Appendix T:

Appalachian Basin- R.E. Burger Plant Geologic CO2 Sequestration Field Test

FINAL REPORT

APPALACHIAN BASIN – R.E. BURGER PLANT GEOLOGIC CO_2 SEQUESTRATION FIELD TEST

DOE-NETL Cooperative Agreement DE-FC26-05NT42589

MRCSP
MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP

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DISCLAIMER

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EXECUTIVE SUMMARY

As part of the Midwest Regional Carbon Sequestration Partnership's (MRCSP's) Phase II small-scale field validation efforts, carbon dioxide (CO_2) sequestration potential was investigated at FirstEnergy's R.E. Burger power plant located near the town of Shadyside, in Belmont County, Ohio. The objective of the test was to explore geologic storage targets in this area of the Appalachian Basin geologic province and develop CO_2 sequestration technology through drilling of a deep test well and conducting CO_2 injection tests. The Appalachian Basin is a regional structure in which sedimentary rocks form an elongated basin stretching across West Virginia, Pennsylvania, Ohio, New York, Kentucky, and Maryland. The test site location was chosen based on consideration of a variety of factors including its location in a region with many coal-based power plants and the resulting high CO_2 emissions that accompany that; the opportunity to test geologic storage targets in the Appalachian Basin as an important potential regional CO_2 storage area; the possibility of integrating injection operations with a source of CO_2 from an innovative CO_2 capture system planned for pilot testing at the R.E. Burger site in a separate program; and the willingness of the host company, FirstEnergy, to provide site access, technical support, and co-sponsorship. The project included a sequence of tasks as follows:

Preliminary Geologic Assessment- Prior to any field work, a preliminary geological assessment of the general area was completed by the Ohio, Pennsylvania, and West Virginia Geological Surveys. This study reviewed the regional geologic setting, stratigraphy, oil and gas horizons, coal seams, seismic setting, groundwater resources, artificial penetrations, and surface features in the area based on existing data. Several deep saline rock formations were identified as potential injection targets, but there was little information on the nature of these formations since few deep wells were located near the site.

Seismic Survey- In August 2006, a two-dimensional (2-D) seismic survey was completed at the R.E. Burger Power Plant site to help delineate rock formation depths in the area as well as to gain insight into the structure of geological rock layers. The survey included two 5-mile long transects through the test site and one additional parallel trace approximately 1 mile in length to simulate a "quasi-three-dimensional (3-D)" trace. This additional survey line provided greater geologic coverage in the vicinity of the proposed well. The information provided by this shorter trace helped to better delineate the Oriskany Sandstone and Clinton-Medina Sandstone, which have a somewhat variable distribution in the general area. Survey results indicated that the site is located in a structural setting with flat to mildly undulating Precambrian surface overlain by essentially flat strata, the whole having a slight southeast dip into the heart of the Appalachian Basin. No faults or fracture zones were detected that may have affected the testing.

Test Well Drilling- A deep test well, FEGENCO#1, was drilled at the R.E. Burger site to a total depth of 8,384 ft in February 2007 including completion of associated logging and characterization tests. The test well was completed with injection casing in February 2008, which included several casing runs cemented to surface to isolate the well from the shallow groundwater zones. The injection zones were perforated in September 2008.

Test Well Characterization- A full program of mud logging, wireline logging, sidewall coring, core testing, and petrophysical analysis was completed to characterize the geologic units. This information was used to identify injection targets, define confining layers, and plan injection testing. A full suite of wireline logs was completed in the well in three runs. Wireline logs showed zones of porosity between 2% and 10% within the key injection targets. A total of 48 rotary sidewall rock cores were collected in the test well from key injection targets and caprocks based on wireline logs. Core samples were tested for porosity, permeability, mineralogy, and density with standard procedures. Results generally showed porosity less than 5% and permeability less than 1 mD for most of the cores. Based on characterization efforts, three targets were selected for injection testing: the Oriskany Sandstone, Middle Salina Carbonate, and Clinton/Medina Sandstone. Hydraulic analysis of injection potential suggested that high injection pressures would likely be encountered due to the relatively low permeability and thickness of the injection targets at the test well location. Based on these results, a flexible testing plan was developed to vary injection rates and readily move from one testing zone to another.

Underground Injection Control Permitting- The main permits required for the injection tests included well drilling permits and the underground injection control (UIC) permit. The FEGENCO #1 test well was first permitted as a stratigraphic test well with the Ohio Department of Natural Resources (ODNR) Division of Mineral Resource Management. The permit form required standard information on well location, construction specifications, and site restoration that any oil and gas well would necessitate. CO_2 injection was regulated by the Ohio Environmental Protection Agency (EPA) UIC program. A UIC Class V permit application was submitted to the Ohio EPA UIC program on January 17, 2008, and the permit was issued on September 3, 2008. During injection, Ohio EPA was notified of daily activities. Monthly reports were submitted to Ohio EPA summarizing maximum injection pressure, annular pressure, injection rates, and total injection volumes. While the test was small in scale, the permit process established familiarity with CO_2 sequestration with regulators and the public.

CO_2 Supply and Delivery System Design- A commercial source of liquid food grade CO_2 was used for the injection testing at this site. Initially it was hoped that the injection test could be integrated with a pilot CO_2 capture plant being developed by Powerspan and to be tested at the Burger site in a separate project. Because the Powerspan capture pilot plant was not available at the time needed for testing, a decision was made in early 2008 to utilize commercial CO_2 as the backup source. Nevertheless, this test site offered a chance to evaluate various technologies needed to monitor, verify, and account for the CO_2 sequestration at an operating coal-fired power plant.

Tanker trucks carrying about 20 tons of CO_2 each from the Praxair Marmet, West Virginia facility delivered the liquid CO_2 at approximately -10°F and 250 PSIG to the R.E. Burger injection site. Three 50 ton mobile storage tanks were set up on the R.E. Burger site to provide an interim holding system before injecting into the well. The tanks were connected to a trailer-mounted injection system which included a triplex pump, a propane fired heater, and a programmable logic controller (PLC). At the wellhead, the system included flow meters, automated annulus pressure system, wellhead and downhole pressure gauges. Because this was a limited injection test with a single injection well, much of the monitoring was focused on assessing hydraulic response in the reservoir, vertical distribution of CO_2 in the injection targets, and health and safety.

Test Results and Analysis- A series of injection tests was completed in the Clinton, Salina, and Oriskany formations in the fall of 2008. The testing started in the deepest formation (Clinton) and moved upward to the shallower formations.

- Testing of the Clinton formation was conducted in three events. In addition to the attempts at CO_2 injection, the well was stimulated with acid on two separate occasions. During each attempt of injection, injection and formation pressures quickly increased even with relatively low injection rates of about 8 metric tons (tonnes) per day of CO_2 and water/acid (<2 barrels per minute [bpm]).
- Several acid treatments were completed in the Salina to remove any cement from the test zone. Overall, high injection pressures and low flow rates were observed in the Salina

Formation. Hydraulic analysis predicted injection rates approaching 50 tonnes per day for the Salina at pressures less than 2000 psi; in actuality, injection rates of less than 20 tonnes per day were not sustainable at twice that pressure.

- Finally, the Oriskany was also treated with acid before injection and then CO_2 injection testing was completed. Initial injection rates were relatively low at approximately 0.25 bpm until the desired pressure limit was approached. The flow rates were then reduced to maintain pressures below the limit until they were less than 20 tonnes per day. Analysis of pressure response curves suggest that mainly borehole storage was encountered during the pressure falloff tests. It did not appear that radial flow was observed during the pressure falloff after injection.

Site Closure- After the injection tests, the well was temporarily abandoned with bridge plugs above the injection intervals. Wellhead pressure readings were completed and monthly reports were submitted to the Ohio EPA UIC program. In the fall of 2009, an oil and gas company inquired about leasing the well for gas production from shallow formations. The possibility was considered, but using the well for gas production was found infeasible in April 2010 due to pipeline siting issues. As a result, the well was closed out beginning in April 2010 according to the Ohio EPA approved plugging and abandonment plan.

Stakeholder Outreach- An outreach plan was developed to link outreach activities to technical activities as the research project progressed. The purpose of the plan was to ensure that the partners involved in the test were coordinating with each other in conducting outreach activities aimed at building a solid foundation of public support for this test and for the longer-term concept of geologic sequestration. Major outreach tasks included production of informational materials, informal public-employee meetings, an EPA UIC program public hearing, site tours, and press releases. In general, the project was well received with little opposition, probably due to the importance of the plant for the local economy and familiarity with oil and gas operations in the area.

Conclusions- The R.E. Burger Plant was selected as an exploratory CO_2 storage site for several key reasons:

1) It is central to the Appalachian Basin and, in particular, the Upper Ohio River Valley Power Corridor (Gallipolis to East Liverpool, Ohio). Nearly 20,000 MW of coal fired capacity exists in this region including some of the largest and most modern coal fired power plants in the world.

2) The original target formations for this site, the Oriskany and Clinton sandstones, are pervasive throughout the Appalachian Basin and were, thus, of keen geological interest.

3) The Burger plant was also the site for a demonstration of Powerspan's ECO multi-pollutant control technology, which was to include the addition of the ECO2 capture technology being developed by Powerspan at the time. Thus, this site offered the possibility of integrating the ECO2 capture process with MRCSP subsurface injection, which would have been a world first for a coal fired power plant.

The above, combined with excellent support from FirstEnergy, including access to the Burger plant, made the site attractive for a Phase II small-scale validation test.

Although injectivity at this site was less than expected the test did help establish familiarity with CO_2 sequestration technologies in the region and provided an important deep well data point in a strategically valuable portion of the MRCSP region. The test also highlights the variability of geologic environments, especially in the geologically deep and complex Appalachian Basin. The Burger test described here, as well as the other two MRCSP Phase II tests at East Bend (Mt. Simon Sandstone in the Cincinnati Arch) and Otsego County, Michigan (Bass Island Dolomite in the Michigan Basin) described in separate MRCSP reports, showed that characterization methods (rock core tests, wireline logging, and geologic logging) may only provide indicators of injectivity. True injection potential needs to be proven with field injection tests.

A well stimulation/hydraulic fracture operation was not completed in the well per Ohio EPA UIC permit restrictions. The formations that were tested are commonly fractured for oil and gas production in the Appalachian Basin, although fracturing for injection purposes would be looked at differently by regulators than for production operations. It may have been possible to obtain better injection results after hydraulically fracturing the well. Given the relatively low injection volume of 3,000 metric tons initially planned for this test, well stimulation was not considered during the test design and would have added complexity, time and cost to the permitting process. However, the flexibility to complete a hydraulic fracture operation in the near well bore may be an important consideration for future CO_2 sequestration testing and permitting in the Appalachian Basin.

This Burger site highlights the value of these smaller, research-oriented tests, which allow valuable experience to be gained in site characterization, permitting, infrastructure implementation, and injection testing with significantly less capital investment compared to full-scale application.

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Acronyms and Abbreviations

2-D	two-dimensional
3-D	three-dimensional
AOR	area of review
API	American Petroleum Institute
bbl	barrel (42 US gallons)
bgs	below ground surface
bpm	barrels per minute (1 bpm of CO_2 = 272 metric tons per day of CO_2)
CBL	cement bond log
CO_2	carbon dioxide
DOE	U.S. Department of Energy
EDI	Exploration Development, Inc.
EPA	Environmental Protection Agency
ESP	Elite Seismic Processing
gpm	gallons per minute (1 gpm of CO_2 = 6.5 metric tons per day of CO_2)
GR	gamma ray
HCl	hydrochloric acid
MRCSP	Midwest Regional Carbon Sequestration Partnership
msl	mean sea level
MW	megawatt
NETL	National Energy Technology Laboratory
ODNR	Ohio Department of Natural Resources
PLC	programmable logic controller
psi	pounds per square inch
QA/QC	quality assurance/quality control
Tonne	metric ton (1000 kilograms, 2205 pounds, or 1.1 short tons)
UIC	Underground Injection Control

1.0 Introduction

Geologic carbon storage is the term used to describe a broad class of technologies for permanently storing, or sequestering carbon dioxide (CO_2) in deep geologic reservoirs. Affordable and environmentally safe CO_2 storage approaches could offer a way to help stabilize atmospheric levels of CO_2.

The Midwest Regional Carbon Sequestration Partnership (MRCSP) is one of seven partnerships in a nationwide effort to explore and demonstrate carbon storage capability in regionally significant geologic formations. These partnerships are part of an overall effort by the U.S. Department of Energy's (DOE's) National Energy Technology Laboratory (NETL) to develop robust strategies for mitigating CO_2 emissions.

The MRCSP covers a nine-state region of Indiana, Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, and West Virginia. The MRCSP partnership is led by Battelle and includes over 35 organizations from the research community, energy industry, non-government organizations, and government.

The objective of the MRCSP is to test the feasibility, safety and effectiveness of carbon storage and to further understand the best approaches to implementing it in the region through a series of focused field tests and mapping of regional carbon sinks. The overall approach for the MRCSP is to test different sequestration options. For example, terrestrial sequestration tests have been conducted on croplands, reclaimed mine lands, and wetlands. Geologic tests are being conducted into three different deep saline rock formations along distinct, regional geologic features.

This report describes an MRCSP geologic field test conducted in the Appalachian Basin geologic province at FirstEnergy's R.E. Burger power plant near the town of Shadyside, in Belmont County, Ohio. The R.E. Burger test is part of the MRCSP's Phase II project, which is focused on small-scale field validation. MRCSP Phase II geologic sequestration tests are also being conducted in Boone County, Kentucky, and Otsego County, Michigan. The primary objective of these tests is to evaluate the regional and local-scale geology with respect to the storage and containment using small-scale CO_2 injection tests. In addition to the hydrogeological assessments, the projects have a strong emphasis on advancing CO_2 sequestration technology through permitting, monitoring, public outreach and education on various levels.

MRCSP Phase I was completed in the fall of 2005 and included an assessment of major CO_2 sources in the region, terrestrial sequestration potential, geologic sequestration potential, economic components of sequestration, and regulatory aspects of carbon sequestration options (Wickstrom et al., 2006; Ball, 2005). Phase II was focused on three main geologic test sites (Gupta, 2006) and several terrestrial test areas. The geologic tests were designed to take advantage of the existing infrastructure and CO_2 sources as well as previous research (Gupta et al., 2002; Gupta et al., 2004; Smith et al., 2002) on carbon sequestration for the region.

The location for this exploratory, small-scale validation test was chosen based on several key factors:

1) It is central to the Appalachian Basin and, in particular, the Upper Ohio River Valley Power Corridor (Gallipolis to East Liverpool, Ohio). Nearly 20,000 MW of coal fired capacity exists in this region including some of the largest and most modern coal fired power plants in the world.

2) The original target formations for this site, the Oriskany and Clinton sandstones, are pervasive throughout the Appalachian Basin and were, thus, of keen geological interest.

3) The Burger plant was also the site for a demonstration of Powerspan's ECO multi-pollutant control technology, which was to include the addition of the ECO2 capture technology being developed by Powerspan at the time. Thus, this site offered the possibility of integrating the ECO2 capture process with MRCSP subsurface injection, which would have been a world first for a coal fired power plant.

The above, combined with excellent support from FirstEnergy, including access to the Burger plant, made the site attractive for a Phase II small-scale validation test.

The objective was to evaluate various geologic, regulatory, monitoring, and scale-up aspects of geologic storage of CO_2. Injection of up to 3,000 metric tons of supercritical CO_2 into several deep saline rock formations over a period of 4 to 6 weeks was planned as part of the evaluation. The plan included:

(1) Background review of geologic conditions for the site based on existing information,
(2) Design, acquisition, and interpretation of a two-dimensional seismic survey
(3) Drilling and characterization of a test well (called FEGENCO #1) for injection testing,
(4) Design of a CO_2 injection system and test plan based on well data,
(5) CO_2 field injection testing,
(6) Analysis of test results,
(7) Site closure, including plugging of the well followed by surface completion.

The original target injection zones included the Oriskany and Clinton-Tuscarora Sandstones (Figure 1-1). The Salina formation was added to the target storage reservoir list based on analysis of log and core tests.

The three formations were present within a depth interval of 5,900 to 8,300 ft below ground surface (bgs). Numerous confining layers are present above the target zones, including the Onondaga Limestone and several thousand feet of Devonian Shales.

The original intent at the R.E. Burger test site was to integrate the MRCSP injection test with CO_2 produced by the ECO2 capture process to be conducted in a separate program but in the same time frame by developer Powerspan. This was expected to not only provide a potentially cost effective source of CO_2 for the injection test, but also provide a unique opportunity to evaluate integration of capture with injection.

A decision was made in early 2008 to use commercial grade liquid CO_2 delivered in tanker trucks instead of CO_2 from the ECO2 pilot plant due to the differences in scheduling between the Powerspan ECO2 project and the MRCSP injection test that evolved as the MRCSP project proceeded. The liquid CO_2 was delivered to the site by Praxair in 20 ton tanker trucks and stored on site in three 50 ton portable storage tanks. It was then pumped to injection pressure and heated to obtain supercritical conditions before being conveyed to the test well. Composition of the injected fluid was more than 99% pure, food-grade CO_2 at supercritical conditions with only minor impurities.

The project at the R.E. Burger site was a test of the technology and principals of geologic CO_2 storage. It was designed to be temporary in nature and involved a small total injection volume of high purity CO_2.

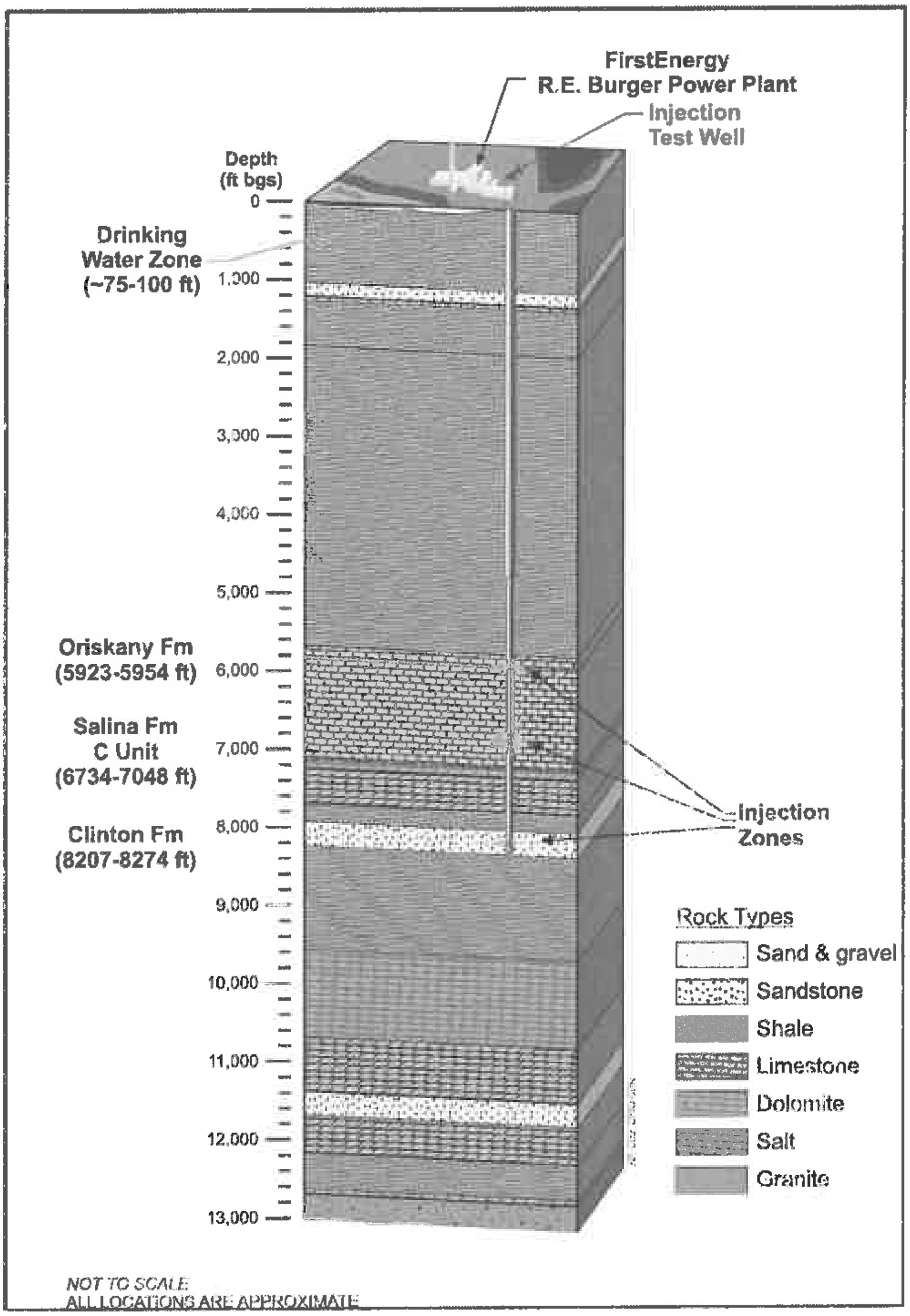


Figure 1-1. Conceptual Diagram of Injection System

The planned test injection volume of 3,000 metric tons was a small fraction of the CO_2 output from the R.E. Burger power plant, which produced 3,000 metric tons of CO_2 over a two-day day period at the time. There were no plans mentioned by FirstEnergy at time of site selection to consider this site as a possible future commercial CO_2 injection site. As will be discussed in this report, several modifications to the test plan were necessary as the project progressed.

1.1 Site Description

The test location is along the Ohio River near Shadyside, Ohio, across from Moundsville, West Virginia (Figure 1-2). The field site is on FirstEnergy's R.E. Burger facility, a 413 megawatt (MW) coal-burning power plant located on 100 acres along a bend in the Ohio River (Figure 1-3). The drill site itself was located in a vacant field approximately 1500 ft northeast of the R.E. Burger power plant itself.

