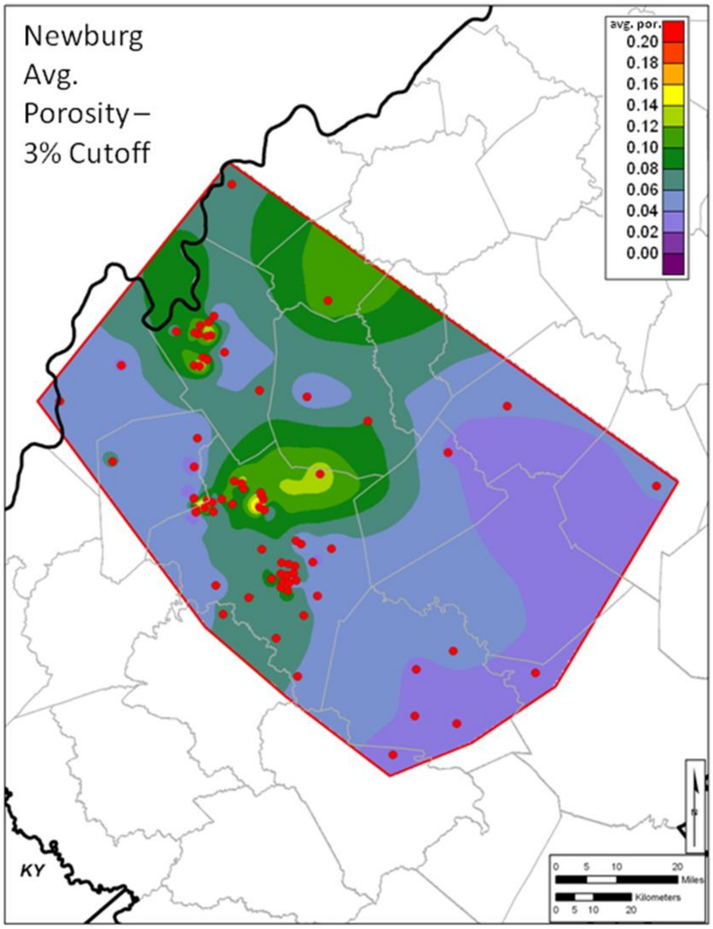


Figure 8.7 - 3% Cutoff porosity-foot and well control map.

3% Cutoff: Within the study area, 72 wells contain intervals within the Newburg sandstone that exceed 3% porosity. Average porosity of the Newburg interval is 2.3% and average porosity-footage is 0.77 (Figure 8.7).

Applying the formula $G_{CO2}=Ah_g\Phi_{tot}\rho E$ where:
A = 158 billion ft^2
h_g = 11.72 ft
Φ_{tot} = .065
$.01 < E < .04$

G_{CO2} = 158 billion sq. ft. X 11.72 ft X .065 X 49.32 lbs/ft^3 X (**E**)
= 5,936 trillion pounds of CO_2 / 2200 lbs./tonne= 2,698 million tonnes X **E**

For an efficiency factor **E** of 0.01: G_{CO2} = 2,698 million tonnes X .01 = 27.0 million tonnes
For an efficiency factor **E** of 0.04: G_{CO2} = 2,698 million tonnes X .04 = 107.9 million tonnes