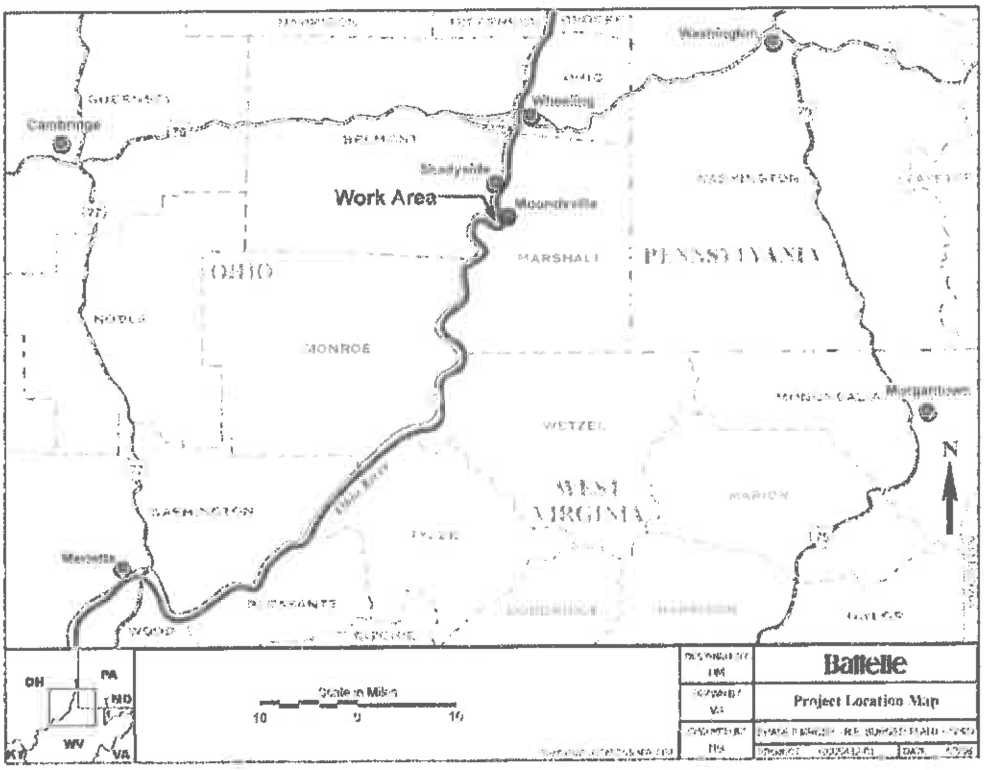


Figure 1-2. Site Location Map

Figure 1-3. First Energy R.E. Burger Facility

1.2 Geologic Setting

The site is located in the Appalachian Basin, a regional structure in which sedimentary rocks form an elongated basin stretching across West Virginia, Pennsylvania, Ohio, Kentucky, and Maryland. The site is on the western flank of the basin where rocks slope toward a structure called the Rome Trough, a Cambrian-age rift valley in the deep subsurface. Younger sedimentary rocks drape over the Rome Trough and thicken to depths over 20,000 ft below the surface. More substantial deformation is present toward the Allegheny Front which is east of the study area.

Due to its size and thickness of sedimentary layers, there appear to be numerous potential options for geologic CO_2 storage in the Appalachian Basin. However, the complex geologic structure, heterogeneities, and relatively unexplored geology of the candidate formations make prediction of actual storage potential very difficult. This is especially the case for the carbonate layers and the deeper sandstone units that have not been targeted for oil and gas production so far. The caprock layers appear to be represented by numerous thick and low permeability carbonate and shale sections. There is a history of gas production in shallow sands, Devonian Shales, and the Oriskany Sandstone in the general area. Rocks in the Appalachian Basin are saturated with very concentrated brines (or oil and gas). Several salt solution wells completed in the Salina Group are present in the study area. The site is located adjacent to the Rome Trough where a series of faults lead into the trough. No previously known faults are present through the project area.

Prior to any field work, a preliminary geological assessment of the general area was completed by the Ohio, Pennsylvania, and West Virginia Geological Surveys (Wickstrom et al., 2006). This detailed report is included herein as Appendix A. This study reviewed the regional geologic setting, stratigraphy, oil and gas horizons, coal seams, seismic setting, groundwater resources, artificial penetrations, and surface features in the area. Available literature, petroleum well and storage field data, well and core descriptions and analyses, and coal information were compiled and analyzed for an area within a study area of 20 miles radius around the R.E. Burger Power Plant. Records on producing oil and gas wells, dry holes, stratigraphic core tests, and brine-solution wells were identified in public archives in the 20 mile study area. Core tests and analyses of prospective injection reservoirs and caprocks were non-existent or not known to be available for public use in this study area. Other than shallow stratigraphic core hole tests, only one well was found to contain a deeper interval (Ohio Shale) that has been cored, and only one short description of the Oriskany Sandstone is known; both are from wells drilled in Belmont County, Ohio. Only 59 wells have been drilled into or deeper than the Devonian-age Onondaga Limestone in 20 mile study area. Of these wells, only four wells were drilled deeper than the Silurian-age "Clinton-Medina" interval and just one well penetrated the Cambrian-age Knox Dolomite within the 20 mile study area. The nearest well penetrating Precambrian rocks occurs 30 miles northwest of the R.E. Burger Power Plant. The limited geophysical well log data for the few deep prospective saline reservoirs suggested thin and tight reservoirs beneath the Devonian black shales at the R.E. Burger Power Plant site. However, there were not enough data to quantify the hydraulic properties or the storage potential based on prior information.

Overall, the preliminary geologic assessment identified a number of possible injection targets at the R.E. Burger site. The Hamilton Group, Oriskany Sandstone, and Clinton Sandstone were identified as possible storage reservoirs based on limited well control within the study area. During drilling the Hamilton Group showed natural gas and borehole instability requiring it to be cased off on the way to the lower formations. The Lockport Dolomite, Salina Group, Bass Islands Dolomite, Onondaga Limestone, and Devonian Shale and siltstones were also identified, but, were considered speculative intervals. Deep unmineable coal beds beneath the site were also identified as possible storage zones, however, the focus of the MRCSP tests was deep saline injection. Converse to reservoir rock, caprock was generally considered very favorable throughout the region as it is relatively predictable from well log analyses tied to core and testing data from great distances.

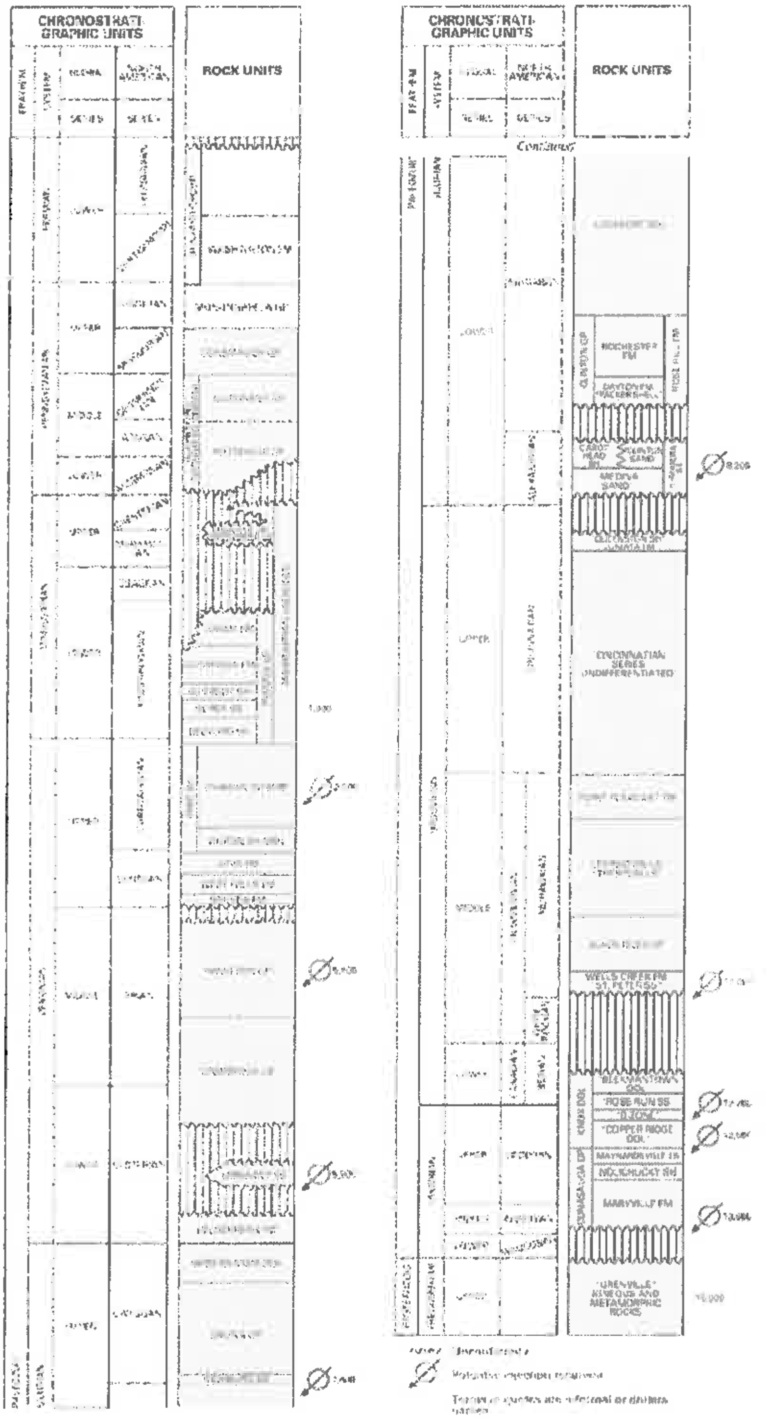


Figure 1-4. Chart Illustrating the Estimated Depth of Geologic Units Identified in Preliminary Geological Assessment of the Test Site

2.0 2-D SEISMIC CHARACTERIZATION

In August 2006, a two-dimensional (2-D) seismic survey was completed at the R.E. Burger Power Plant site in support of the CO_2 sequestration test. The purpose of this seismic survey was to help delineate formation tops in the area as well as to gain insight into the structure and stratigraphy of local geology as it relates to testing injectivity of the identified formations. Potential storage reservoirs were thought to reflect regional structural trends of the Ohio Platform in that they dip slightly (~70 ft/mile) to the east. Because the target reservoirs are 5000 to 8,500 feet, below where oil and gas are typically found, structural data from previous exploration at these depths were limited. The seismic survey would help discover any previously unknown faults, highlight reservoir continuity, and ensure safety and overall performance aspects of the sequestration project. Detailed seismic stratigraphy was not completed for these sections. An overview of seismic survey plan, permit documentation, a summary report describing the seismic acquisition and interpretation is provided in Appendix B.

2.1 Planning

Seismic survey planning consisted of delineating the survey traces, planning the data acquisition parameters, determining the general logistics for the survey work, procurement of a seismic acquisition vendor, and information meetings with staff of the R.E. Burger Power Plant. Survey traces were selected in collaboration with the Ohio Geological Survey and consultants from the Appalachian Basin, and were discussed with the Ohio EPA. Subsurface coal mines were a major concern, as most areas adjacent to the Ohio River have been mined and the seismic signal would have been disrupted through an empty mine shaft. Consequently, mine maps were consulted in selecting the survey traces. Final routes were defined mainly along State Route 7 and along local roads (Figure 2-1). The routes were each approximately 5 miles long for an estimated 10 miles of total survey. The planned survey routes followed along the strike and the dip of sedimentary layers. Both of the traces cross the Ohio River. Consequently, telemetry methods were necessary to obtain data across the river. Both traces cross into West Virginia.

Initially, two to three shorter "quasi-three-dimensional (3-D)" traces were planned along the Ohio River around the well in addition to the two main, longer traces. Eventually, only one additional parallel trace approximately 1 mile in length was selected. Combined with the longer traces, this additional survey line provided greater geologic coverage in the vicinity of the proposed well. The information provided by this shorter trace helped to better delineate the Oriskany Sandstone and Clinton-Medina Sandstone, which have a somewhat variable distribution in the general area.

Data acquisition parameters were selected to provide adequate resolution, fold, and depth extents. Appalachian Geophysical Services was contracted for data acquisition due to their experience in the Appalachian Basin. The company visited the site with Battelle and scouted the routes to ensure that they were feasible for an acquisition program. Initial meetings were held to inform the employees of the R.E. Burger Power Plant about the seismic survey and CO_2 injection tests in general. The permitting and permission process for the seismic survey consisted of contacting and informing land owners along the survey routes. A representative from the geophysical survey acquisition company explained the survey to the concerned property owners and obtained their approval to access the properties. The pertinent parties included, but were not limited to: State of Ohio, State of West Virginia, Belmont County, Ohio, Marshall County, West Virginia, Mead Township, Ohio, and City of Moundsville, West Virginia, as well as local businesses and homeowners.

PROPOSED SEISMIC LINE LOCATIONS

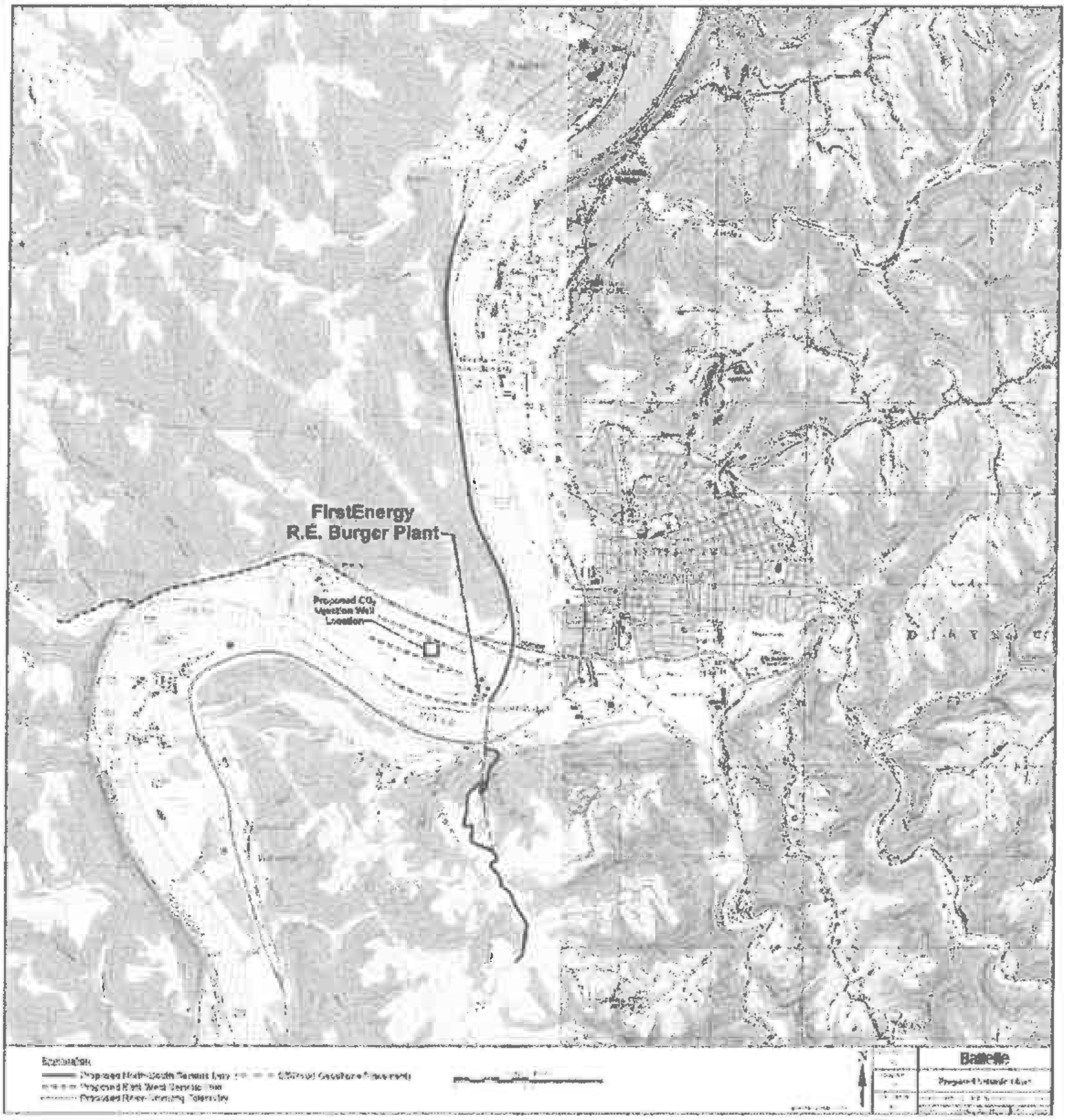


Figure 2-1. Initial Proposed Routes for Seismic Survey at R.E. Burger Site

2.2 Acquisition

The seismic acquisition for the R.E. Burger site was performed in August 2006 and extended into Belmont County, Ohio and Marshall County, West Virginia. The first step of the seismic acquisition process involved conducting a topographic survey to flag the final routing of the seismic lines. Once the lines were surveyed, the acquisition equipment (geophones, recording system, etc.) was then laid out. Three to four vibroseis trucks were utilized to provide the source (energy) pulses on the roads. Each step in the seismic process was preceded by a safety and coordination meeting between Battelle, FirstEnergy, and Appalachian Geophysical Services, the seismic acquisition vendor selected for this project. A microwave link was used to obtain subsurface data across the Ohio River. Figure 2-2 lists the equipment and parameters of the seismic survey instrumentation.

Acquisition

Appalachian Geophysical Services, LLC, Killbuck, Ohio, USA acquired three lines of seismic, Burger-V1-06, Burger-V2-06 and Burger-V3-06 in Belmont County, Ohio and Marshall County, West Virginia. The ARAM MK II distributive digital recording system was used for instrumentation. The following parameters were used for field acquisition:

Recording:	
Nominal fold	60
Channels	**240**
Sample rate	2 ms
Gain	30 dB
Field filters	3 Hz, low cut
	123 Hz, high cut
Record length	4 seconds
Receiver:	
Geophone type	Sensor SM-4-High Sensitivity
Frequency	10 Hz
Station interval	110 feet (33.5 m)
Geophone array	12 phones over 110 feet (33.5 m)
Geophone spacing	9+ feet (3+ m)
Source:	
Source interval	220 feet (67 m)
Source type	Vibroseis
Source array – vibe	3 and 4 vibes over
	110 feet (33.5 m), shot on ½ station
Sweep:	
Sweep length	8 sweeps x 12 seconds
Sweep type	Linear
Frequency range – vibe	16 – 120 Hz
Start taper	500 ms
End taper	300 ms

Figure 2-2. Seismic Acquisition Parameters for R.E. Burger Site

2.3 Processing

Once the seismic data in the field were collected, it was sent to a third party for processing. Standard processing methods were used to reduce noise in the data which can yield better imaging quality. Better image quality resulted in more reliable geologic interpretations because the geologic structures and reflection geometries were more apparent. Using a third-party processing company helped eliminate subjective tendencies of the processor to "adjust" the dataset to reflect his or her own biases.

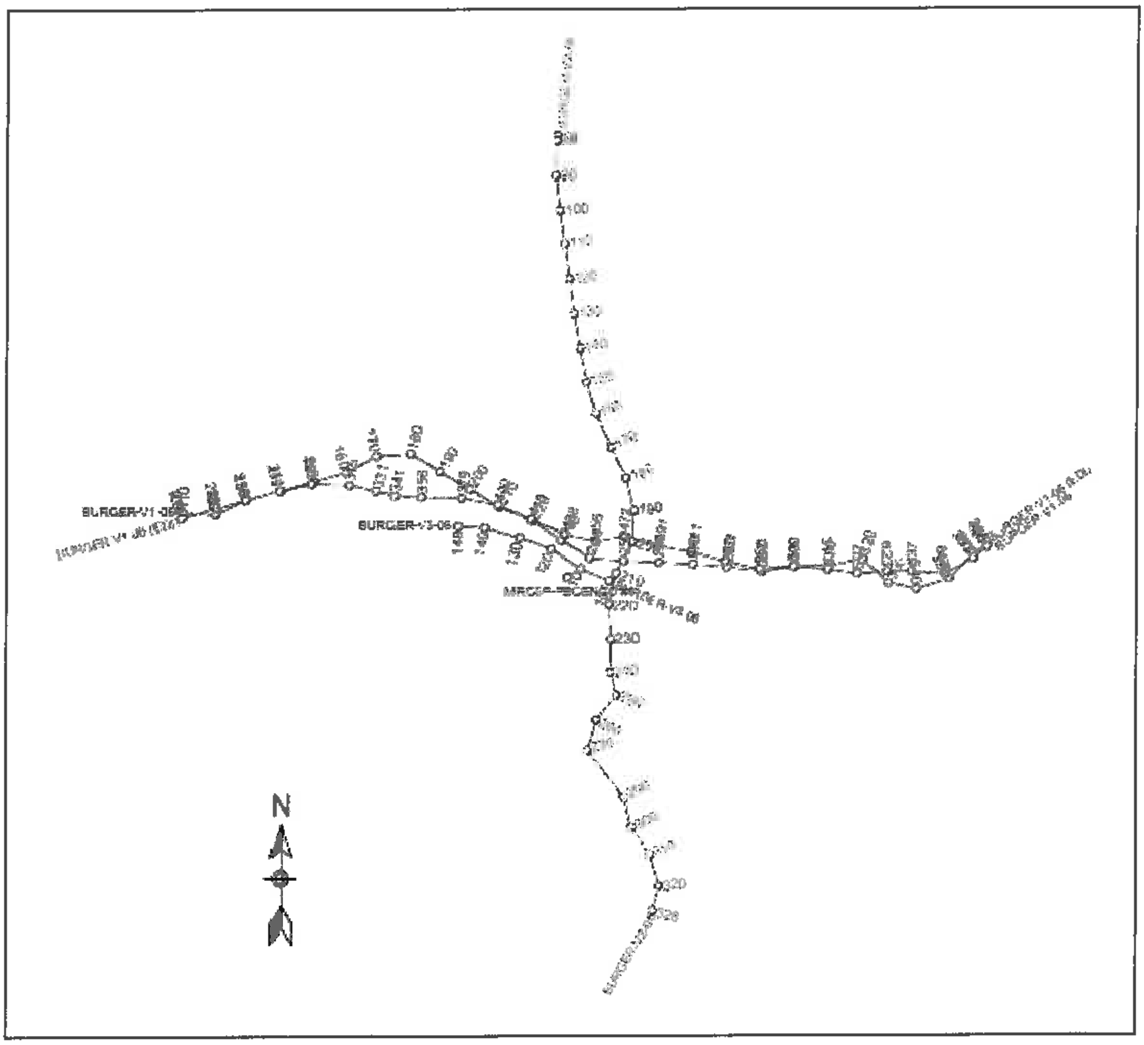


Figure 2-3. Seismic Lines and Well Location Map for R.E. Burger Site

Once the seismic data acquisition was completed, all three lines were processed by Elite Seismic Processing (ESP) using their conventional Appalachian Basin processing sequence. The following parameters were used in the digital processing flow:

- Read and output SEGY files
- Geometry and trace edits
- Exponential gain correction
- Relative amplitude scaling
- Elevation and drift correction
    - Datum: 700 feet (213 m)
    - Replacement velocity: 12,000 ft/sec (3658 m/sec)
    - Refraction statics: hand and automatic

- Deconvolution (Surface Consistent)
  - Shot domain:
    - Design gate
    - Operator length: 80 ms
    - Prewhitening: 0.1%
    - Bandpass: 10/20 to 115/120 Hz
- Velocity analysis
- Normal move out analysis
- Mute
- Automatic residual statics
- Second pass velocity analysis
- Second pass NMO
- Second pass mute
- Trim statics
- Zero phase spectral whitening: 15 to 115 Hz
- Stack
- Filter: Bandpass: 10/20 to 115/125 Hz
- Relative amplitude scaling
- Post stack spectral whitening
- Random noise attenuation with FX-Decon
- Migration for migrated sections only

Because of some ambiguities in the data at lower depths, the decision was made to have Exploration Development, Inc. (EDI) reprocess Burger-V1-06 to focus more closely on the deeper strata. However, both ESP and EDI's processing method was developed to focus on structural and stratigraphic characteristics. Using their conventional Appalachian Basin processing sequence, they followed these parameters in the digital processing flow:

- Load SEGY data
- Geometry update and trace edit
- Gain recovery
- Surface consistent deconvolution
- CDP sort
- Zero phase spectral enhancement 15 to 120 Hz
- Refraction statics
  - Datum: 1500 feet (457 m)
  - Velocity: 12,000 ft/sec (3658 m/sec)
- Velocity analysis – 2 passes
- Normal move out corrections
- Mute
- Surface consistent statics – 2 passes
- Trace balance
- CDP trim statics
- DMO/velocity analysis/NMO

- Two band split trim static
- Stack (CDP)
- Trace balance
- Migration
- 33% noise estimation and subtraction
- Time variant spectral whitening
- FK box filter
- Trace balance

2.4 Interpretation – Formation Tops

Interpretation of the processed seismic data from both ESP and EDI was performed in conjunction with Appalachian Geophysical Services and the Ohio Geological Survey. Seismic stratigraphy methods and interpretation tools were used for the R.E. Burger seismic analyses. Seismic stratigraphy refers to the utilization of seismic characteristics displayed by particular rock units to differentiate one unit from another.