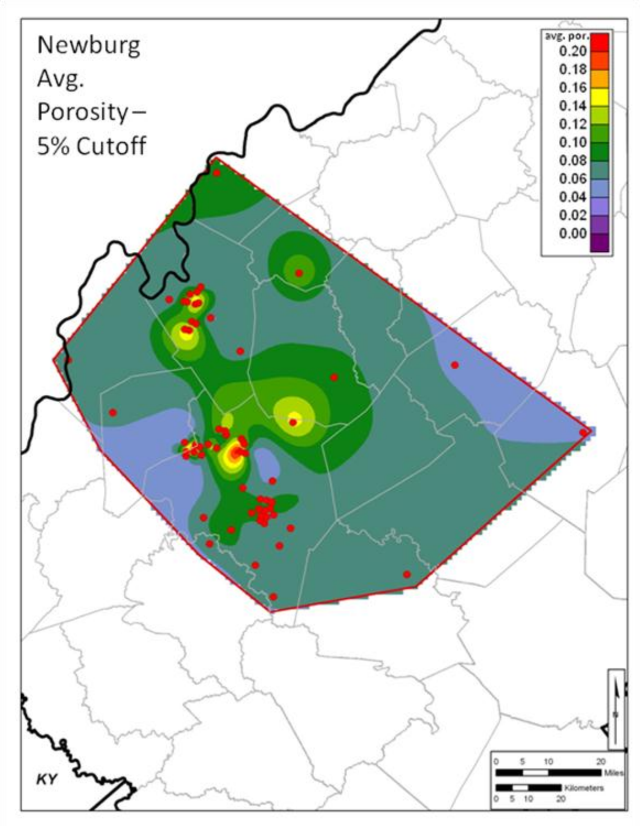


Figure 8.8 - 5% Cutoff Porosity-foot and well control map.

5% Cutoff: Within the study area, 59 wells have intervals within the Newburg sandstone that exceed 5% porosity. Average porosity of the Newburg interval is 2.5% and average porosity-footage is 0.80 (Figure 8.8).

Applying the formula $\mathbf{G_{CO2}=\mathit{A h_g \Phi_{tot} \rho} E}$ where

$\mathbf{A}$ = 136 billion ft^2

$\mathbf{\mathit{h_g}}$ = 12.02 ft

$\mathbf{\mathit{\Phi_{tot}}}$ = .076

.01 < $\mathbf{E}$ < .04

$\mathbf{G_{CO2}}$ = 136 billion sq. ft. X 12.02 ft X .076 X 49.32 lbs/ft^3 X $\mathbf{E}$
= 6,127 trillion pounds of CO_2 / 2200 lbs./tonne= 2,785 million tonnes X $\mathbf{E}$

For an efficiency factor $\mathbf{E}$ of 0.01: $\mathbf{G_{CO2}}$ = 2,785 million tonnes X .01 = 27.6 million tonnes
For an efficiency factor $\mathbf{E}$ of 0.04: $\mathbf{G_{CO2}}$ = 2,785 million tonnes X .04 = 110.6 million tonnes

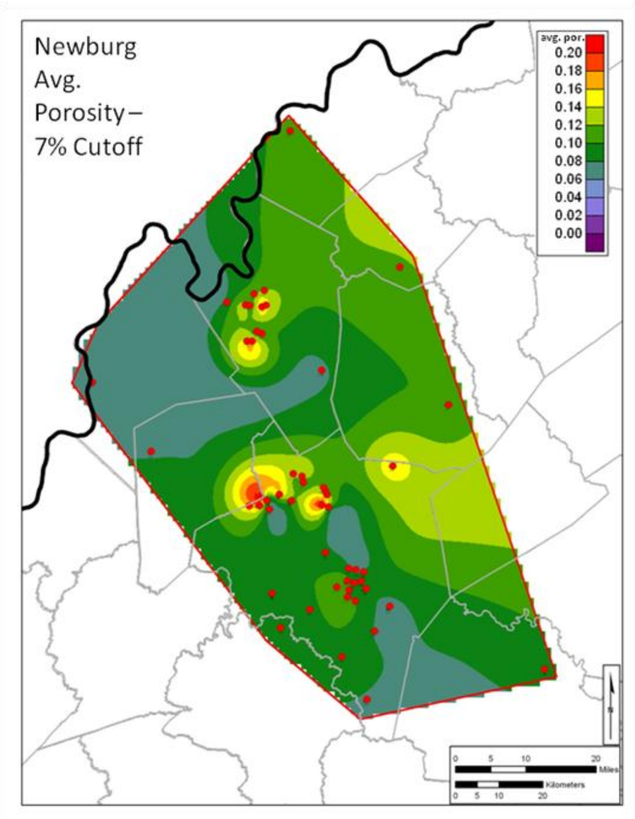


Figure 8.9 - 7% Cutoff Porosity-foot and well control map.

7% Cutoff: Within the study area, 52 wells have intervals within the Newburg sandstone that exceed 7% porosity. Average porosity of the Newburg interval is 2.6% and average porosity-footage is 0.79 (Figure 8.9).

Applying the formula $\mathbf{G_{CO2}}=\boldsymbol{A h_g \Phi_{tot} \rho}\mathbf{E}$ where:

$\mathbf{A}$ = 90 billion ft^2
$\boldsymbol{h_g}$ = 12.76 ft
$\boldsymbol{\Phi_{tot}}$ = .079
.01 < $\mathbf{E}$ < .04

$\mathbf{G_{CO2}}$ = 90 billion sq. ft. X 12.76 ft X .079 X 49.32 lbs/ft^3 X ($\mathbf{E}$)
= 4,474 trillion pounds of CO_2 / 2200 lbs./tonne= 2,083 million tonnes X $\mathbf{E}$

For an efficiency factor $\mathbf{E}$ of 0.01: $\mathbf{G_{CO2}}$ = 2,083 million tonnes X .01 = 20.3 million tonnes
For an efficiency factor $\mathbf{E}$ of 0.04: $\mathbf{G_{CO2}}$ = 2,083 million tonnes X .04 = 81.3 million tonnes

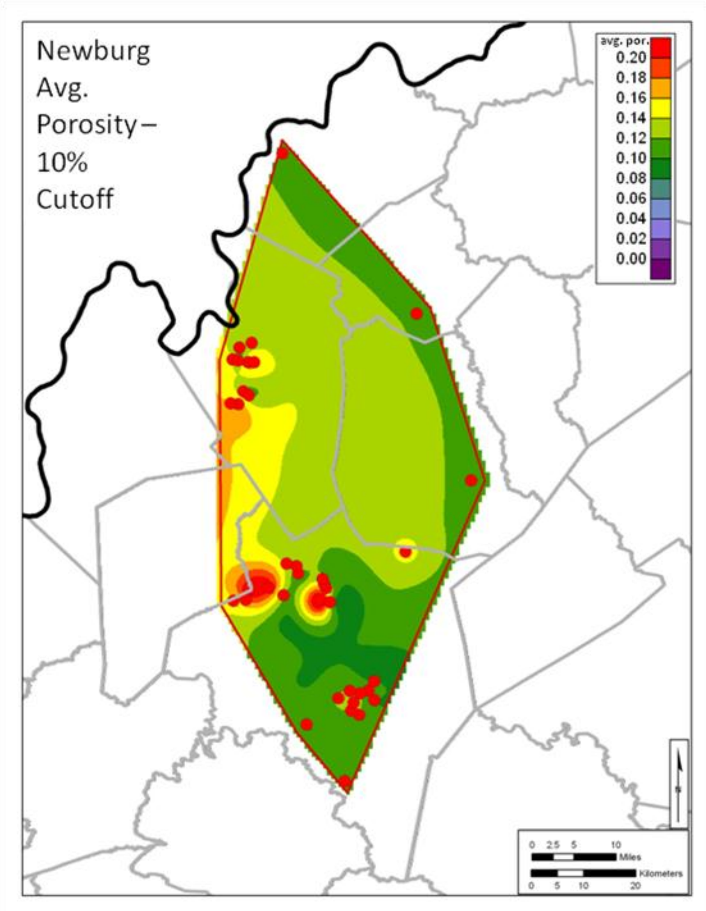


Figure 8.10 - 10% Cutoff Porosity-foot and well control map.

10% Cutoff: Within the study area, 36 wells have intervals within the Newburg sandstone that exceed 10% porosity. Average porosity of the Newburg interval is 2.6% and average porosity-footage is 0.75 (Figure 8.10).