Figures 2-4 and 2-5 show the estimated Big Lime, Trenton and Precambrian horizon picks. The horizon picks were estimated due to the lack of nearby data. However, the Burley #1 synthetic (Appendix B, Figure 7) was used in the interpretation because it is located in the southeast corner of Marshall County, West Virginia (~11 miles from the R.E. Burger site). It was recommended that sonic data be acquired when the R.E. Burger test well was drilled to aid in the correlation of the horizons.

Both ESP and EDI commented on the challenge in processing the data across the river valley. There is no way to determine whether the features beneath the Ohio River are real or a result of static and velocity processing issues. The unconsolidated sediment (sand and gravel) in the valley caused the energy to be more absorbed than surrounding areas, causing the difficulty in interpreting whether or not there was structure present.

In order to further aid the seismic horizon picks a synthetic seismogram had to be created. During drilling, sonic data were acquired for the FEGENCO #1 well, which was then used to calculate the expected seismic data (Figure 2-6). The synthetic model was then compared to the actual seismic data to check for any major inconsistencies.

This synthetic seismogram was useful for filling information gaps in the actual seismic survey. As shown in Figure 2-6, several major lithologic units lie between the observable horizons seen in the original seismic data. By integrating the synthetic seismogram into the actual seismic dataset more formation tops become apparent. Figure 2-7 shows the resulting horizon picks when the synthetic data are used in conjunction with the actual seismic data.

The White Clinton Sandstone, a potential storage reservoir, becomes discernible in the resultant interpretation. If injection was to have taken place successfully in the White Clinton Sandstone, then post-injection changes may have been detectable.

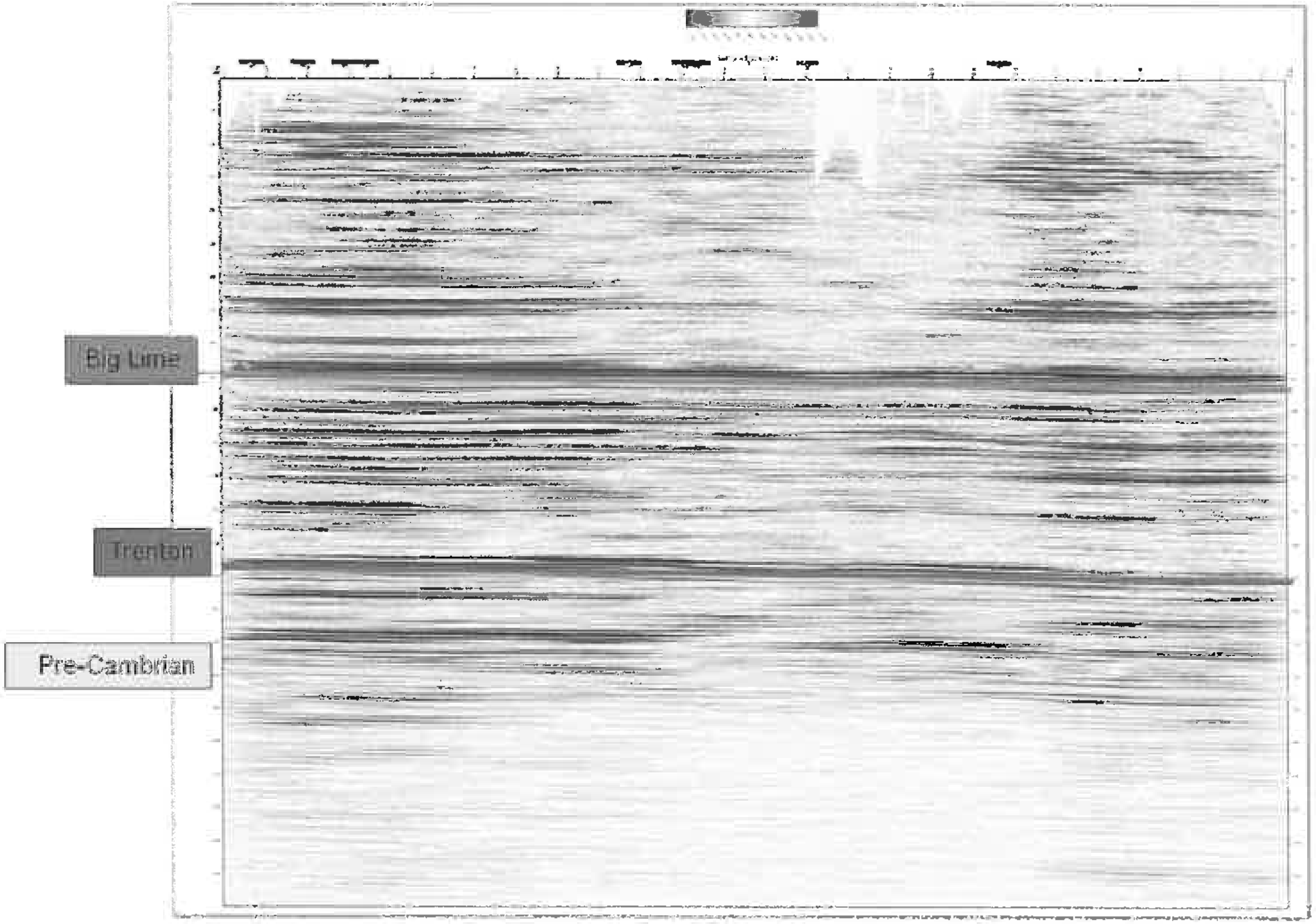


Figure 2-4. Full Section Presentation of Seismic Line Burger-V1-06 (E-W line) as Processed by ESP (Note that these picks were made prior to integration with FEGENCO #1 synthetic seismogram. The storage zones were located beneath the Big Lime and above the Trenton.)

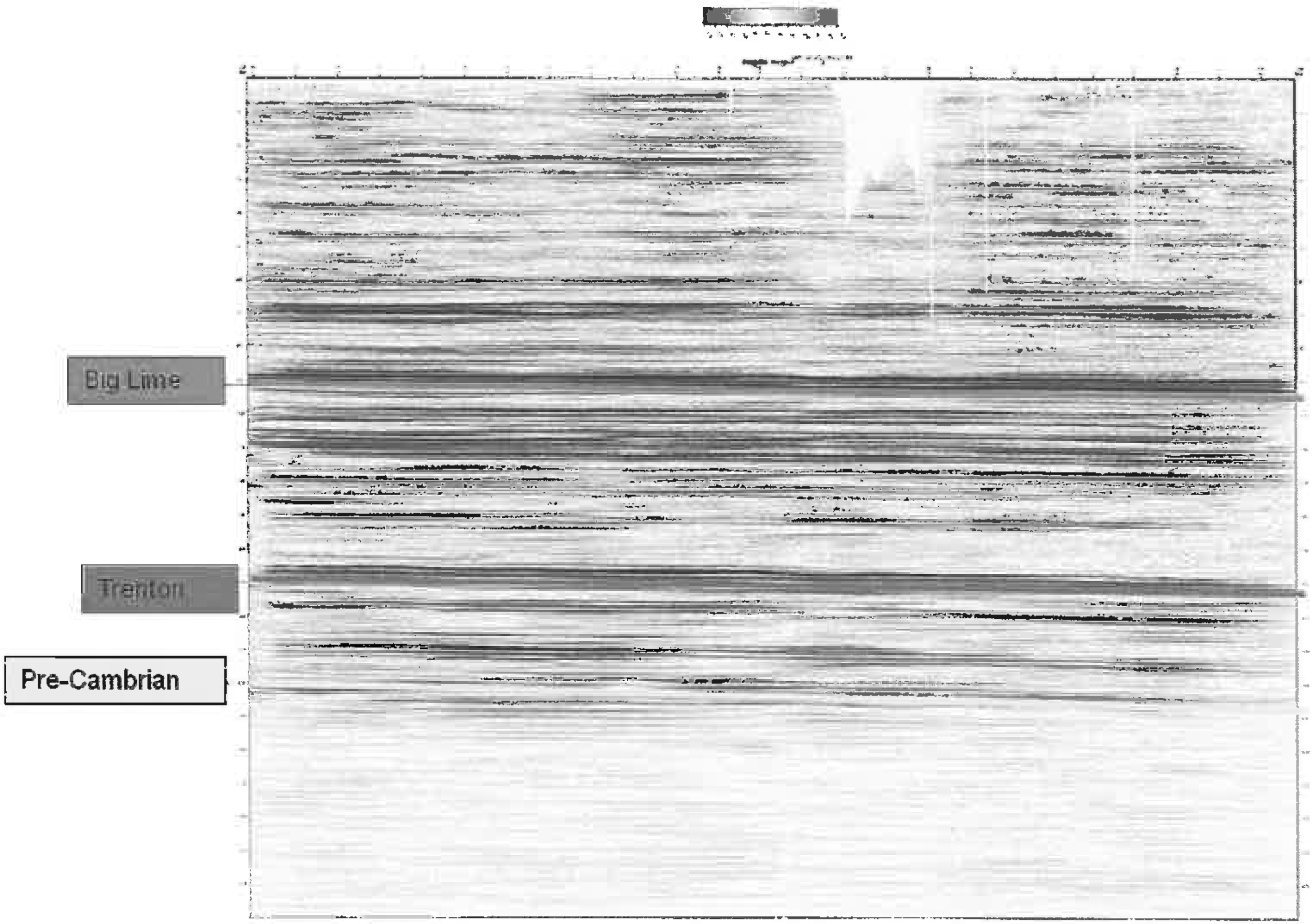


Figure 2-5. Full Section Presentation of Seismic Line Burger-V2-06 (N-S line) as Processed by ESP (Note that these picks were made prior to integration with FEGENCO #1 synthetic diagram. The storage zones were located beneath the Big Lime and above the Trenton.)

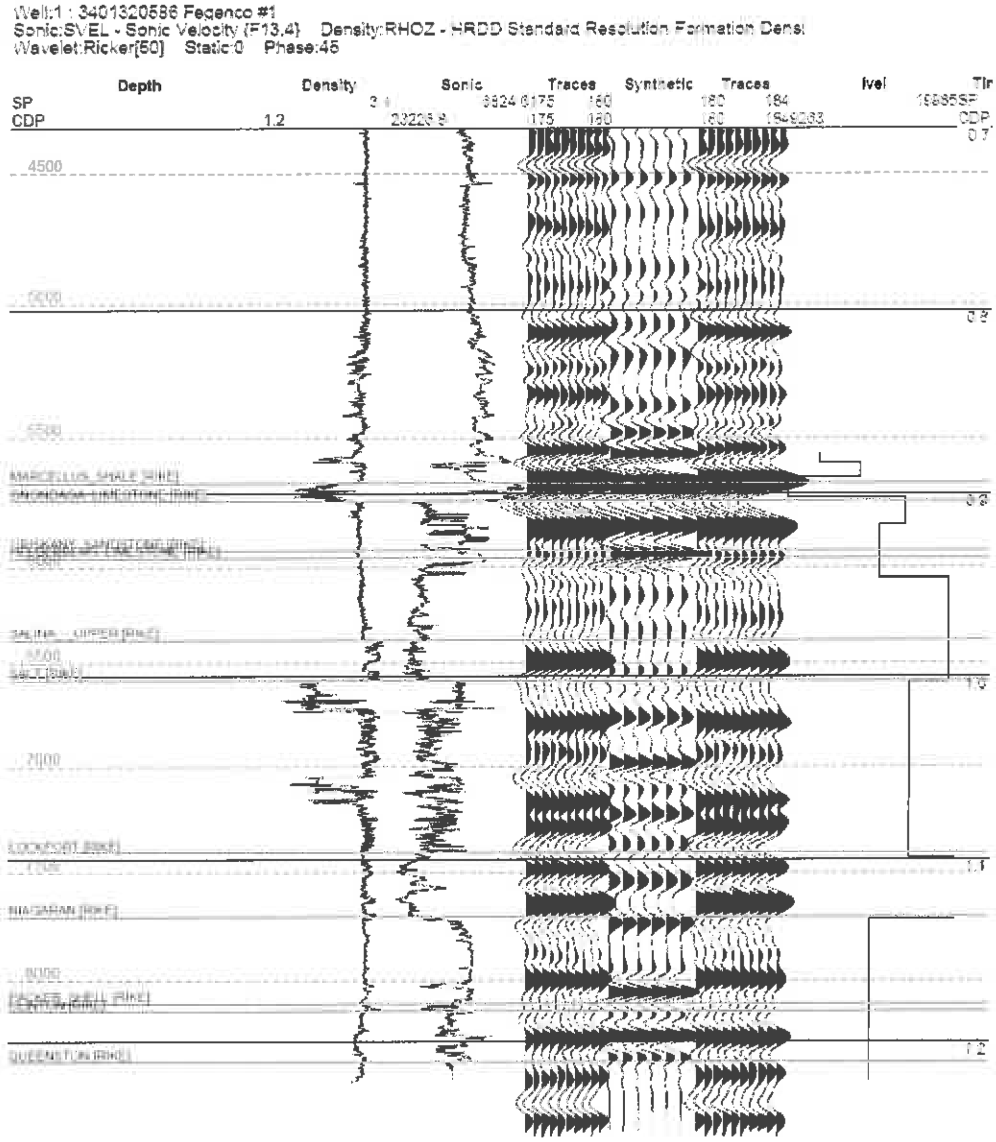


Figure 2-6. Synthetic Seismogram Created from Sonic Data in FEGENCO #1 Well at R.E. Burger Site

2.5 Interpretation – Structural Setting

Detailed seismic stratigraphy was not completed for these sections. Further information regarding the depositional environment can be found in Appendix A.

The R.E. Burger Power Plant site sits on the eastern edge of the Ohio Platform. The typical structural setting is one of a flat to mildly undulating Precambrian surface overlain by essentially flat strata, the whole having a slight southeast dip into the heart of the Appalachian Basin.

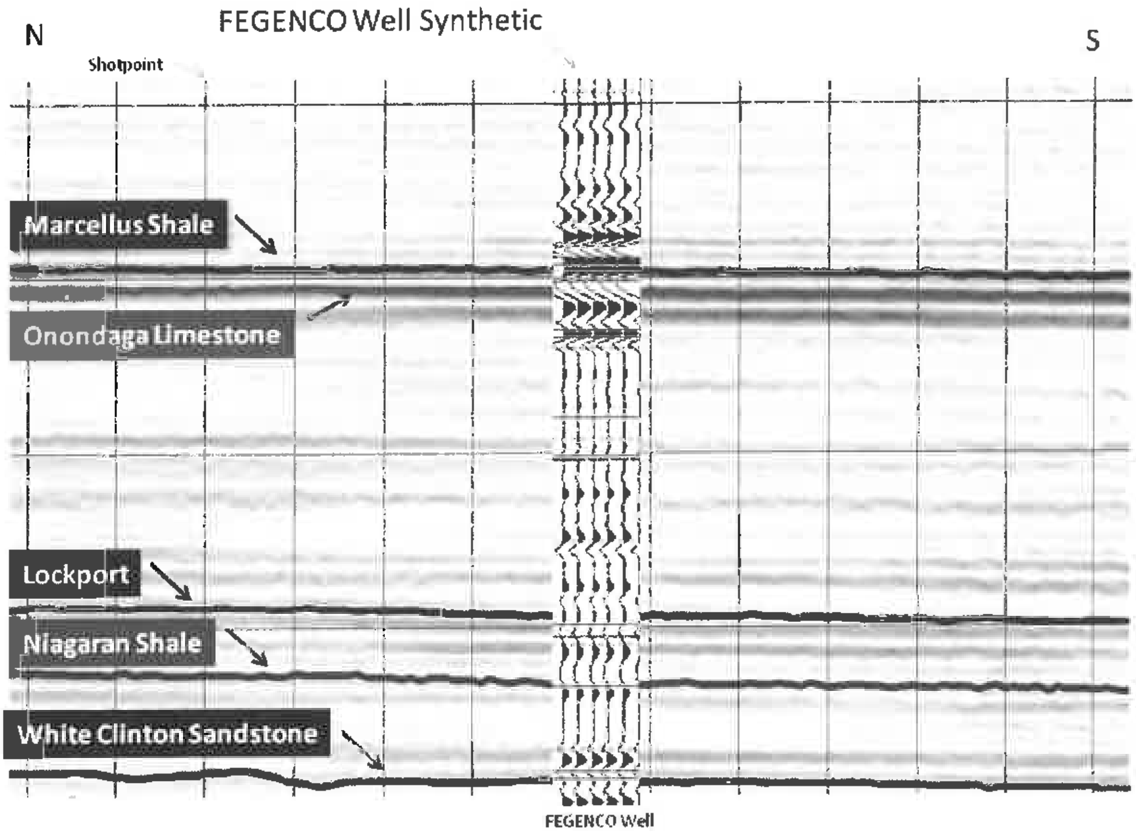


Figure 2-7. Diagram following Seismic Line Burger-V2-06 (N-S)
(Additional rock units are discernible once sonic data is used for calibration; a more detailed view reveals the White Clinton Sandstone, a potential storage reservoir.)

Three counties located southeast of the R.E. Burger site are the western edge of the Rome Trough, which is sharply delineated by the occurrence of strong basinward (down to the east) faults with throws of up to several thousand feet at the Precambrian surface. Typically, these fault systems sustained several periods of reactivation, but each successive reactivation was weaker than that preceding it. Although the initial faulting was normal, subsequent episodes were a mixture of normal and reverse movement. Rarely did faulting occur later than the mid-Ordovician (Trenton) time.

The structural sequences observed in the Rome Trough are generally illustrative of those occurring elsewhere in the Appalachian Basin. Specifically, the most intense deformation occurred during the Precambrian. Some additional deformation, either primary or reactivated, can be seen during the Cambrian and Early and mid-Ordovician periods. Deformation of any significance that occurred after the mid-Ordovician is uncommon.

Although the Ohio Platform is structurally separate from the Rome Trough, it is not entirely without structural features. Some basement-influenced arching of low relief is encountered. Small, isolated domes of low relief are to be found. They are generally the result of deep structure and may exert some stratigraphic influence in younger sediments. Draping over topographic highs on the Precambrian surface is seen in many instances. Surface lineations may hint at deeper structure. Burger-V1-06 and Burger-V2-06 were acquired to see if there were any possible structural anomalies present.

Seismic lines Burger-V1-06 (Figure 2-4) and Burger-V2-06 (Figure 2-5) do not depict any notable structure in the post-Ordovician sediments as indicated in the Devonian Big Lime marker horizon.

In Silurian and later time, structure on the Ohio platform was limited primarily to gentle subsidence to the east into the Appalachian Basin. Expectedly, the shallow formations mimic the shallow rolls of the deeper beds and adhere to the rate of dip and direction dictated by the Cambrian and Ordovician rocks. As was previously noted, differential compaction over early features may produce some discernable draping of younger strata, but none is evident on the seismic in this report.

The Precambrian surface on the Ohio Platform is an erosional surface. The area of the R.E. Burger Power Plant presumed to be granitic in nature and may be bare granite or a wash composed of either in situ weathered granite or transported clastics derived elsewhere from the Precambrian basement. Based on limited penetrations to the Precambrian, the washes are typically thin and suggest a long period of exposure that produced an essentially flat featureless surface.

The Precambrian surface on the R.E. Burger seismic lines does not generate a coherent seismic reflector. The nature of that surface is in part inferred from nearby reflectors in the basal Paleozoic section and from reflectors contained within the Precambrian mass.

The ESP and EDI seismic versions are inconclusive as to structure within the Precambrian. A rate of dip is approximately 70 feet per mile (13.3 m/km) in an eastern direction. The reflectors below the top of the Precambrian are weak or inconsistent. However, no discernable faulting appears in the basement complex.

3.0 TEST WELL DRILLING

The R.E. Burger test included drilling and characterization of one injection test well at the site. The well was drilled to a total depth of 8,384 ft in February 2007 with associated logging and characterization tests. The test well was completed with injection casing in February 2008. The injection zones were perforated in September 2008.

3.1 Test Well Description

Site preparation activities were completed in the fall of 2006 and included grading the area, digging mud pits, and constructing access roads. The well was permitted by the Ohio Department of Natural Resources (ODNR) Mineral Resources Management Division in November 2006 and assigned American Petroleum Institute (API) well number 34-013-2-0586-00-00 (Appendix C). The FEGENCO #1 well was drilled in a series of smaller boreholes and casing was cemented in place to surface to isolate the well from any sources of drinking water. The shallowest conductor section was drilled with a smaller water well rig. The deep well was drilled with a rotary drilling rig and a combination of air and mud circulation.

Conductor Casing: Initial drilling was completed in December 2006 with a smaller water well drilling rig, which is more suited to working with unconsolidated sediments (Figure 3-1). A 24-inch borehole was advanced to a depth of 105 ft through the base of the Ohio River Valley alluvial aquifer into bedrock. A 20-inch conductor casing was then cemented in place to a depth of 83 ft with 175 sacks of Class A cement. Well cuttings indicated the conductor was set within 20 ft of competent shale bedrock, isolating the well from any source of drinking water. Once the conductor casing was set, the water well rig was removed from the site to allow a deep drilling rig to complete the remainder of the drilling program.

Figure 3-1. Water Rig Drilling Conductor Casing for FEGENCO #1 Test Well

Surface Casing: The deep drilling rig was mobilized to the site in December 2006 and began drilling the surface borehole on January 9, 2007. A 17 ½ inch borehole was advanced to a depth of 930 ft. Shallow casing consisted of 906 ft of 13 3/8 inch, 48# H-40 8R ST+C casing. Casing was cemented in place with 800 sacks of Class A cement.

Intermediate Casing: The intermediate drilling run consisted of a 12 ¼ inch borehole advanced on air to a depth of 1960 ft into the Bedford/Huron shale. Intermediate casing included 1,939 ft of 9 5/8, 36#, 8R ST+C casing cemented in place with 400 sacks of 50/50 POZ mix and a tail of 210 sacks of 15.6 Class A cement.

Deep Casing: The deep drilling run was drilled on air with an 8 ¾ inch borehole to a depth of 5,785 ft into the Onondaga Limestone. The casing string included a total of 5,752 ft of 7 inch 26# N-80 8R LT+C and two 812 LT+C P up joints. Due to the depth, the casing was cemented in two stages to prevent damage to the lower cement from the overlying column of cement. A stage cement tool was set at a depth of 1,797 ft to enable the two stage cement operation. The lower stage was completed with 395 sacks of Lite Crete with 100 sacks of Class A cement. The upper stage was completed to surface with 255 sacks of Class A cement.