Applying the formula $\mathbf{G_{CO2}=}\boldsymbol{A h_g \Phi_{tot} \rho}\mathbf{E}$ where:
A = 42 billion ft^2
$\boldsymbol{h_g}$ = 12.83 ft
$\boldsymbol{\Phi_{tot}}$ = .09
.01 < **E** < .04

$\mathbf{G_{CO2}}$ = 42 billion sq. ft. X 12.83 ft X .09 X 49.32 lbs/ft^3 X (**E**)
= 2,392 million pounds of CO_2 / 2200 lbs./tonne= 1,087 million tonnes X **E**

For an efficiency factor **E** of 0.01: $\mathbf{G_{CO2}}$ = 1,087 million tonnes X .01 = 10.9 million tonnes
For an efficiency factor **E** of 0.04: $\mathbf{G_{CO2}}$ = 1,087 million tonnes X .04 = 43.5 million tonnes

Summary of Calculations for Porosity Cutoff Values in the Newburg

	min capacity (million tonnes)	max capacity (million tonnes)	no. of wells	Area (billions of sq ft)	Thickness (ft)	Porosity (%)
No cutoff	12.3	49.1	102	200	15.20	1.8
3% cutoff	27.0	107.9	74	158	11.72	6.5
5% cutoff	27.6	110.6	61	136	12.02	7.6
7% cutoff	20.3	81.3	53	90	12.76	7.9
10% cutoff	10.9	43.5	38	42	12.83	9.0

Application of even a modest 3% porosity cutoff more than doubles the calculated storage capacity compared with that calculated from the complete set of logs. This happens because the better and poorer wells are scattered throughout most of the study area. Similar results are seen for the 5% and 7% cutoffs. Only at the highest cutoff does estimated storage capacity come close to the value computed from the complete set of logs.

Although a map of wells used for the highest cutoff (Figure 8.10) defines a clear north-south fairway from Wood to Kanawha County, results overall emphasize the uncertainty in estimates of storage capacity. Uncertainty can result from geological factors such as reservoir heterogeneity or sampling problems such as a non-representative set of well logs used in the calculations. Only the drilling of new wells and the acquisition and study of modern geophysical logs in proximity to a proposed sequestration project can provide reasonable estimates of storage capacity.

8.4 Recommendations

Obviously, more well control should be used in analyzing the Tuscarora Sandstone to obtain a more accurate estimation of its CO_2 storage potential. Perhaps in future studies of this unit, more emphasis should be placed on the structure and regional stress regimes within this sandstone, due to the idea that most of its porosity is thought to come from fractures within the interval.

Initially, the highly porous zone of the Newburg sandstone was thought to be mainly confined to the upper section of the interval. While this is generally true in the gas fields, on a regional scale more porous zones may be located lower in the section. The data set appears sufficient for a regional estimation for the storage of CO_2 within the Newburg sandstone; however, more analysis concerning the connectivity of the porous zones within this interval should be conducted.

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Appendix A: Minimum Miscibility Pressure Analysis

SCAL, Inc.

SPECIAL CORE ANALYSIS LABORATORIES, INC.

West Virginia University

Minimum Miscibility Pressure

L. J. Fluharty 3
Wetzel County, West Virginia

SCAL, Inc.

SPECIAL CORE ANALYSIS LABORATORIES, INC.