Injection Casing: The injection section was drilled into the Queenston shale with a 6 1/8 inch borehole. Salt was encountered at a depth of 6,589 ft and drilling was switched to mud circulation. A total driller's depth of 8,364 ft was reached on February 3, 2007. The well was circulated clean and well logs were run, but the rotary sidewall coring tool could not be run below 6,500 ft. The well was left open hole, pending analysis of well log data. A well completion form was provided to Ohio Department of Natural Resources, Mineral Resources Management.

In January 2008, the well was completed with injection casing. The well was circulated clean with fresh drilling mud and additional rotary sidewall cores were collected from the deeper section (6,515 to 8,332 ft). The casing string consisted of 8,344 ft 11.6# N-80 8R LT+C casing. The casing was cemented in two stages through a DV stage tool set at 4,512 ft. The lower cement interval consisted of 322 sacks of Class A cement. The upper was completed to surface with 400 sacks Class A blend with 2% gel. The well was circulated clean, wireline logs were run, and the deep drilling rig was moved offsite in early February 2008.

Well Completion and Cement Assessment: The FEGENCO #1 well was completed for injection in January 2008 with a service drilling rig. Well completion activities included perforating the injection intervals, installing injection tubing, and installing the wellhead flange (Figure 3-2). The three target injection zones were penetrated with a perforation gun. The Clinton-Medina was perforated across an interval of 8,197 to 8,284 ft. The Salina Formation was perforated across an interval of 6,740 to 7,026 ft. Finally, the Oriskany was perforated across the interval of 5,944 to 5,964 ft.

In association with well completion activities, a cement bond log was completed on August 5, 2008. Schlumberger's Isolation Scanner was run from total depth to as close to the surface as possible while maintaining proper tool operations. The logged interval was from 100 to 8,310 ft bgs. The well was filled to surface with fluid and kept under pressure during logging. Due to the use of a brand new cable, there was some fluid loss at the surface; however, surface pressures were maintained between 1,000 and 1,050 psi during logging operations, staying at or above the maximum pressure seen during initial cement operations. The Isolation Scanner was tied in with a gamma log to the initial cement bond log, which was run by Schlumberger on January 24, 2008.

The Isolation Scanner was designed to analyze the sonic waveform to evaluate cement and well integrity. The log allows for the detection of the 'third interface.' While in a single string of casing, this third interface is the contact between the formation and the cement. While logging through two strings of casing, the third interface represents the cement-second casing contact. Details are provided below on the cement bond log across the bottom string from 5752 ft to total depth. Data were collected further up hole but are not discussed here.

The interval from 5,752 to 6,744 ft showed very good cement. A few instances showed evidence of 'galaxy' patterns, such as at approximately 6,100 ft. The patterns may represent locations where the casing was decentralized and lying against the formation. Although these patterns were evident, there was still very good cement, both above and below, as well as along the outside of the galaxies.

The interval from 6,744 to 6,900 ft did not indicate very good cement. There appeared to be sections, such as from 6,781 to 6,819 ft and 6,863 to 6,899 ft, which showed both gas and liquid behind the pipe. This interval encompasses the Salina Subgroup where logs indicated natural gas throughout, as well as numerous gas shows on the mud log, including two shows greater than 400 units. Mitigating areas of bad cement this small is generally cost prohibitive and would be unlikely to significantly increase cement integrity. However, because there is high quality cement both above and below this interval, cement quality in this interval was not considered a threat to the well integrity. In addition, this interval encompasses the target injection zone where perforating for injection purposes would have intentionally compromised cement integrity anyway.

The interval from 6,900 to 7,294 ft showed consistent cement bond. There were no striking galaxy patterns in the interval seeming to indicate that the casing was well centered in the well. There was also no indication of a micro-annulus.

The interval 7,294 to 7,537 ft also showed consistent cement bond. There were some indications of the casing being off center in the hole, which can be determined by the 'galaxy' type patterns seen along the raw acoustic impedance map (Figure 3-3). A slight indication of a micro-annulus was evident through part of this interval, as shown in green in the solid-liquid-gas track. Despite the micro-annulus, there appeared to be decent cement through this interval.

From approximately 7,537 to 7,587 ft, the Isolation Scanner suggested mostly gas behind the casing. The mud log showed a minor amount of gas (less than 200 units) in this interval, which may explain the gas reading. Parts of this interval may be the result of fast formation effects, however this should not affect the reading of gas behind the casing.

The interval from 7587 to 8012 ft showed excellent cement bond and was in good agreement with the original cement bond log. Again, there were some indications of the casing being off center in the hole, visible by the 'galaxy' type patterns on the raw acoustic impedance map. For example, one of these patterns was present at approximately 7800 ft. Despite the apparently decentralized nature of the casing, there was no indication of micro annuli or any other type of cement defect in this interval. Some intervals appeared to indicate fast formation, an effect where the wavespeed of the rock is faster than the casing and the cement. This causes the first arrival on the variable density log to be the formation, rather than the casing/cement as is typically seen.

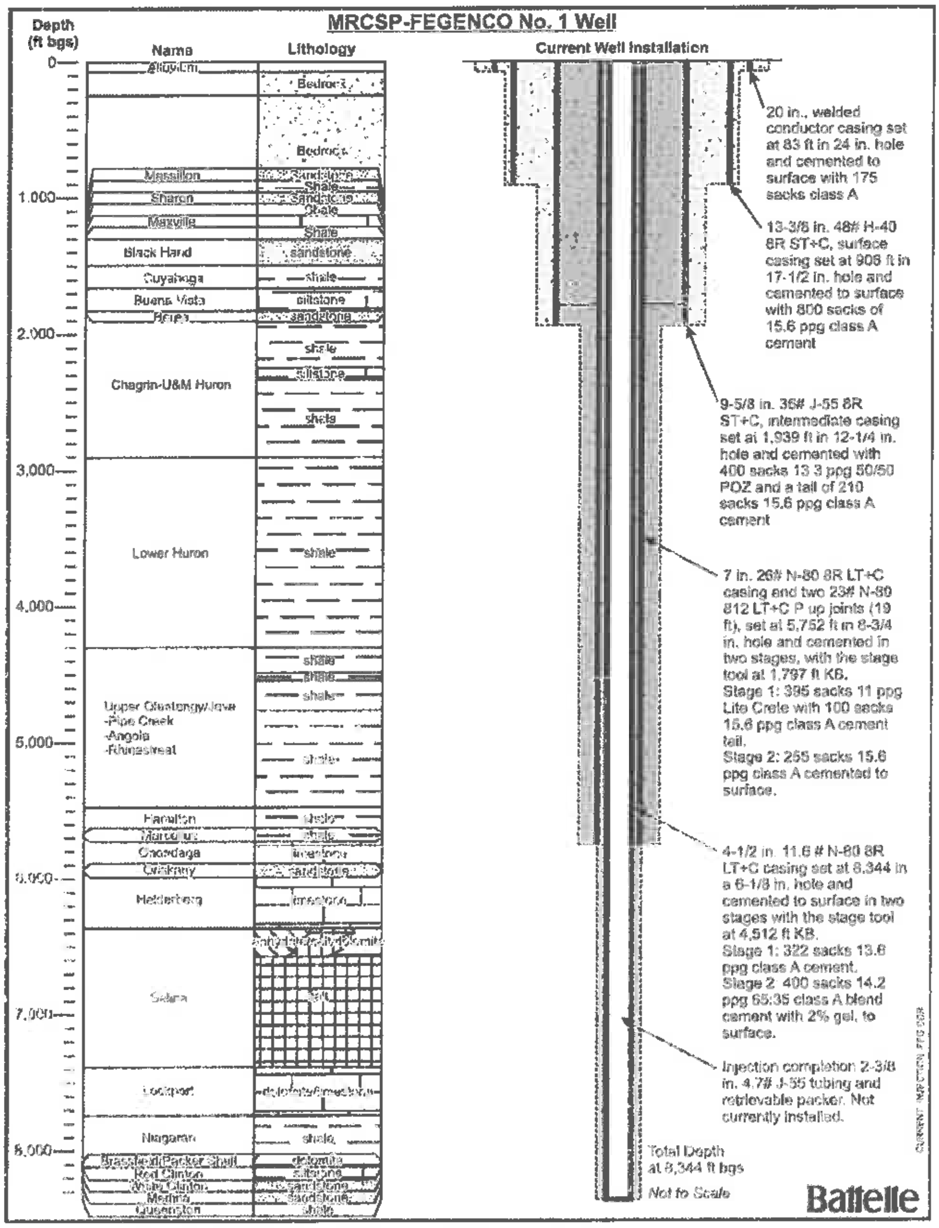


Figure 3-2. FEGENCO #1 Well Diagram

From 8012 to 8080 ft, there appeared to be both liquid and cement in the August, 2008 log. This interval was identified as well bonded in the initial cement bond log. Most likely there is some cement present in this interval, however, it is mixed with brine and does not represent competent cement. The interval would not show free pipe, as is seen on the traditional cement bond log and would show a mixture of cement and liquid, as is seen on the Isolation Scanner. Some intervals appeared to indicate fast formations, consistent with the original cement bond log.

The interval from 8,080 to total depth was previously identified as having no cement. The initial bond log showed anomalously high amplitude values, generally greater than 100 mV, indicating the presence of gas behind the free pipe. The Isolation Scanner suggested somewhat different results, although it still showed no cement from approximately 8080 to total depth. However, the log showed liquid behind the free pipe, not gas as was initially thought. The solid-liquid-gas map showed the majority was liquid (shown in blue) with some indication of gas (shown in red). While drilling, there were some relatively small gas shows across the Clinton Formation, all of them being less than 155 units. The open hole logs also indicated the presence of small amounts of natural gas. Therefore, the small amounts of gas detected behind the pipe were not unexpected; however, they did not likely represent an appreciable amount of natural gas. It appeared that the casing was not centered in this interval and it was particularly evident from 8,200 to 8,220 ft and 8,125 to 8,178 ft. Despite the lack of cement, the high quality cement above these intervals indicated there should be good hydraulic isolation between the Clinton injection target and the Salina injection target.

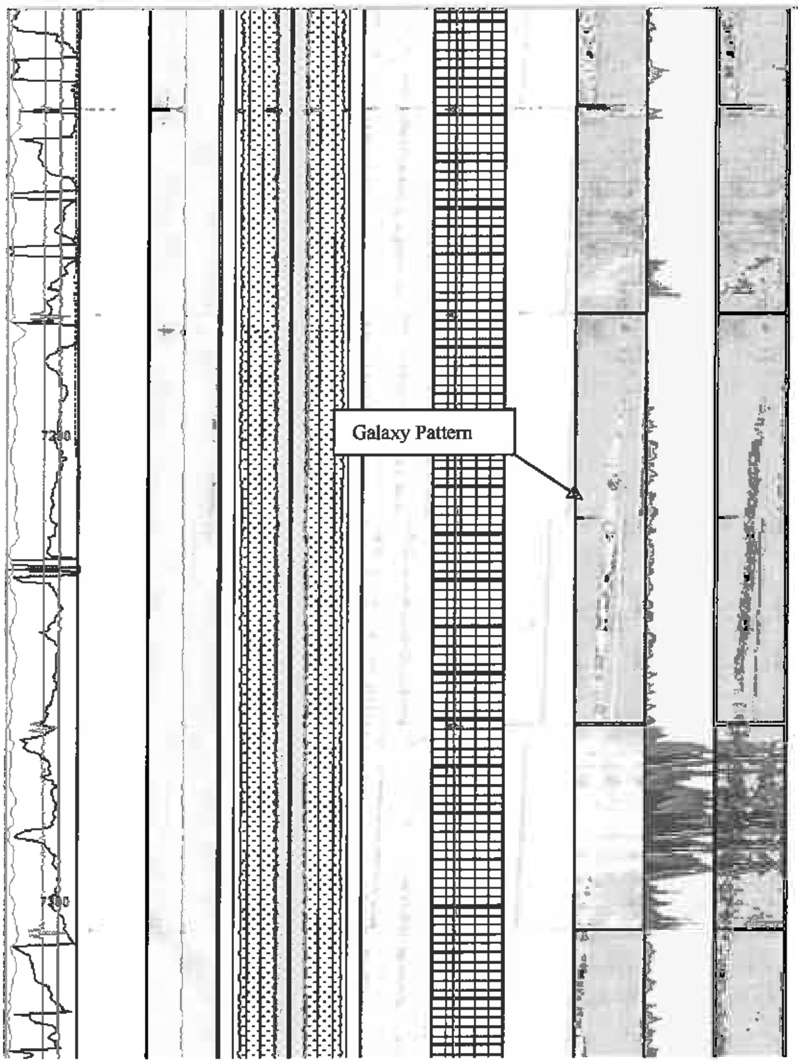


Figure 3-3. Cement Evaluation Showing Galaxy Patterns Around 7,200 ft

Injection Tubing: Injection tubing was 2 3/8 inch, 4.7# EUE J-55 tubing with retrievable packer. The tubing was temporarily installed during injection activities.

3.2 Mud Logging

Mud loggers were on site any time the borehole was being advanced to record geologic conditions through continuous observations of rig conditions, rock cuttings, and core samples. Drill cuttings were collected once for every 10 to 20 ft of hole drilled throughout borehole advancement and more often in zones of interest. Cuttings provided near real-time information about the formations in contact with the drill head, and were valuable for determining how to drill and in defining a sampling strategy.

Mudlog parameters included:

- Depth
- Rate of penetration
- Lithology: including mineralogy, texture, trace minerals, rock formation classification
- Continuous total gas
- Chromatograph percent volume of gas analyzed (optional)
- Bit log
- Mud log (daily)
- Drilling remarks (WOB, rpm, pressure, drill method)

The information obtained from the mud log is summarized in Section 4.0. Significant observations in the mud log included gas shows in the Hamilton Shale and the Marcellus Shale. A gas show was observed in the Salina at 6,800 ft and carried through the rest of the well.

3.3 Wireline/Geophysical Logging

A full suite of wireline logs was completed in the well. Table 3-1 lists the wireline tools used for each run. Gamma ray, compensated neutron, compensated density, photo-electric, resistivity, caliper, digital sonic, resistivity image log, and electron capture wireline logs were run at various depths in a total of three runs. Additionally, four cement bond logs were completed in conjunction with gamma ray tools in January 2007, February 2007, January 2008, and August 2008. To complement the geophysical logs, two runs of sidewall cores were collected in 2008.

The first logging run of the FEGENCO #1 well was performed on January 12, 2007. A cement bond log (CBL) along with a gamma ray (GR) log was run to evaluate the cement behind the first string of casing.

On January 14, 2007, several more wireline tools were run in the open hole section (963 to 1,960 ft) including: caliper GR, photoelectric, resistivity, density, and compensated neutron. Because upper hole sections are mainly used as reference points, this logging run utilized few wireline tools. Targeted potential reservoir formations all lie below 5,500 ft so tools in stratigraphically higher sections of the hole need only relay the most basic information.

Another CBL was produced on January 15, 2007 after casing had been set. The logged interval was from 0 to 1,960 ft and also included a GR dataset.

The next logging run for the FEGENCO #1 well was performed on January 20, 2007 across the intermediate string. The logged interval was from 1,936 to 5,780 ft and included caliper GR, photoelectric, resistivity, density, compensated neutron, and dipole sonic. In addition, more detailed study was completed from 5,060 to 5,750 ft. This included an elemental capture log and an image log.

A cement evaluation log was run on February 6, 2007 for the interval of 0 to 5,752 ft.

The deep string logging run for the R.E. Burger site was conducted in two episodes, the first following drilling in early 2007 and the second approximately 18 months later following issuance of the UIC permit, well completion and injection. In February, 2007, a suite of logging tools was run to gather open hole information that included compensated neutron, resistivity, density, GR, caliper, borehole imaging, nuclear magnetic resonance, elemental capture log and digital sonic data. The logged interval for these measurements was from 5,752 to 8,381 ft.

Sidewall core samples were collected in this run between 2,000 and 8,332 ft at various times during drilling. A total of 40 sidewall cores, of 48 attempted, were successfully pulled over the interval. The cores were meant to be representative samples of several formations and are discussed in detail in Section 4.2.

The CBL for the interval 2,000 to 8,322 ft was performed on January 24, 2008, after the installation of the deep casing string. This CBL was performed along with a GR tool and a variable density tool. This particular log showed that no cement was present in the bottom ~300 ft of hole behind casing. It also indicated the presence of gas behind the casing.

In August, 2008, the Isolation Scanner was used for more detailed cement evaluation. At that time several cased hole logging tools were run including a pulsed neutron capture device, GR, and collar locator tool. The depth interval logged with these tools was from 5,752 to 8,310 ft.

The final geophysical logs for FEGENCO #1 were captured in September, 2008 for the entire length of the well, 0 to 8,327 ft. Temperature, pressure, GR, and a collar locator were run to measure the conditions of the well prior to injection.

Table 3-1. Summary of Wireline Logging Program in FEGENCO #1 Test Well

Log	Depth (ft KB)
Triple Combo	963-1,956
Cement Bond Log	0-860
Cement Bond Log	0-1,960
Triple Combo	1,936-5,,780
Dipole Sonic	1,936-5,780
Processed Geochemical Log	1,936-5,780
Resistivity Image Log	1,936-5,780
Cement Bond Log	0-5,752
Triple Combo	5,752-8,381
Dipole Sonic	5,752-8,381
Nuclear Magnetic Resonance	5,752-8,381
Resistivity Image Log	5,752-8,381
Processed Geochemical Log	5,752-8,381
Cement Bond Log	2,000-8,322
Isolation Scanner	100-8,310
Temperature	0-8,327

4.0 Characterization and Testing

A full program of mud logging, wireline logging, sidewall coring, core testing, and petrophysical analysis was completed to characterize the geologic units. This information was used to identify injection targets, define confining layers, and plan injection testing. More details on the regional geology can be found in Appendix A.

4.1 Lithologic Description

The FEGENCO #1 test well penetrated over 8,300 ft of Paleozoic age rock formations. Numerous rock formations were identified through rock cuttings, wireline logs, and sidewall rock cores. Table 4-1 lists the depths of the rock formations as interpreted in the test well. Many of the rock formations are fairly typical throughout most of the Appalachian Basin. Key formations are described in more detail as follows. More details on the regional geology and depositional setting can be found in Appendix A.

Ohio River Valley Aquifer. Unconsolidated sediments were present in the first 85 ft of the well. These sediments consisted of loose silt, sand, and gravel that fill the Ohio River Valley. The aquifer is the main source of drinking water in the area. Bedrock was encountered at a depth of approximately 85 ft.

Shallow Bedrock Units. Throughout southeastern Ohio, the various units above the Buena Vista (Weir) sandstone may be laterally discontinuous by deposition, or bounded above or below by unconformities that limit their areal distribution. For these reasons, the thickness or even the presence of any given unit can change markedly over very short distances. Beyond the intricate stratigraphy, there exists no evidence of any significant or unusual structures at the R.E. Burger site.

The silty, fine- to medium-grained Homewood sandstone (928 to 962 ft) was tentatively identified on the basis of its position below the Newland-Brookville (#4 coal). Because the coals in the FEGENCO #1 are soft in nature and relatively thin, they were poorly represented in the cuttings. Aided by the Ohio Geological Survey, the identification of the coals was made on the basis of wireline correlations and core descriptions. They are considered reasonable but tenuous. Correlations proved difficult as neither thicknesses nor intervals were especially good matches from well to well.

Salt Sand. The Salt sand (1,069 to 1,096 ft) is a reliable producer of brine in southeastern Ohio and, in a few instances, has been found to contain oil and gas. In the cuttings, the Salt sand appeared as an excellent reservoir, being composed of friable, medium- to coarse-grained sand. Despite the poorly sorted nature of the sand and angular shape of the grains, it appears mature enough to be composed primarily of quartz. Porosity is approximately 15 to 17% throughout the section and is indicated by the logs to be water saturated.

Maxville Limestone. The Maxville limestone (1,224 to 1,263 ft) is laterally discontinuous in southeastern Ohio due to the uneven erosional surface on which it was deposited and the erosional surface that may bound it on top. In some instances, it is found to be porous, the result of a localized oolitic development, but more commonly the unit is found without porosity. At this site the Maxville was somewhat unusual in that is was extremely arenaceous (silt-very fine grained), but even with the included clastics, the porosity did not exceed 3%.

Table 4-1. Lithology of FEGENCO #1 Test Well

FORMATION	TOP (FT KB)	BOTTOM (FT KB)	THICKNESS (FT)
Alluvium	0	85	85
Top bedrock	85	243	158
Bedrock	243	1,069	826
Massillon (Salt) sandstone	1,069	1,096	27
Shale	1,096	1,153	57
Sharon (Maxton) sandstone	1,153	1,185	32
Shale	1,185	1,224	39
Maxville (Jingle Rock) limestone	1,224	1,263	39
Shale	1,263	1,292	29
Black Hand (Big Injun) sandstone	1,292	1,490	198
Cuyahoga shale	1,490	1,636	146
Buena Vista (Weir) siltstone	1,636	1,667	31
Cuyahoga shale	1,667	1,822	155
Berea sandstone	1,822	1,850	28
Bedford-Chagrin, Huron shale	1,850	2,900	1,050
Lower Huron shale	2,900	4,306	1,406
Upper Olentangy/Java shale	4,306	4,495	189
Pipe Creek shale	4,495	4,536	41
Angola shale	4,536	4,770	234
Rhinestreet shale	4,770	5,481	711
Hamilton shale	5,481	5653	172
Marcellus shale	5,653	5,708	55
Onondaga limestone	5,708	5,923	215
Oriskany sandstone	5,923	5,954	31
Helderberg limestone	5,954	6,369	415
Salina anhydrite/salt/dolomite	6,369	7,391	1,022
Lockport dolomite/limestone	7,391	7,736	345
Niagaran shale	7,736	8,086	350
Brassfield/Packer Shell dolomite	8,086	8,118	32
Clinton	8,118	8,318	200
Queenston shale	8,318	(>8,344)	NA

*KB = 625 ft mean sea level

Black Hand/Injun Sandstone. Between about 1,895-1,945 the Black Hand, or Injun, sandstone (1,292 to 1,490 ft) was a prolific producer of oil and gas in Ohio and West Virginia. Across its expanse in those two states, the Black Hand ranges from a fine-grained to a conglomeratic sandstone. Oil and gas entrapment in the Black Hand is commonly of the secondary stratigraphic type. The Black Hand is water-bearing in most localities and oil and gas production is localized elsewhere. At the R.E. Burger site, the Black Hand is 198 ft thick and is composed of a white, fine- to medium-grained arkosic sand that fines downward. Density porosities approximate 8% throughout most of the section. The Black Hand was drilled on air and only a minor gas show (to 20 units) was noted.

Buena Vista/Weir. The Buena Vista (1,636 to 1,667 ft), also known informally as the drillers' Weir, is an identifiable siltstone contained within the Cuyahoga shale. Density logs commonly indicate some porosity and, at the R.E. Burger site, this value is in the 8 to 9% range. However, in Ohio the practical reputation of the Weir is that of a very poor oil and gas reservoir, and there was no sign of any fluid from the unit at this site.