December 22, 2010

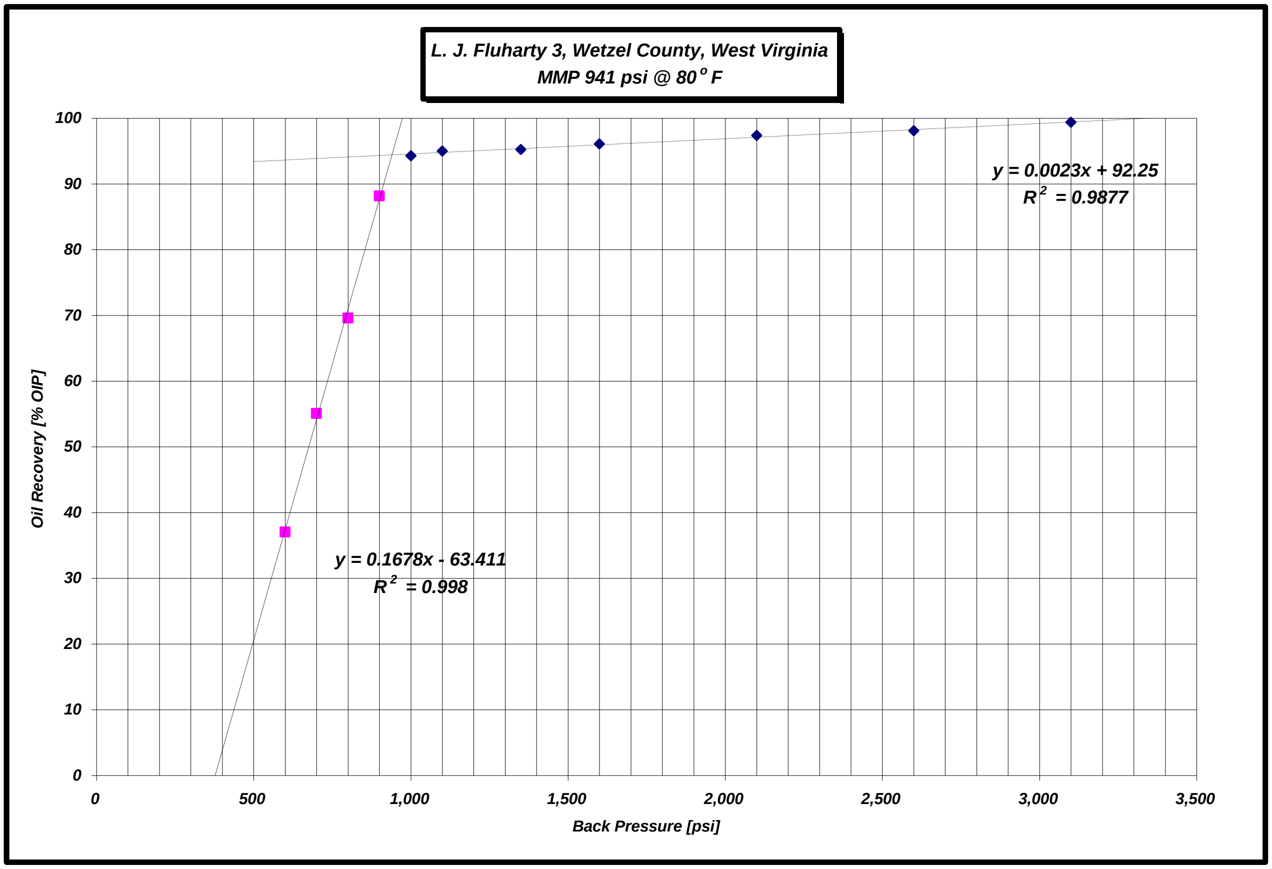
Dr. Timothy R. Carr
Marshall Miller Professor of Energy

Department of Geology and Geography
Room 133, Brooks Hall
P.O. Box 6300, 98 Beechurst Ave.
West Virginia University
Morgantown, Wv 26506
(304) 293-9660

Reference: Minimum Miscibility Pressure
L. J. Fluharty 3
API No.: 4710300911
Wetzel County, West Virginia

The oil sample was shipped to our laboratory in Midland, Texas.
A 40 ft sand packed slim tube equipped with a high-pressure glass capillary and a dome loaded back pressure regulator was used for the multiple contact miscibility study. The porosity of the sand pack is 35% and the permeability is approximately 1.5 Darcy. The cleaned slim tube was saturated with toluene. The back-pressure was set at the desired test conditions and the toluene was displaced by a minimum of 2 pore volumes of crude oil before each displacement test.
The CO_2 was injected at constant rate of 0.125 cc/min using a motorized high pressure pump. The oil produced in the separator at the end of the test was recorded and the oil recovery as function of the original oil in place was calculated.
Displacement tests were conducted at various back pressures at 80^{o}F. The data was plotted; the lines representing recovery versus pressure below and above the MMP were identified. The intersection of these two lines represents the MMP (941 psi).

Back Pressure	***Oil Recovery***
psi	***% OIP***
3,100	99.4
2,600	98.1
2,100	97.4
1,600	96.1
1,350	95.2
1,100	95.0
1,000	94.3
900	88.2
800	69.6
700	55.1
600	37.1



We also measured the density of the oil sample at reservoir temperature (80 ^{o}F). The density is .7954 g/cc (46.5 deg API).
It was a pleasure performing these analyses for you. If you have any further questions please feel free to contact our laboratory.

Sincerely,

Mihai Vasilache
Petroleum Engineer, President