Berea Sandstone. The Berea (1,822 to 1,850 ft), a widespread producer of oil and gas in southeastern Ohio, is very poorly developed in the vicinity of Mead Township. Typical development is a 30 ft thick interval of shale, bounded at the top and bottom by thin (to 3 ft) sandstone stringers. At the R.E. Burger site, the upper sandstone had been replaced by an essentially non-porous siltstone, and the lower sandstone was 2 ft thick with approximately 7% porosity. There were no shows of oil or gas while drilling.

Devonian Shales. West of the R.E. Burger site, units of the Devonian shale section are readily discernable on the basis of lithology, and those lithologic differences translate well to distinctive characteristics on wireline logs. The distinctions between the rock units diminish eastward into the Appalachian Basin. At the R.E. Burger site, many of the correlations, particularly above the Lower Olentangy, are made on the basis of tenuous wireline picks that are in general agreement with the expected eastward thickening of the section. However, most of those correlations cannot be substantiated by changes in lithologic composition. Combining multiple units as "undifferentiated" would not be entirely out of line. Ron Riley of the Ohio Geological Survey assisted with the wireline correlations.

In overview, the rock above 5,150 ft (Chagrin, Upper, Middle, and Lower Huron, and Upper Olentangy) is generally a moderately hard, light gray, silty shale that is only moderately fissile. Portions were found to be slightly micaceous or calcareous. No natural shows of any significance were recorded from this section.

From about 5,150 to 5,650 ft, which includes the Rhinestreet and Hamilton, the shale is darker, showing as medium to dark gray, or dark gray-brown. The shale is also more fissile and softer, especially where dark, and may wash out badly in the wellbore. Silt, mica, and calcite are generally absent, but pyrite appears in trace to abundant amounts. Despite the suggestions of organic content by way of the dark color and pyrite, there was no evidence of fossil such as pollen or spores noted in the cuttings. From 5,650 to 5,708 ft (Marcellus) the shale is black, fissile, and soft.

Gas shows from the shales were noted only from 5,150 ft to the base of the Marcellus. The later availability of the wireline logs showed that each of the shows was correlative with that portion of the shale that was of low density. Some of the low density shale was drilled out-of-gauge due to combined conditions of reservoir gas pressure, lower competency, and greater fissility. Most of the shows were mild, not more than 30 units, but the base of the Hamilton produced a 600 unit show (5,570 to 5,580 ft) and the Marcellus peaked at 1,200 units. All of these shows were short lived, blowing down to background levels once the drill bit was through the low-density shale. The Devonian shales in the Appalachian Basin are almost invariably encountered as being under pressured, rarely exceeding 50% of normal hydrostatic. The short duration of the shows can also be attributed in part to the absence of an open fracture system in the near vicinity of the wellbore, but that is a condition that could be localized and can change over short distances.

The Onondaga (5,708 to 5,923 ft) is a dense, mottled, light to medium brown, micro- to coarsely crystalline limestone. Rock (rip-up clasts) and fossil fragments are common. Chert, primarily a translucent light gray, was abundant in the cuttings, making up as much as 50% of the sample.

Oriskany Sandstone. In Belmont County, the Oriskany sandstone is poorly developed with regard to both areal distribution and reservoir quality. Ostensibly, both elements should improve to the east where the sand is of better quality and less subject to removal by post-depositional erosion. Such is the case at the R.E. Burger site, where the Oriskany (5,923 to 5,954 ft) is developed as an identifiable sand to a thickness of 31 ft. The unit is composed of a friable, coarse- to fine-grained, angular to sub-angular quartz sand. Individual grains are frosted in most instances. The type of cementation could not be determined from the cuttings. The Oriskany fines downward and is mirrored by the density porosities which decrease linearly from a maximum of 7% at the top to about 3% at the bottom. Only the slightest, short-lived 15 unit gas show was noted at the very top of the sand. Elsewhere in the county the Oriskany is regarded as non-productive.

Helderberg-Bass Island. The Helderberg (5,954 to 6,190 ft) and Bass Island (6,190 to 6,369 ft) are present as dense, micro- to very finely crystalline limestone that includes colors of light to dark brown and gray-brown. The Bass Island is described in the literature as dolomite, but at this site there is no basis for that claim inasmuch as both the cuttings and wireline logs identify limestone. The Helderberg is slightly argillaceous and the Bass Island contains minor anhydrite and minor to abundant amounts of chert near its base. Otherwise the two units are nearly indistinguishable with regard to color and texture. A short-lived 76 unit gas show was sourced from the Bass Island at 6,300 ft while drilling on air. The exact source of this gas remains unknown. The samples gave no indication of porosity at this point but did herald the first appearance of anhydrite. The density log showed slight but unremarkable porosity of 4% across from an ambiguous photo-electric curve, such that the mineralogy can only be inferred as a limestone-anhydrite interface.

Salina. The Salina (6,369 to 7,391 ft) represents over a thousand feet of interbedded dolomite, anhydrite, and salt. The wellbore became damp upon reaching the top of the Salina and a change to fluid drilling was made at that point. The actual salt amounts to 177 ft net thickness over a 574 ft thick gross interval. Most of the salt is contained in beds more that 20 ft thick. Dissolution of the salt was minimized by the use of a salt-saturated drilling fluid. The upper portions of the salt, those that sustained the longest exposure to the fluid, were the most out of gauge. This salt is commercially mined with solution wells at several points along the Ohio River, south of the R.E. Burger site.

The dolomite and anhydrite portion of the Salina presents a relentless succession of thinly interbedded lithologies. The anhydrite is seen in the samples as white to light gray, and dense. The dolomite appeared in a spectrum of light to dark grays and browns, and was noted to be predominantly micro- to very finely crystalline, but near the top of the unit a few rock fragments were finely sucrosic. It is probable that the actual lithology of the Salina is more complex than a simple anhydrite and dolomite mix, and likely contains a host of associated evaporate accessory minerals, such a polyhalite, that would considerably cloud estimations of rock type and porosity.

The carbonates contained within the gross salt section produced a series of strong gas shows of up to 445 units despite the heavy (10.2 lb/gal) drilling fluid. Due to the intimate association of the anhydrite and dolomite, and because the photo-electric log in this instance is not indicative of a discrete mineralogy, a precise description of the gas source is problematic. More or less common to the wireline log at points that correspond to gas shows is a density of approximately 2.65 g/cc, a neutron porosity of about 18%, and a photo-electric factor of about 3.5, all of which may suggest an impure dolomite with about 14% porosity.

Figure 4-1 shows sequence stratigraphy interpretation of the Salina interval. As shown, the well logs suggest a moderately restrictive marine environment with some high frequency cycles and no large packages. The middle interval suggests a maximum flooding zone representing the deepest and freshest marine environment. The lower section suggests a gradual rise in sea level creating aggradational dolomites and moderate porosity.

Lockport. The Lockport, or drillers' Newburg (7,391 to 7,736 ft), is composed of alternating beds of limestone and dolomite, beginning as medium to dark gray-brown at the top and becoming lighter toward the bottom. Textures are micro- to medium crystalline throughout. The limestone portion of the section in particular becomes argillaceous near the bottom and includes some red and green marls. A 350 unit gas show at 7,476 ft correlated to a 2 ft thin silty zone that crossplots at 8% porosity. A 190 unit show occurred at 7,565 ft but no definitive lithology could be found, nor were there any demonstrative indicators on the wireline log.

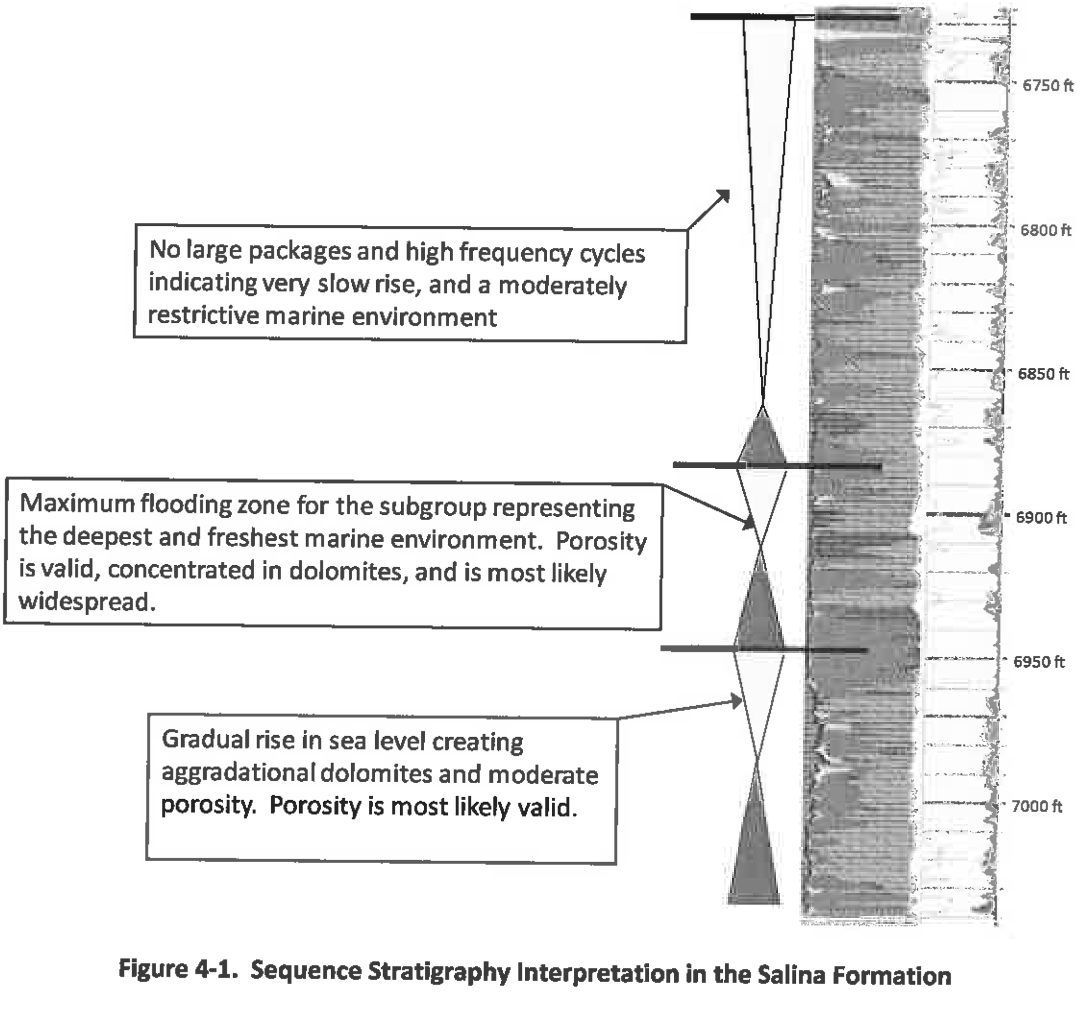


Figure 4-1. Sequence Stratigraphy Interpretation in the Salina Formation

Niagaran Shale. The Niagaran shale (7,736 to 8,086 ft) is considered a confining layer that consists primarily of light to medium gray, calcareous shales. The Niagaran transitions into the underlying Brassfield dolomite (8,086 to 8,118 ft) over a distance of about 30 ft, becoming increasingly calcareous at its base and includes shades of red and green. Minor amounts of chert are included at the interface between the units. The Brassfield is a mottled gray and white, micro- to coarsely crystalline dolomite, gradational with the overlying Niagaran, and has distinctive calcareous oolitic hematite at its base.

Clinton/Medina Sandstone. The Clinton/Medina sandstone is a 200 ft thick package composed predominantly at this site of siltstone and sandstone encased in shale. The term "Clinton" is typically used by local drillers, whereas the Medina is a more formal term referring to the group of rock formations at the base of the Silurian system. The Clinton is commonly divided into an upper red unit and a lower white unit. The so-called Red Clinton is poorly developed in southeastern Ohio and consists primarily of iron-stained siltstone. At the R.E. Burger site, the siltstone is unusually massive, containing very little shale. The red unit is dense and without workable reservoir quality. At this site, the White Clinton is unusually well developed with regard to thickness, showing 45 net-feet greater than 5% in a 67 ft gross interval. Maximum porosity, however, is severely constrained, and only 5 ft has porosity in excess of 6%. Although the White Clinton's thickness somewhat offsets the low porosity, porosity less than 6% is typically accompanied by very reduced permeability. Lithologically, the white unit is composed of a well cemented, well sorted, very fine-grained quartz sand. Small gas shows to 155 units were recorded across from the White Clinton, which elsewhere throughout eastern Ohio is commonly found to be gas-charged.

Queenston Shale. The FEGENCO #1 achieved a total driller's depth of 8,384 ft in the Queenston shale, a distinctive silty red shale beneath the Clinton that should be considered as a confining layer. Only 83 ft of the Queenston was penetrated in the test well, but this formation is probably over 1,000 ft thick based on other regional geologic data.

4.2 Rock Core Testing

A total of 48 rotary sidewall rock cores were collected in the test well. Rotary sidewall cores are small diameter (1 inch diameter by 2 inch long) core plugs that are collected with a wireline tool from the side of the borehole. Core points were identified from key injection targets and caprocks based on wireline logs. In the first coring run, a total of 25 cores were collected to a total depth of 6,500 ft in February 2007. An obstruction in the borehole prevented the next deeper core run. In January 2008, the borehole was cleaned out, and an additional 23 sidewall cores were collected from the remaining 6,515 to 8,332 ft. Figure 4-2 shows the core points in relation to lithology in the test well. Sidewall cores were taken at regular intervals in the caprocks. More cores were selected from key storage intervals.

Core samples were tested for porosity, permeability, and density with standard procedures (note that final core test results from the second core run were not received until April 2008). Table 4-2 lists rock core results. The laboratory core analyses are provided in Appendix D. Many of the cores were listed as damaged or too short for testing, and these results may be unreliable. Results generally showed porosity less than 5% and permeability less than 1 mD for most of the cores. Sidewall cores from the Salina interval had porosity of 5 to 13%, with some indications of permeability more than 1 mD. Core test results from the Clinton and Oriskany Formations were difficult to interpret because many of these samples were unsuitable for testing. However, results suggest porosity less than 5% and permeability less than 0.1 mD.

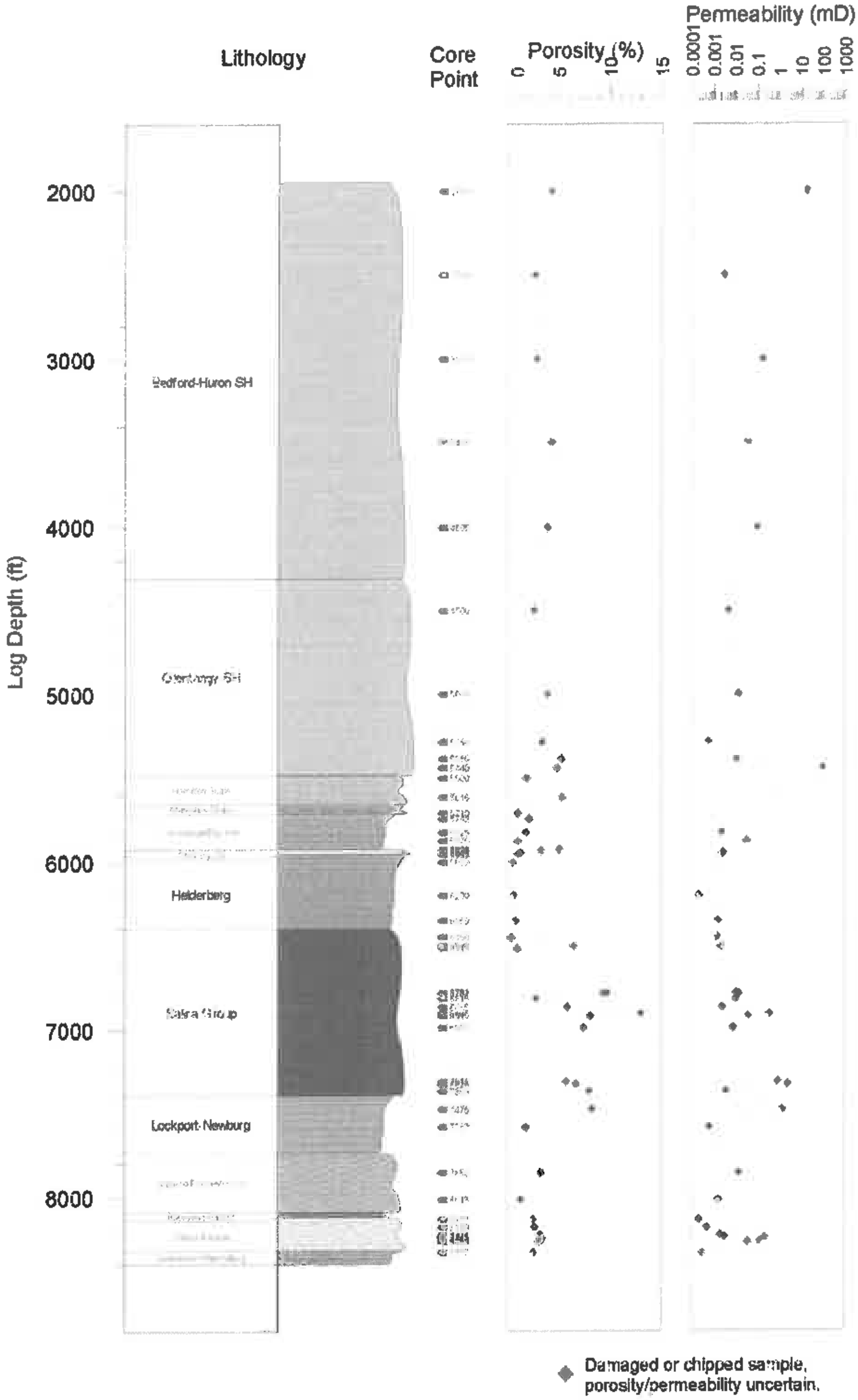


Figure 4-2. Sidewall Core Locations and Rock Testing Results

Table 4-2. Rotary Sidewall Core Test Results from FEGENCO #1 Test Well

CL Sample Number	Depth (ft)	Net Confining Stress (psig)	Porosity (%)	Permeability Klinkenberg (mD)	Permeability Kair (mD)	Beta ft(-1)	Alpha (microns)	Grain Density (g/cm3)	Footnote
Rotary Run No. 1									
14-2	2000	1200	4.29	17.8	28.0	8.24E+09	4.77E+02	2.778	(1)
13-2	2500	1200	2.71	.003	.007	6.39E+14	7.87E+03	2.759	(1)
12-2	3000	1200	2.87	.171	.248	8.95E+11	5.16E+02	2.782	(1)
11-2	3495	1200	4.30	.037	.040	4.55E+12	5.74E+02	2.784	(1)
10-2	4005	1200	3.91	.099	.107	1.36E+12	4.38E+02	2.798	(1)
9-2	4500	1200	2.63	.005	.006	7.24E+13	1.23E+03	3.064	(1)
8-2	5000	1200	3.97	.013	.017	7.19E+12	3.05E+02	2.787	(1)
7-2	5286	1200	3.45	.001	.002	1.72E+16	3.79E+04	2.650	
6-2	5386	1200	5.30	.012	.015	3.82E+13	1.45E+03	2.760	
5-2	5440	1200	4.91	103	106	1.98E+09	6.60E+02	2.783	(1)
4-2	5500	1200	1.89	Below instrument limits.				2.597	(2)
3-2	5616	Ambient	5.35			NA	NA	2.498	(5)
2-2	5710	1200	1.03	Below instrument limits.				2.706	(2)
1-2	5742	Ambient	2.12			NA	NA	2.660	(5)
12-1	5825	1200	1.82	.002	.005	9.17E+14	9.35E+03	2.680	
11-1	5875	1200	1.03	.033	.037	2.62E+13	2.85E+03	2.620	(1), (3)
10-1	5926	Ambient	5.07			NA	NA	2.658	(5)
9-1	5935	Ambient	3.31			NA	NA	2.659	(5)
8-1	5945	1200	1.31	.003	.007	1.01E+15	9.77E+03	2.658	
7-1	5955	1200	1.05	.002	.006	1.64E+15	1.23E+04	2.667	
6-1	6000	Ambient	0.54			NA	NA	2.709	(5)
5-1	6200	1200	0.64	.0002	.001	1.38E+17	1.01E+05	2.707	
4-1	6350	1200	0.85	.002	.004	3.31E+15	1.71E+04	2.718	
3-1	6450	1200	0.43	.002	.004	3.36E+15	1.73E+04	2.903	(1)
2-1	6500	1200	6.54	.002	.005	1.47E+15	1.17E+04	2.842	
Rotary Run No. 2									
24	6515	1200	1.00	Below instrument limits.				2.720	(2)
23	6782	1200	9.82	.011	.017	1.01E+13	3.50E+02	2.822	
22	6784	1200	9.43	.014	.023	9.49E+12	4.23E+02	2.876	
21	6815	1200	2.85	.010	.021	1.07E+14	3.48E+03	2.896	
20	6865	1200	5.91	.003	.006	1.57E+15	1.30E+04	2.835	
19	6905	1200	13.12	.370	.513	2.77E+10	3.24E+01	2.838	
18	6919	1200	8.18	.037	.045	1.25E+12	1.44E+02	2.830	
17	6988	1200	7.53	.008	.010	8.41E+12	2.05E+02	2.792	
16	7311	1200	5.82	.884	.973	1.51E+11	4.24E+02	2.832	(1)
15	7326	1200	6.71	2.45	2.60	7.89E+10	6.17E+02	2.814	(1)
14	7369	1200	8.08	.004	.009	6.68E+14	8.52E+03	2.833	
13	7476	1200	8.35	1.38	1.50	8.32E+10	3.68E+02	2.839	
12	7582	1200	1.85	.001	.002	1.56E+16	3.59E+04	2.730	
11	7856	1200	3.30	.015	.030	4.85E+13	2.32E+03	2.824	
10	8013	1200	1.37	.002	.004	2.85E+15	1.61E+04	2.897	
9	8133	1200	2.57	.0002	.001	1.46E+17	1.03E+05	2.733	
8	8180	1200	2.71	.001	.001	2.47E+16	4.45E+04	2.682	
7	8224	1200	3.25	.002	.005	2.08E+15	1.38E+04	2.646	
6	8235	1200	3.21	.003	.007	9.22E+14	9.36E+03	2.647	
5	8245	1200	3.39	.215	.269	1.20E+11	8.38E+01	2.670	(1)
3	8260	1200	3.32	.128	.150	8.53E+11	3.46E+02	2.763	(1)
2	8269	1200	3.05	.036	.041	3.64E+12	4.13E+02	2.754	(1)
1	8332	1200	2.58	.0003	.001	8.20E+16	7.84E+04	2.729	

Footnotes :

(1) Denotes fractured or chipped sample. Permeability and/or porosity may be optimistic.

(2) Sample permeability below the measurement range of CMS-300 equipment at indicated net confining stress (NCS). Data unavailable.

(3) Denotes very short sample, porosity may be optimistic due to lack of conformation of boot material to plug surface.

(4) Sample contains bitumen or other solid hydrocarbon residue.

(5) Denotes sample unsuitable for measurement at stress. Porosity determined using Archimedes bulk volume at ambient conditions.

Sample unsuitable for permeability measurement.

4.3 Petrographic Analysis

Selected cores were also analyzed for mineralogy with petrographic analysis methods. Thin sections were obtained from 14 samples in key injection targets and caprocks. The objectives of the study were to determine texture, mineralogy, pore-filling constituents, pore types, and diagenetic features. A list of samples analyzed is presented in Table 4-3. Complete descriptions and photographs of the core samples are provided in Appendix D. A description of samples is provided as follows.

Table 4-3. Summary of Petrographic Analysis

SAMPLE ID	DEPTH (FEET)	FORMATION	LITHOLOGY
Burger_14_2000	2000.0	Chagrin U & M Huron shale	Silty Claystone
Burger_12_3000	3000.0	L. Huron shale	Silty Claystone
Burger_5_5440	5440.0	U. Olentangy shale	Silty Claystone
Burger_4_5500	5500.0	Hamilton shale	Silty Claystone
Burger_2_5710	5710.0	Onondaga limestone	Limestone (packstone)
Burger_8_5945	5945.0	Oriskany sandstone	Sandstone
Burger_5_6200	6200.0	Helderberg limestone	Limestone (grainstone)
Burger_2_6500	6500.0	Salina anhydrite/salt/dolomite	Dolostone
Burger_23_6782	6782.0	Salina anhydrite/salt/dolomite	Dolostone (dolomitized silty claystone)
Burger_20_6865	6865.0	Salina anhydrite/salt/dolomite	Dolostone (dolomitized claystone)
Burger_19_6905	6905.0	Salina anhydrite/salt/dolomite	Dolostone (dolomitized grainstone)
Burger_13_7476	7476.0	Lockport dolomite/limestone	Dolostone (dolomitized wackestone)
Burger_9_8133	8133.0	Red Clinton siltstone	Argillaceous siltstone
Burger_6_8235	8235.0	White Clinton sandstone	Sandstone

Chagrin-Huron Shale (2,000 ft). This sample is a silty claystone. Silt-rich burrows are locally present (Figure 4-3). Detrital clay matrix (mainly illitic clay) is the predominant constituent. Silt-sized grains are mostly quartz and feldspars; mica grains are minor to moderate in abundance. Minor amounts of authigenic pyrite are scattered throughout. Macropores are absent; micropores associated with the clay matrix are the principal pore type.

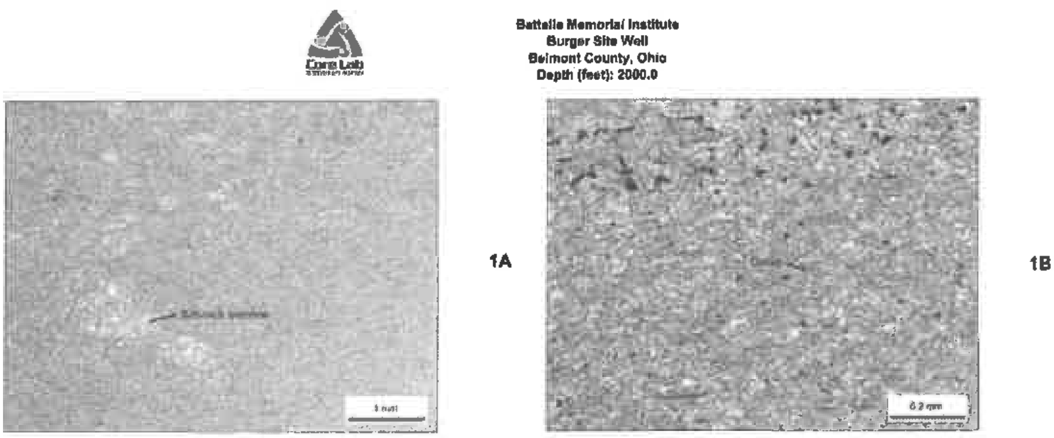


Figure 4-3. Chagrin-Huron Shale Lower Huron Shale (3,000 ft).

This silty claystone consists of alternating silt-rich laminae/burrows and clay-rich laminae/burrows (Figure 4-4). Quartz, mica and feldspars are the most common grains; detrital clay matrix fills intergranular areas; minor amounts of authigenic pyrite are dispersed throughout. Visible pores are absent; micropores are the major pore type and associated with the detrital clay matrix. Open fractures are probably artificially induced.

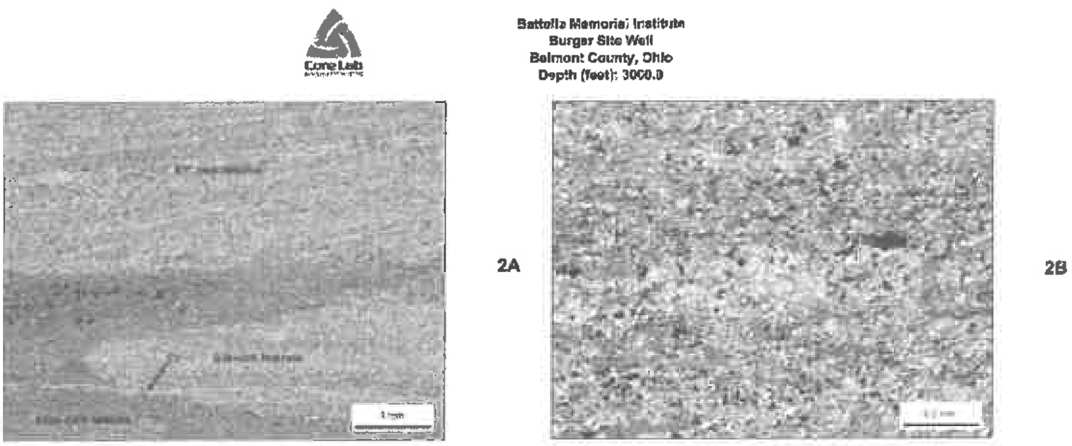


Figure 4-4. Lower Huron Shale

Upper Olentangy Shale (5,440 ft). This silty claystone contains minor amounts of silt-rich laminae (Figure 4-5). Note that organic stringers are locally present and partly replaced by pyrite. Detrital clay matrix is the predominant constituent, followed by quartz, feldspars and mica grains. Iron-dolomite (stained blue) is relatively common in the silt-rich laminae. Macropores are absent; micropores are associated with the clay matrix.

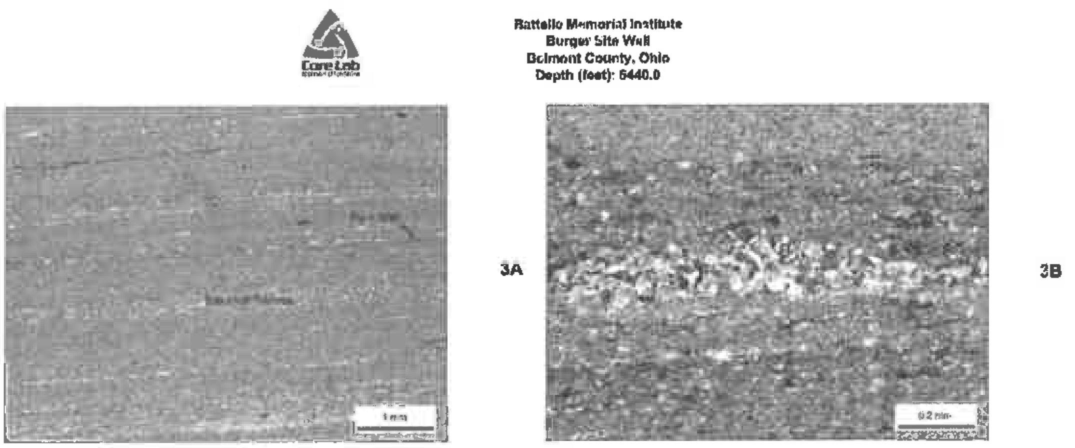


Figure 4-5. Upper Olentangy Shale

Hamilton Shale (5,500 ft). This silty claystone is organic-rich, as indicated by the relatively dark color of some clay-rich laminae (Figure 4-6). Minor amounts of silt-rich laminae are also present in this sample. Authigenic pyrite is locally common and probably replaces organic matter (plant fragments). Detrital clay matrix consists mostly of illitic clays; silt-sized detrital grains are largely quartz and feldspars. Visible pores are absent; micropores are the major pore type and associated with the detrital clay matrix.

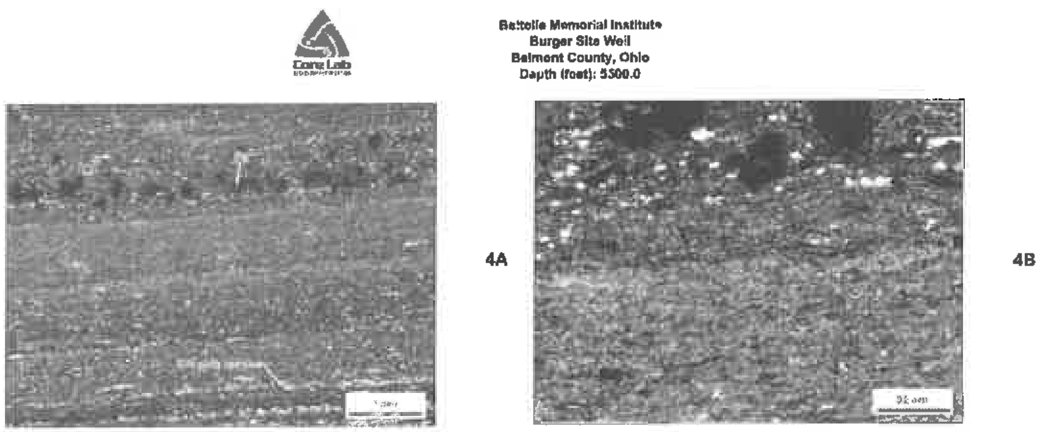


Figure 4-6. Hamilton Shale

Onondaga Limestone (5,710 ft). This limestone sample is a packstone; fossil fragments are the most common allochem grains and consist mostly of mollusks and echinoderms (Figure 4-7). Interparticle areas are filled with micrite matrix, which is locally replaced by dolomite crystals. Intraskeletal pores have been occluded by iron-calcite cement. Authigenic pyrite is a trace component. No pores are visible; micropores associated with the micrite matrix are the principal pore type. Stylolites are also observed in this packstone.

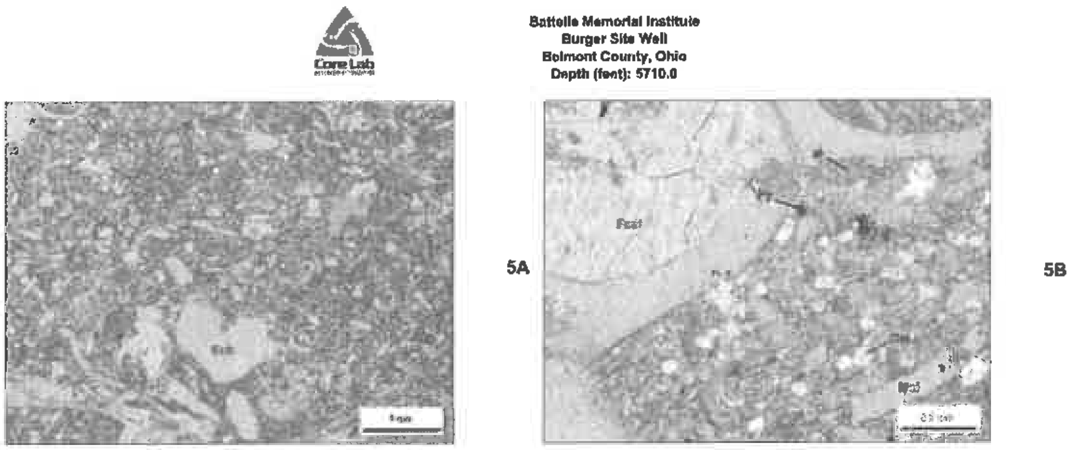


Figure 4-7. Onondaga Limestone

Oriskany Sandstone (5,945 ft). White grains are mostly quartz and feldspars; fossil fragments are minor to moderate and stained red (Figure 4-8). Framework grains are subrounded to rounded and well sorted. Intergranular areas are occluded by quartz overgrowths and minor amounts of iron-calcite (stained bluish purple). Open intergranular pores are very rare; micropores are trace to minor in this fine-grained sandstone. Stylolites are common, crosscutting quartz overgrowths and iron-calcite cements.

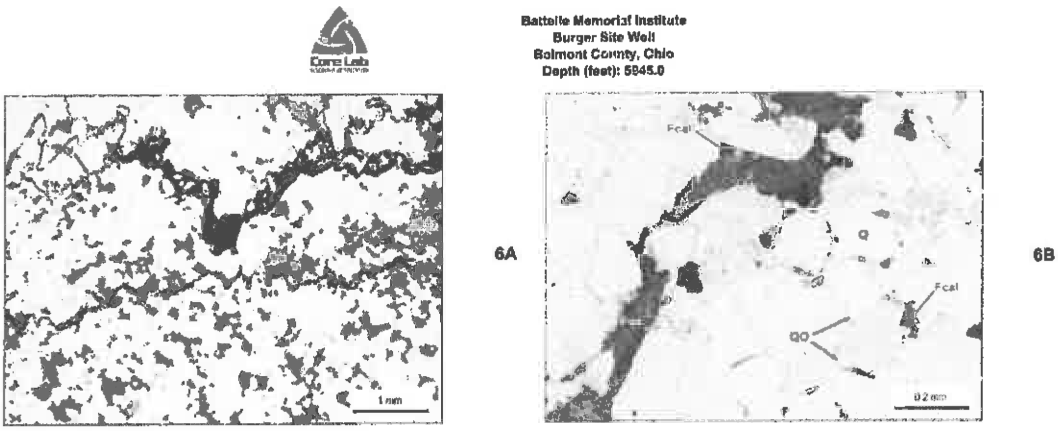


Figure 4-8. Oriskany Sandstone

Helderberg Limestone (6,200 ft). This limestone sample is a grainstone; fossil fragments are the principal allochem grains and consist mostly of mollusks and echinoderms (Figure 4-9). Minor amounts of detrital quartz grains are scattered. Interparticle areas are occluded with calcite cement. No pores are visible; micropores are estimated to be minor in abundance. Stylolites are present in this grainstone; quartz grains and other insolubles are relatively common along the stylolites.

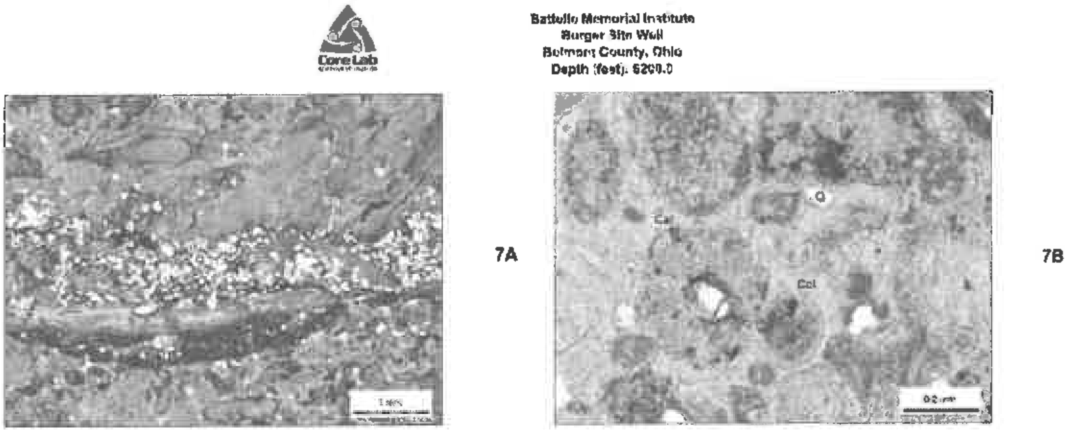


Figure 4-9. Helderberg Limestone

Salina Anhydrite/Dolomite (6,500 ft). This dolostone contains minor to moderate amounts of intercrystalline pores, which make up the principal pore system (Figure 4-10). Dolomite is the predominant mineral in this sample and shows a finely crystalline texture. Authigenic pyrite is a trace component. Dolomitization is overall fabric-destructive and the original rock type is difficult to determine.

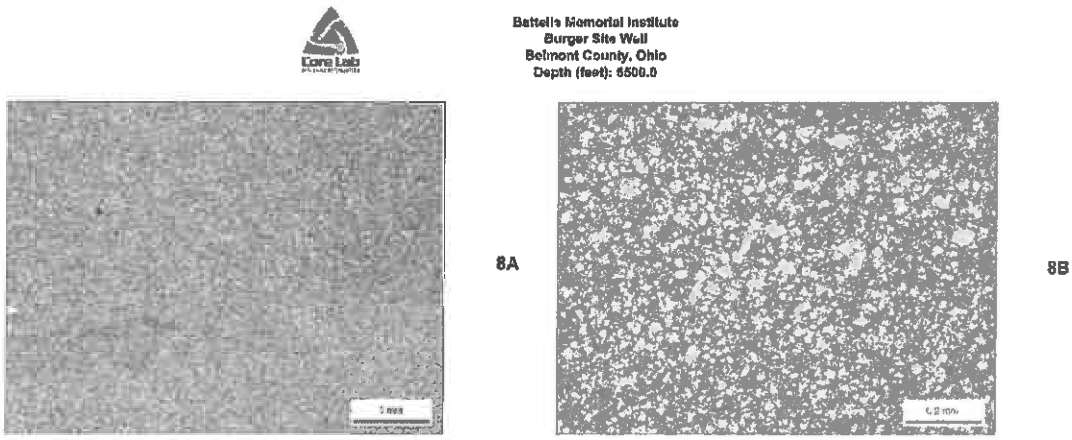


Figure 4-10. Salina Anhydrite/Dolomite (6,500 ft)

Salina Anhydrite/Dolomite (6,782 ft). Dolomite is the dominant mineral in this sample; minor amounts of detrital quartz grains are still present (Figure 4-11). The original rock was probably a silty claystone composed of silt-rich and clay-rich laminae, which have been extensively replaced by dolomite. Trace amounts of barite are present, replacing dolomite. Visible pores are minor in abundance and mainly associated with the dolomitized silt-rich laminae. Micropores among the dolomite crystals are the principal pore type in this sample.

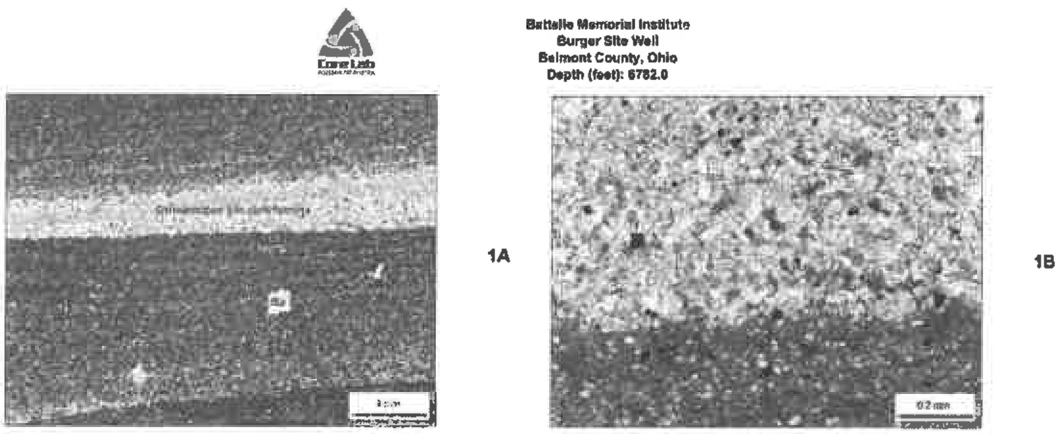


Figure 4-11. Salina Anhydrite/Dolomite (6782 ft)

Salina Anhydrite/Dolomite (6,865 ft). This sample is a dolostone; it appears that the original rock was a laminated claystone, which has been thoroughly replaced by dolomite (Figure 4-12). Dolomite crystals are finely crystalline and exhibit an interlocking texture. Visible pores (blue) are very rare; micropores among the dolomite crystals make up the principal pore system in this sample.

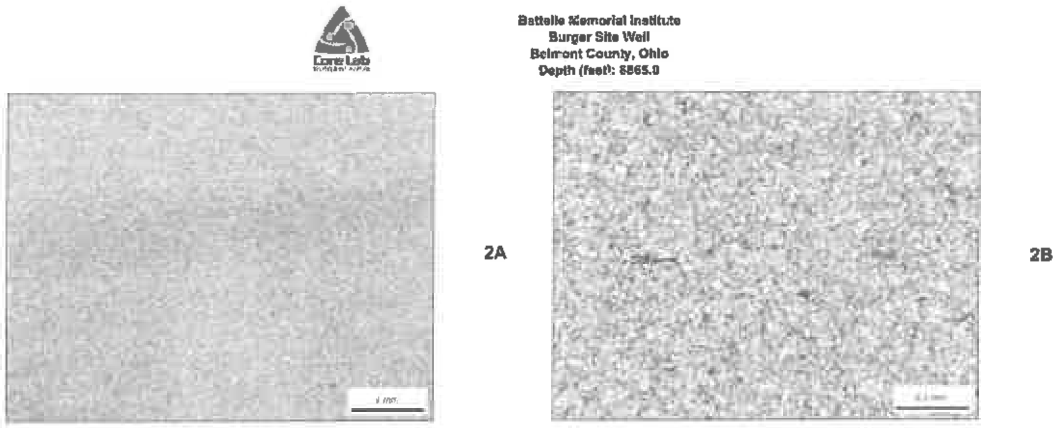


Figure 4-12. Salina Anhydrite/Dolomite (6,865 ft)

Salina Anhydrite/Dolomite (6,905 ft). Visible pores are moderate to common in this dolostone and consist of interparticle and intercrystalline pores (Figure 4-13). The original rock was a lime grainstone; peloids are the most common allochem grains, which have been completely dolomitized. Fractures are locally present and have been filled with clear dolomite crystals. Note that dolomite is locally replaced by barite.

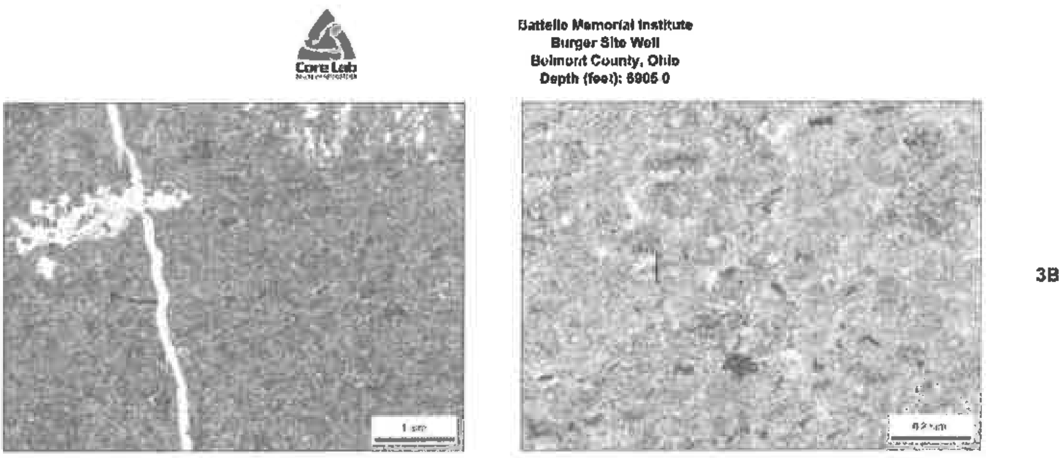


Figure 4-13. Salina Anhydrite/Dolomite (6,905 ft)

Lockport Dolomite (7,476 ft). Visible pores (blue) are moderate to common in this dolostone and consist of interparticle and intercrystalline pores (Figure 4-14). The original rock was a lime grainstone; peloids are the most common allochem grains, which have been completely dolomitized. Fractures are locally present and have been filled with clear dolomite crystals. Note that dolomite is locally replaced by barite.

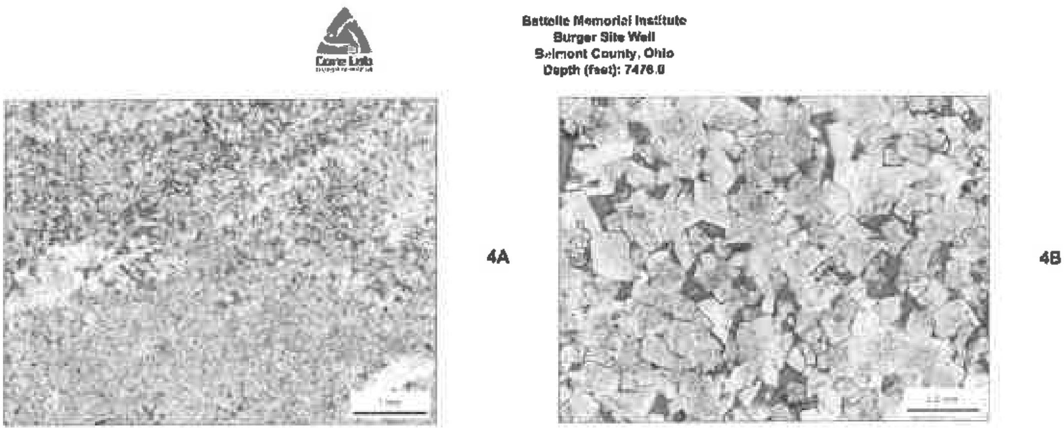


Figure 4-14. Lockport Dolomite

Red Clinton Siltstone (8,133 ft). This sample is an argillaceous siltstone and is locally burrowed (Figure 4-15). The most common framework grains are quartz, K-feldspar (stained yellow) and plagioclase; these silt sized grains are subangular in shape and moderately sorted. Intergranular areas are occluded by detrital clay matrix, which contains minor amounts of highly dispersed hematite. No pores are visible; micropores associated with the detrital matrix are the principal pore type.

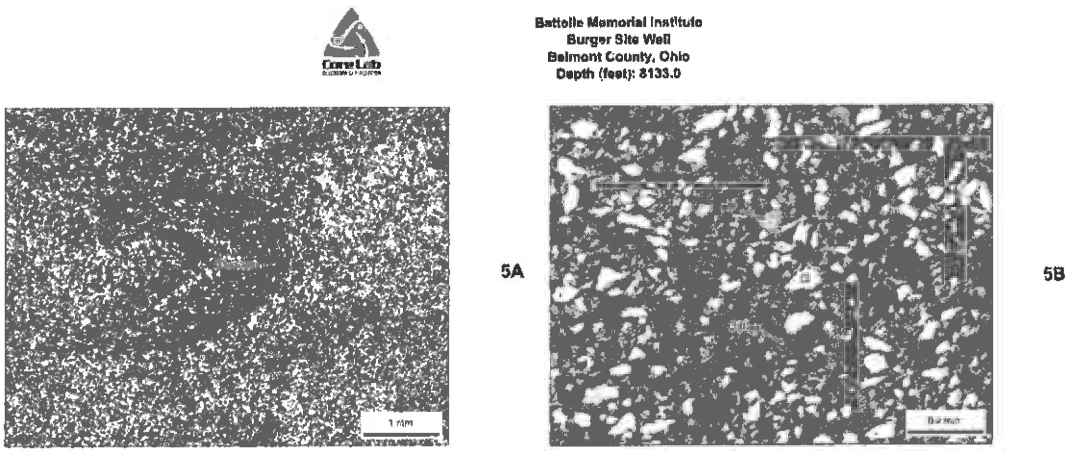


Figure 4-15. Red Clinton Sandstone

White Clinton Sandstone (8, 235 ft). Quartz is the predominant framework constituent in this fine-grained sandstone; feldspars and lithic fragments (dark grains) are much less common (Figure 4-16). Framework grains are subrounded to rounded and well sorted. Intergranular areas are largely occluded by abundant quartz overgrowths and trace amounts of iron-calcite. Intergranular and moldic pores are minor in abundance; micropores are probably minor and mainly associated with lithic fragments. Moldic pores are derived from the dissolution of feldspar grains and lithic fragments.

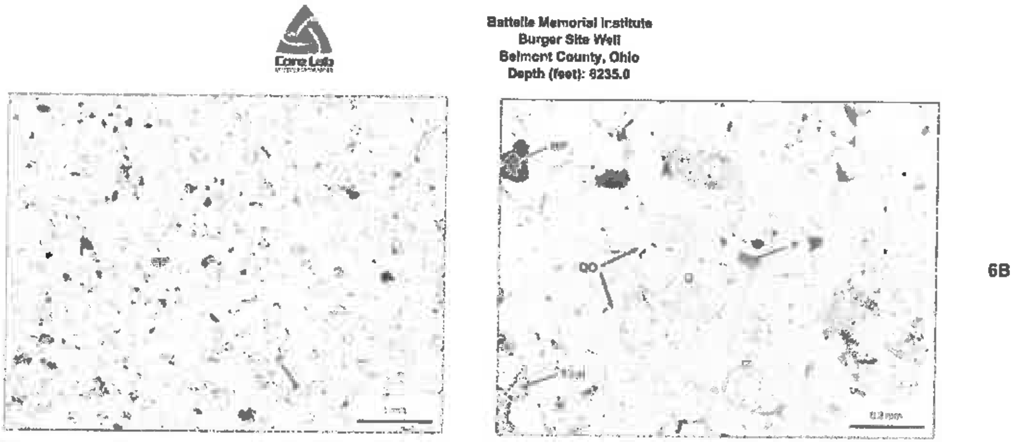


Figure 4-16. White Clinton Sandstone

4.4 Injection Targets and Confining Layers

Based on regional geology, lithology in the test well, wireline logs, rock core testing, and petrographic analysis, three targets were selected for injection testing:

- Oriskany Sandstone
- Middle Salina Carbonate
- Clinton/Medina Sandstone.

The Hamilton Group, which was identified in the preliminary geologic assessment as perhaps the most favorable injection target, was found to have the most significant gas show and was also found unstable during drilling. Therefore, the deep, 7 inch casing was run through this formation and the Marcelus below it to a depth of about 5,752 feet to stabilize the hole and isolate the well from the gas show.

Table 4-4 summarizes geotechnical parameters of the injection targets. As listed, there was some variability in results from wireline compared with rock core tests.

Oriskany Sandstone. The Oriskany sandstone formation is present in most of West Virginia, Pennsylvania, Maryland, and Ohio. MRCSP Phase I mapping suggested that the formation is highly variable in thickness in the study area; however, some wells have encountered Oriskany sandstones with a suitable fraction of pore space to be considered for storage. Phase I MRCSP work suggested that the Oriskany may have capacity to store 2 to 8 gigatonnes of CO_2 in the region. In the test well, the Oriskany was 31 ft thick at a depth of 5,923 to 5,954 ft. The formation consisted of white to tan-light gray, moderately sorted, subrounded sand with occasional calcite. Logs show porosity at 2 to 6% (Figure 4-17).

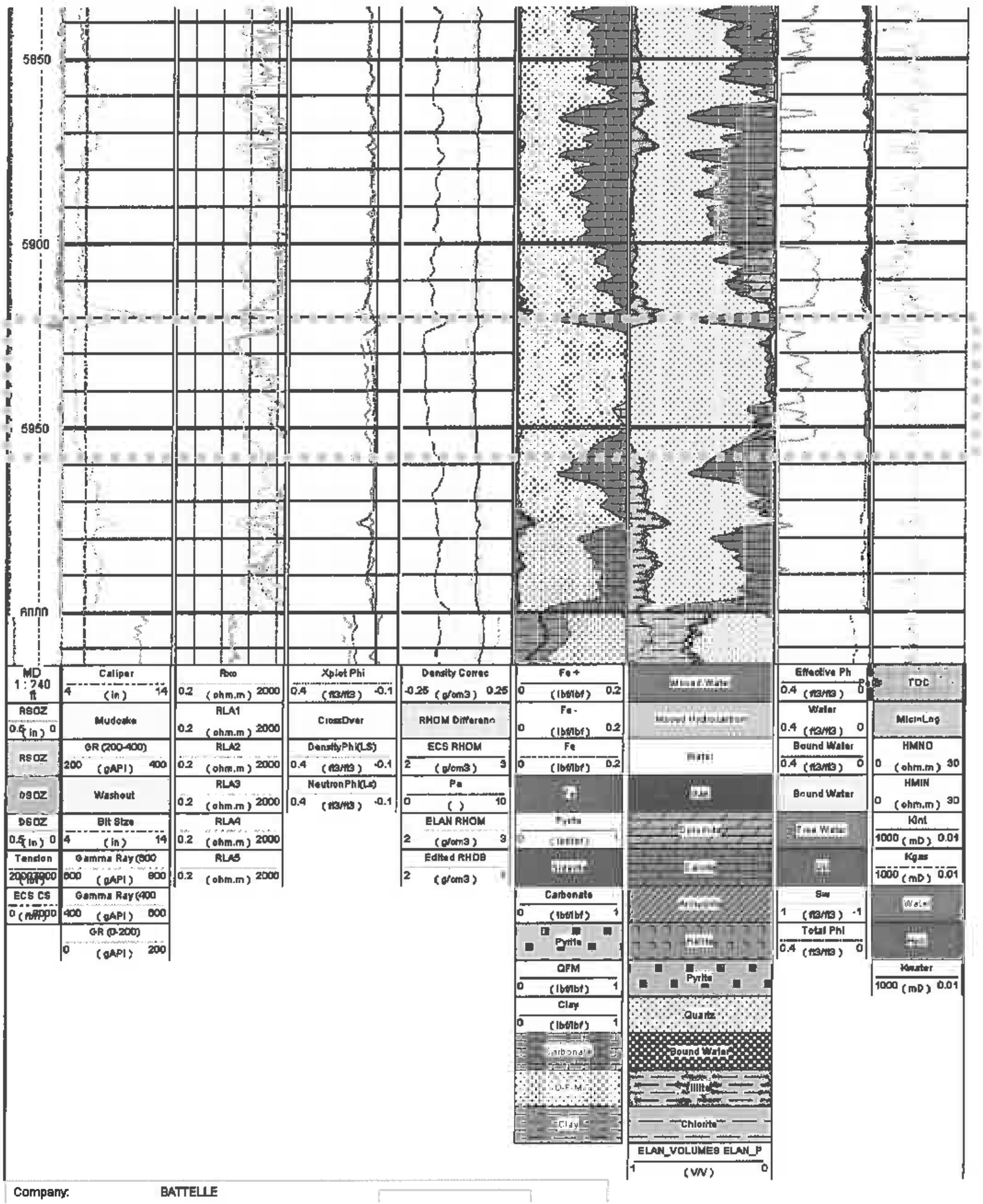


Figure 4-17. Composite Wireline Log from Oriskany Sandstone (Highlighted Area)

Middle Salina Carbonate. The Salina Formation is typically a mixture of evaporites (primarily salt and anydrite) and carbonate rock layers in the Appalachian Basin. Salt layers were several hundred feet thick in the test well at a depth of 6,400 to 7,400 ft. In the middle of this formation, a carbonate unit was identified with shows of permeability and porosity and short-lived gas shows. The formation consisted of a mixture of tan-dark brown, very fine dolomite and salt. Logs show zones of porosity up to 10% (Figure 4-18).

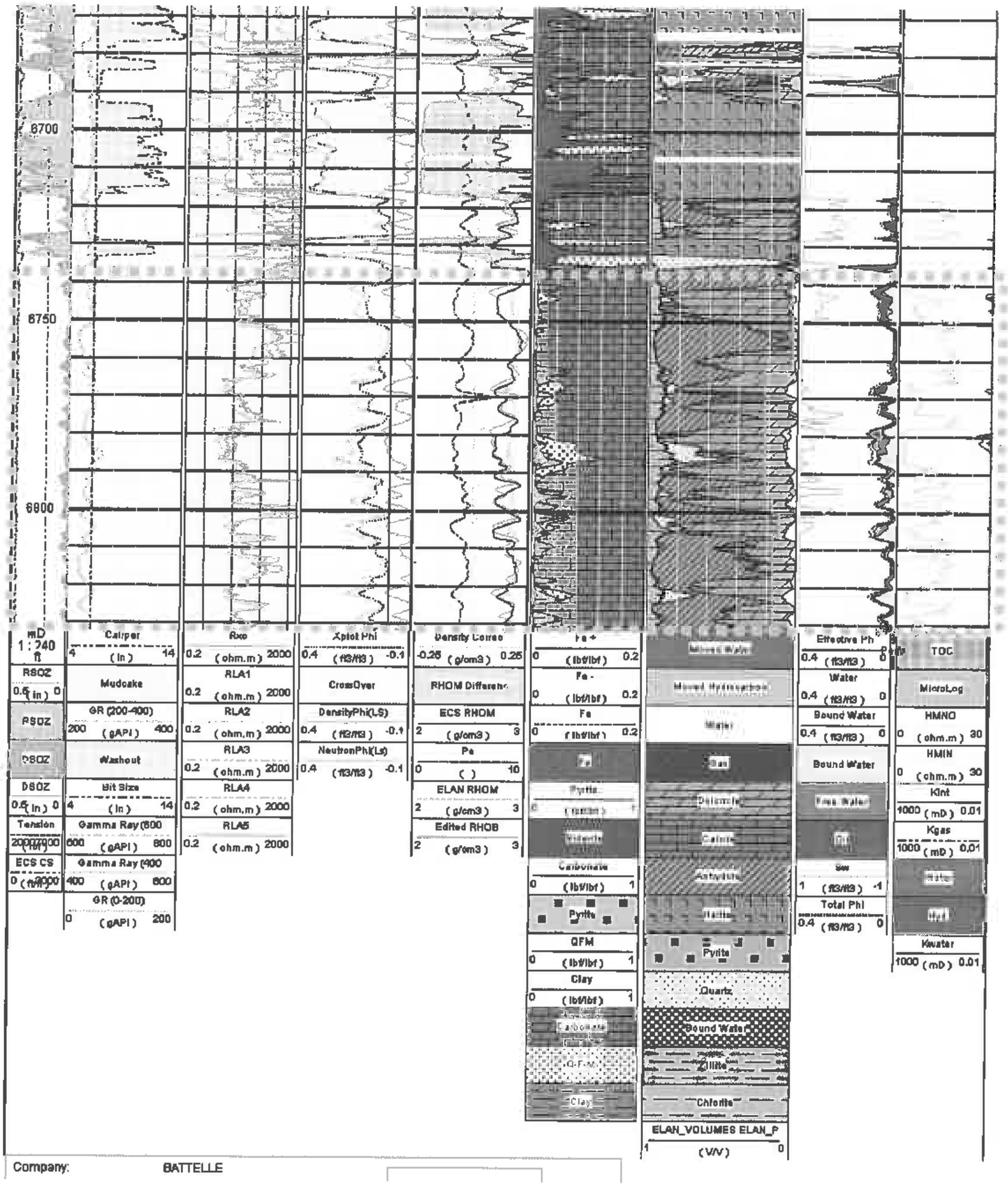


Figure 4-18. Composite Wireline Log from Salina Carbonate Interval (Highlighted Area)

Clinton/Medina Group. The Clinton/Medina Group refers to a series of interbedded sandstones, siltstone, shales, and limestones of Early Silurian age. A large amount of oil and gas have been produced from this group of rocks in central Ohio to northwestern Pennsylvania. Most oil and gas production in the Medina Group is limited to areas east and northeast of the site. This formation was identified as a large target for CO_2 sequestration in Phase I MRCSP research, with estimated capacity of 7 to 29 gigatonnes of CO_2. In the FEGENCO #1 test well, the entire Clinton/Medina was 200 ft in total thickness at a depth of 8,118 to 8,318 ft. However, site characterization data suggested that the lower White Clinton was the most suitable injection target at a depth of 8,207 to 8,274 ft. The formation consisted of white, clean, fine-grained sandstone. Logs showed porosity at 4 to 6% across 67 ft (Figure 4-19).

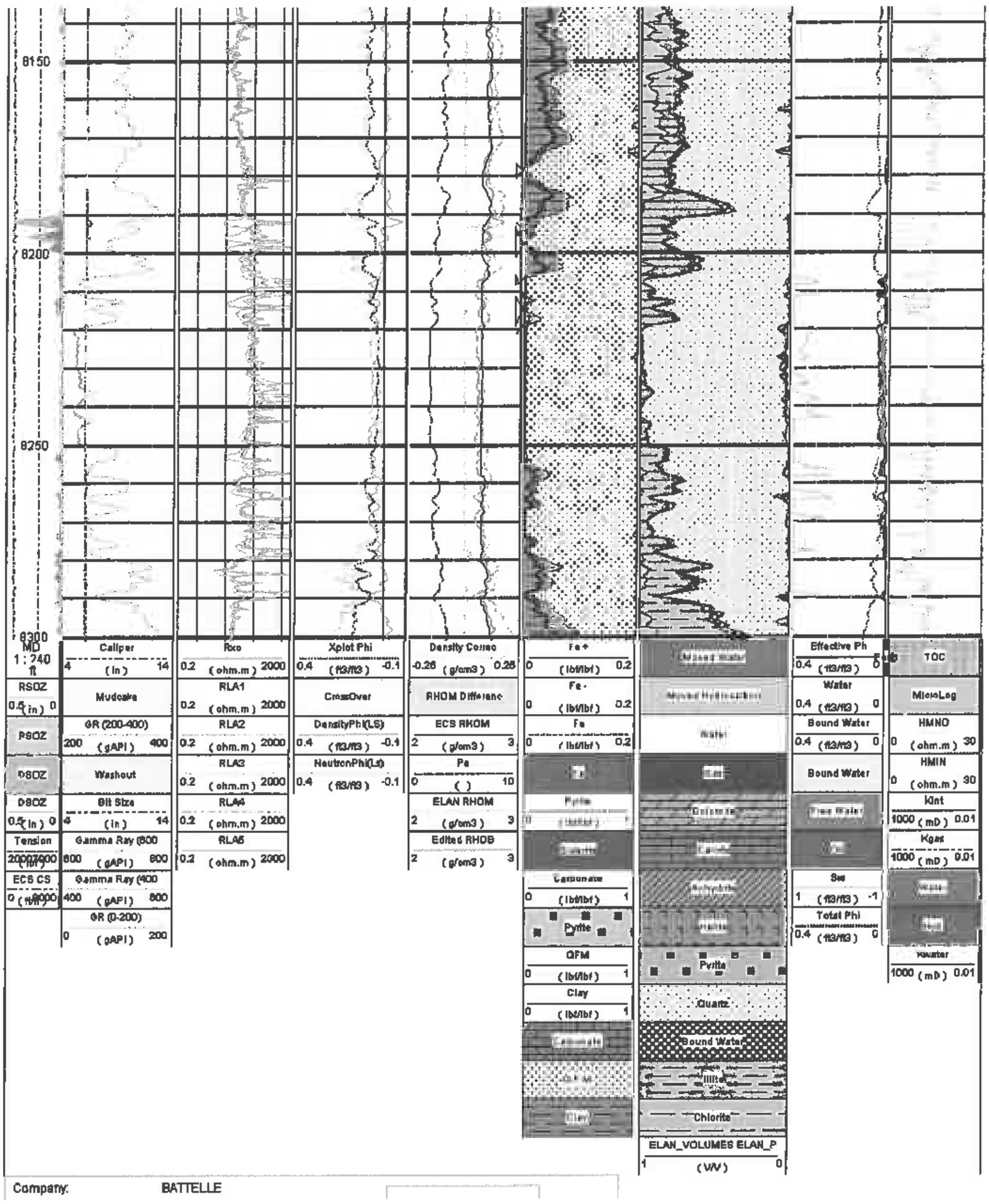


Figure 4-19. Composite Wireline Log from Clinton Formation

Confining Layers. The thick, pervasive presence of multiple confining layers provides considerable containment above the injection targets. The Niagaran Shale and Brassfield/Packer Shell dolomite overlie the Clinton Sandstone. Dense dolomite and salt layers are present above and below the Salina carbonate unit. The immediate confining layer above the Oriskany Sandstone is the Onondaga Limestone, which showed permeability below detection limits in core tests. Devonian shales at depths of 1,850 to 5,800 ft offer several thousand feet of containment above the injection zones. These units are generally dense shales and dolomites with very low porosity values less than 3%.

4.5 Hydraulic Analysis of Reservoir Behavior

Based on the selected injection targets, a general hydraulic analysis was completed to provide an understanding of injection test parameters such as injection rate, pressure buildup, and pressure falloff. This information is important to design the injection test and select proper equipment for the injection. The hydraulic analysis was completed on the three injection targets: Oriskany, Salina, and Clinton. The parameters needed for the analysis were obtained from the well log data and rotary sidewall core testing. Since only limited injection testing is planned for the test, injection scenarios were investigated with relatively simple analytical equations rather than full reservoir models. It should be noted that these equations involve many assumptions and the results are only estimates intended to provide general guidance for designing reservoir tests and determining decision points for the testing. Given the nature of the targeted injection units, it is fairly clear that injection potential is best determined through field testing.

Methods. A modification of the Horner method was used for the hydraulic analysis, which serves in understanding the injection rate pattern that should be followed for injecting CO_2 into the FEGENCO #1 test well. In oil and gas reservoirs, Horner analysis is used to determine if pseudo-radial flow developed during pressure decline after production or injection tests (Horner, 1951; Earlougher, 1977). If a semi-log straight line of pressure versus Horner time is observed and the line can be extrapolated to a reasonable value of reservoir pressure, radial or pseudo-radial flow may be affecting the decline behavior. While Horner analysis is usually used for production analysis, it was modified to account for pressure caused by injection. Basically, the same equation is used as would typically be used for analyzing injection test falloff data to predict injection pressure that may occur during injection. The following Horner transient equation was used to determine the pressure change:

$$\Delta P = \frac{162.6 Q_o \mu_o B_o}{kh} \left[\frac{[\log t_p + \Delta t]}{\Delta t} \right]$$

where

ΔP = pressure change in reservoir (psi)
μ_o = viscosity (cp)
B_o = formation volume factor (RB/STB)
Δt = time after injection stopped (hr)
t_p = total injection time (hr)
h = formation thickness (ft)
Q_o = injection/discharge rate (bpd)
k = permeability (mD).

By inputting a small Δt value, the equation basically predicts the maximum injection pressure after a period of injection. In general, this equation shows that pressure change over time is related to injection rate divided by formation thickness and permeability. As such, these are key input parameters in estimating pressure response to the injection tests. Also, the equation solves for the pressure increase in the reservoir beyond existing reservoir pressures. In situ pressure should be added to the ΔP to estimate bottomhole pressure.

Input Parameters. Hydraulic input parameters were based on wireline and sidewall core test data from the FEGENCO #1 test well. Only limited sidewall test data were and wireline tools do not directly measure permeability, introducing errors into the calculation. Consequently, two sets of calculations were performed. One set is based on estimated wireline permeability input parameters. The other set is based on core test data parameters. Parameters were assumed for viscosity, reservoir barrel/standard barrel ratio, and Δt:

$\mu o = 0.056$ cp
Bo = 1.0 RB/STB

Injection parameters were specified for 24 metric tons of CO_2 per day, which is the minimum rate that may be utilized with the injection equipment, and a 24 hour long injection period:

$t_p = 24$ hr
$Q_o = $ 194 bpd (24 metric tons of CO_2/day)
$\Delta t = 0.017$ hr (1 minute).

Average values for various parameters obtained from wireline logging interpretation are as given in Table 4-4. As shown, wireline logs suggest fairly low permeability in the range typically considered more of a confining layer.

Table 4-4. Summary of Average Parameters for Injection Intervals Based on Wireline Logs

FORMATION	K (MD)	B (FT)
Oriskany	0.005	8.5
Salina	0.008	105
Clinton	0.001	43

Core test analysis was conducted on the rotary sidewall core samples obtained from the three formation intervals. Average parameters are listed in Table 4-5.

Table 4-5. Summary of Average Parameters for Injection Intervals Based on Rock Core Tests

FORMATION	K (MD)	B (FT)
Oriskany	0.003	20
Salina	0.08	100
Clinton	0.08	40

There is a reasonable difference between the values of the log test and the core tests. In general, the rock core tests are more optimistic, but they represent an isolated spot in the coring interval where the rotary sidewall core was taken. Overall, it is reasonable to expect key parameters such as permeability to vary by several orders of magnitude due to natural variability in the rocks.

Results. Based on the wireline logging interpretation data, the Horner analysis predicted high values for pressure buildup for all three formations and that the pressures would exceed regulatory fracture gradients (Table 4-6). These pressure increases are likely the result of the low permeability input parameters.

Table 4-6. Hydraulic Analysis Results Based on Wireline Input Parameters

FORMATION	Q (TPD CO_2)	K (MD)	B (FT)	Q (BPD)	TP (HR)	DELTA P (PSI)
Oriskany	24	0.005	8.5	194	24	130,592
Salina	24	0.008	105	194	24	6,607
Clinton	24	0.001	43	194	24	129,074

Using data obtained from the core analysis, the Salina and Clinton Formations showed lower pressure change estimates (Table 4-7), indicating injection to be more feasible for these two formations than was indicated by the wireline logs. Estimates for the Oriskany Formation suggest that pressure increase would be high, indicating injection would be infeasible, even at the lowest injection rates possible.

Table 4-7. Hydraulic Analysis Results Based on Core Test Input Parameters

FORMATION	Q (TPD CO_2)	K (MD)	B (FT)	Q (BPD)	TP (HR)	DELTA P (PSI)
Oriskany	24	0.003	20	194	24	92,503
Salina	24	0.08	100	194	24	694
Clinton	24	0.08	40	194	24	1,734

Based on these results, the pressure increase caused by higher injection rates and longer injection durations was investigated for the Salina and Clinton Formations. Downhole pressure limits were based on a fracture gradient of 0.75 psi/ft and pressure gradient of 0.48 psi/ft present in the borehole at depth. Figure 4-20 shows the estimated downhole pressure increase for various injection rates and injection durations for the Clinton interval based on core test input parameters. As shown, it appeared that injection rates of 24 metric tons of CO_2 per day may be sustained for up to approximately 4 days without exceeding fracture pressure limits and injection rates up to 40 metric tons per day may be feasible for short time durations.

Figure 4-21 shows the estimated downhole pressure increase for various injection rates and durations for the Salina interval based on core test input parameters. This chart indicates that injection of 24 metric tons per day may be sustained for 10 days or more and injection of 50 metric tons per day may be feasible for 4 days. The analysis further indicated that an injection rate of up to 100 metric tons per day may be possible for short time periods.

The hydraulic analysis provided general guidance for injection testing, but it also highlighted the uncertainty in these injection targets. Overall, the analysis suggested that high injection pressures may be encountered due to the relatively low permeability and thickness indicated by wireline logging and rock core tests in the test well. The best injection potential appeared to be in the Salina and Clinton intervals, whereas the Oriskany appeared to have little potential for injection. Based on these results, a flexible testing plan was developed where it was possible to vary injection rates and to move from one testing zone to another.

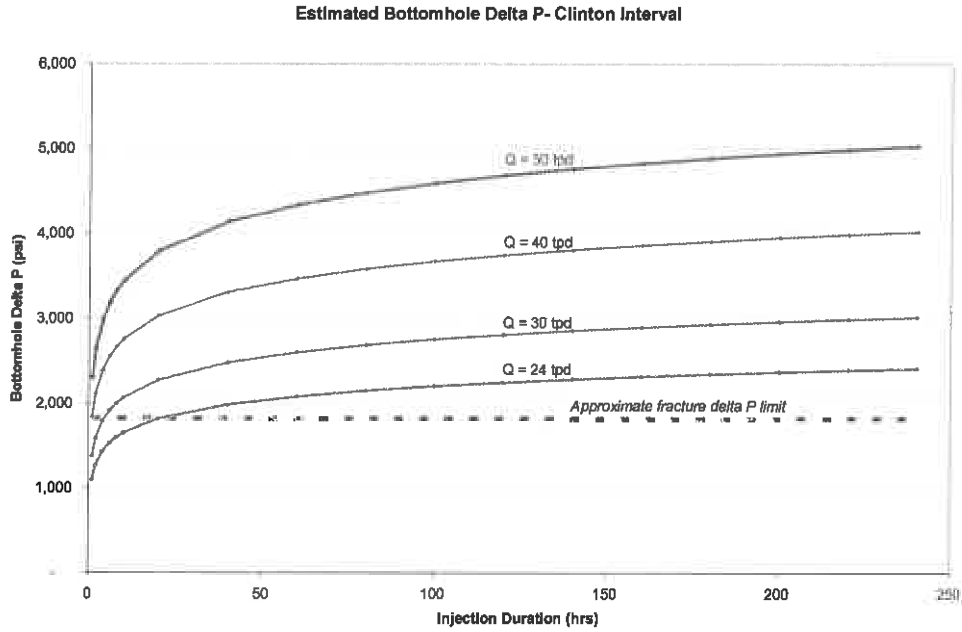


Figure 4-20. Calculated Bottomhole Pressure Increase in Clinton Interval

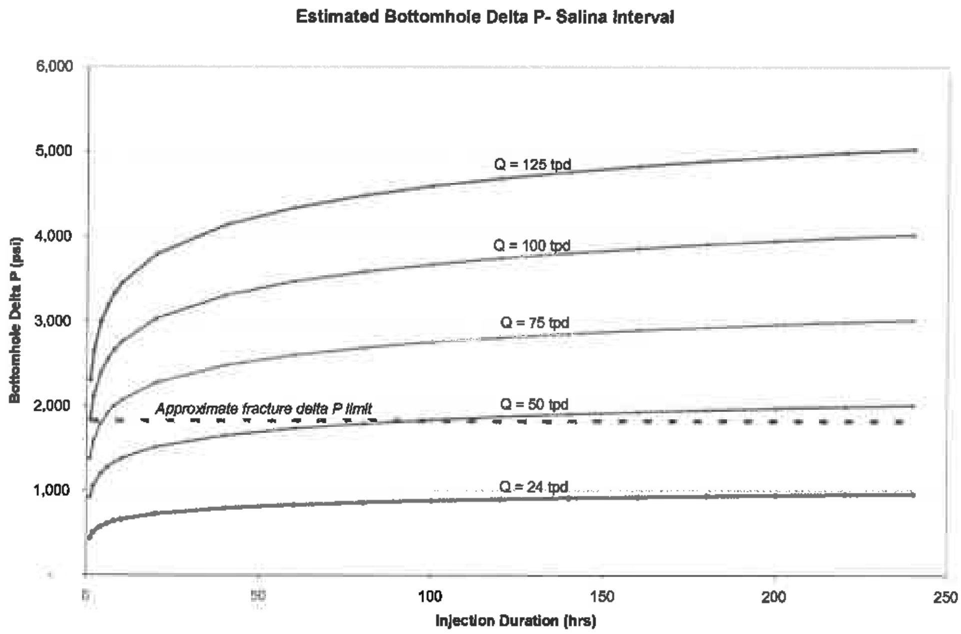


Figure 4-21. Calculated Bottomhole Pressure Increase in Salina Interval

5.0 PERMITTING

The main permits required for the injection tests included the well drilling permit and the Underground Injection Control (UIC) Class V permit, which are included in Appendices C and E, respectively. The ODNR Division of Mineral Resources Management first permitted drilling of the test well and then CO_2 injection was regulated by the Ohio EPA UIC program. Figure 5-1 shows the general permitting sequence completed for the test site. The permit form provided by ODNR required standard information on well location, construction specifications, and site restoration that any oil and gas well would necessitate. Before any field work, several informal meetings were held with Ohio Environmental Protection Agency (EPA) staff to ensure the well would meet UIC requirements. The main design change requested was to cement the well to surface.

Once the well was drilled, a UIC permit application was prepared. The permit was influenced by the U.S. EPA Guidance Using the Class V Experimental Technology Well Classification for Pilot Geologic Sequestration Projects – UIC Program Guidance (UICPG #83) (U.S. EPA, 2007). This document included information on the area of review (Figure 5-2), well construction, injection targets, monitoring, injection fluid, and injection system. Ohio EPA provided a general form for completion of the permit application. Several additional items were requested such as background on deep brine geochemistry in the Appalachian Basin and results of the rotary sidewall core rock samples. This project was seen as a key test of the technology and permitting issues for CO_2 sequestration by Ohio EPA.

Key events in the permitting process included the following items:

- Drilling permit prepared and approved by ODNR Division of Mineral Resources Management in the fall of 2007
- Test well drilled during January-February 2007
- UIC Class V permit application submitted to Ohio EPA UIC program on January 17, 2008
- Draft permit issued on May 23, 2008
- Public hearing held on June 24, 2008
- Public comment period extended from May 23 – July 7, 2008
- Permit to operate effective on September 3, 2008
- Mechanical integrity tests were submitted to Ohio EPA on September 24, 2008, upon which approval was given to proceed with the step-rate test.
- During injection, Ohio EPA was notified of daily activities.
- Monthly reports were submitted to Ohio EPA summarizing maximum injection pressure, annular pressure, injection rates, and total injection volumes.
- After CO_2 injection tests were completed, monthly reports on wellhead pressure conditions were submitted to Ohio EPA.
- In fall 2009, a plugging and abandonment plan was submitted to Ohio EPA. However, FirstEnergy was approached by an oil and gas company to purchase the well for gas production from Devonian shale intervals (these intervals were cased off during drilling

because the formations had high gas pressure and showed instability). As part of the agreement, the well would be cemented across the deeper intervals and transferred from a UIC permit to an oil and gas permit.

- Using the well for gas production was found infeasible in April 2010 due to pipeline siting issues. As a result, the well was closed out beginning April 2010 according to the Ohio EPA approved plugging and abandonment plan.

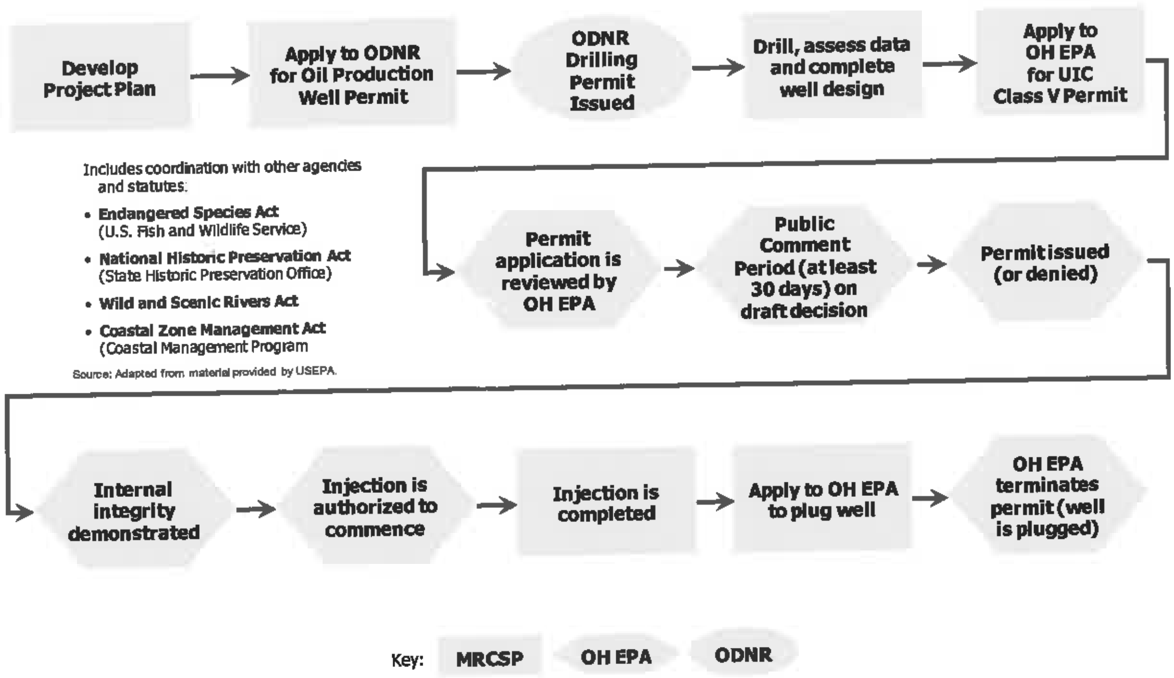


Figure 5-1. Key Steps in Permitting Process for Appalachian Basin R.E. Burger FEGENCO #1 UIC Permit

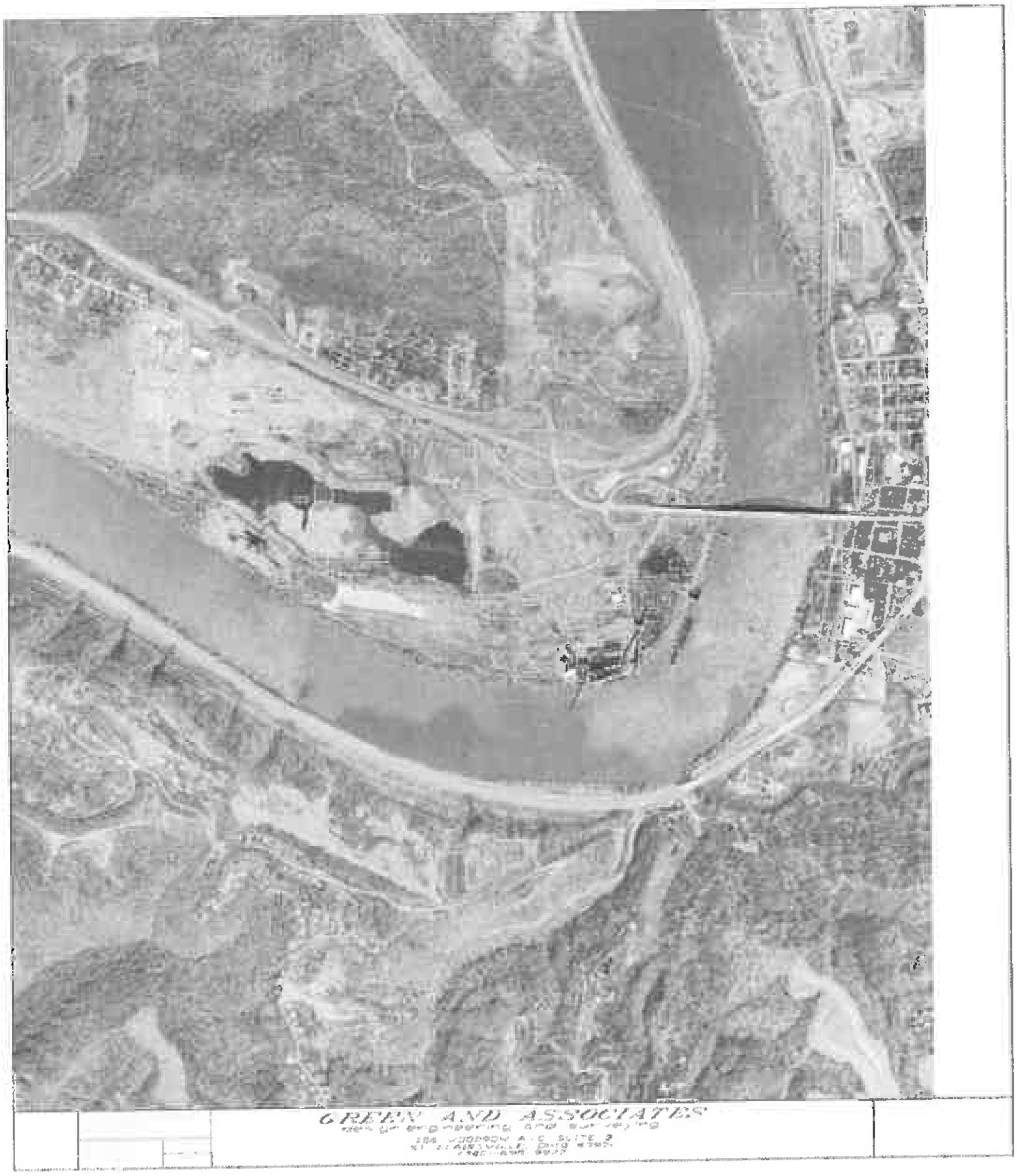


Figure 5-2. Area of Review for Appalachian Basin FEGENCO #1 Permit
(The default ¼-mile area of review was used for the site. UIC regulations also require identification of all drinking water wells within 1-mile of the injection well.)

6.0 CO_2 Supply and Delivery

Initially it was anticipated that a pilot plant for an innovative aqueous ammonia-based capture process being developed by Powerspan would be used as the source of CO_2 for the MRCSP injection test. The Powerspan process, called ECO2, was to be demonstrated at the R.E. Burger site as an adjunct to testing of Powerspan's multipollutant control process called ECO, which was ongoing at the R.E. Burger site prior to the site being selected for the MRCSP injection test. A design study was performed under MRCSP to determine the compressor requirements and system integration and interface requirements to connect the Powerspan pilot plant to the MRCSP injection test. A summary report on that design study is included as Appendix F.

However, as the MRCSP project evolved, the timing of it and the ECO2 demonstration became sufficiently out of synch that, in March 2008, a decision was made by Battelle and FirstEnergy to switch the MRCSP test to the backup option of using commercial liquid source of CO_2. Subsequently, quotes were received and a commercial supplier of CO_2 was selected for the injection test.

Despite not being able to integrate the injection test with the Powerspan capture unit, the test was completed at an active power plant, which offered a chance to test various technologies needed to monitor, verify, and account for the CO_2 storage volume.

6.1 CO_2 Source and Composition

The CO_2 source was provided by Praxair, a commercial supplier of industrial gases. The CO_2 originated from Praxair's Marmet, West Virginia plant, where the CO_2 is the byproduct of purifying locally sourced natural gas. Table 6-1 shows a typical result from the vendor's laboratory analysis of the final product. The CO_2 was liquefied and transported using liquid tanker trucks. The CO_2 purity is designed to serve the "food-grade" markets and certain pharmacological requirements. As such, the CO_2 is adequate for performing a sequestration research injection.

Table 6-1. Typical Laboratory Analysis Composition as Provided by the Vendor

PARAMETER	LABORATORY RESULTS
CO_2	99.99%
Total Hydrocarbons (as methane)	5.4 ppm
Ethane	2.0 ppm
Propane	0.4 ppm
Total Sulfur	<0.025 ppm
Oxygen	0.4 ppm
Nitrogen	1.4 ppm
Non-volatile Residue (NVR = NVOR + Particulates)	1.0 ppm
Non-volatile Organic Residue (NVOR)	0.9 ppm
Moisture	2.3 ppm

6.2 Delivery and Injection System

The tanker trucks from Marmet delivered the liquid CO_2 at approximately -10°F and 250 PSIG to the R.E. Burger injection site. Three 50-ton tanker trailers were set up onsite to provide an interim holding system before injecting into the well (Figure 6-1).

Figure 6-1. CO_2 Injection Setup at the R.E. Burger Power Plant
(Onsite liquid CO_2 storage tanks provided CO_2 to the injection system. These were kept full by regularly scheduled liquid CO_2 deliveries. The injection trailer ["huff-n-puff" machine] provided pumping and heating to deliver the CO_2 at the correct wellhead pressure and temperature for injection. The injection well is behind the injection trailer – with the service rig mast visible on the right hand side of the photo.)

The tanks were connected to a trailer-mounted injection system (i.e., the "huff-n-puff" machine [Figure 6-2]). The main components of the injection system included a triplex pump, a propane fired heater, and a programmable logic controller (PLC). The CO_2 was first pressurized by the triplex pump, and then heated by the gas-fired propane heater. By properly adjusting the pumping and heating rate, the CO_2 delivered to the wellhead could be adjusted to the desired pressure and temperature. The PLC monitored and controlled the entire injection process so that the proper injection set point could be achieved, alarms could be triggered, and the system could be shut down if necessary. The output from the injection trailer could vary between approximately 20 to 100 tons per day depending on the temperature and pressure. The output temperature could vary from unheated to approximately 110°F. This wide range was sufficient for the injection requirements at the R.E. Burger site. Higher injection rates could be supported if the injection trailer CO_2 pump plungers were changed.

In addition to a turbine flow meter on the CO_2 injection trailer, the CO_2 flow rate was monitored with a coriolis mass flow meter. The coriolis meter was capable of directly measuring the density and mass flow rate of the CO_2 into the well. The instrument included built-in totalizers that summed the flow rate over time. The meter was found to be stable and easy to set up in the field.

A unique automated annular monitoring and injection system was conceptualized and tested at this site. The process flow diagram is presented in Figure 6-3. The Battelle system consisted of two tanks mounted on a trailer, one for annular fluid supply and one for annular fluid overflow. The supply tank was coupled to the injection well annulus via a high pressure positive displacement electric pump, a flow meter, and several valves. The electric pump was controlled by the Praxair injection trailer PLC, and was activated whenever the well annulus required a pressure boost. The PLC monitored the difference between the CO_2 injection pressure and the annulus pressure, and through this system maintained the desired difference. The PLC also provided alarming and shutdown functions for the entire operation. The overflow tank could be used to release annulus fluid while keeping the released fluid separate from the supply fluid. This prototype annular monitoring system performed well, and is being refined further for several other MRCSP sequestration projects.

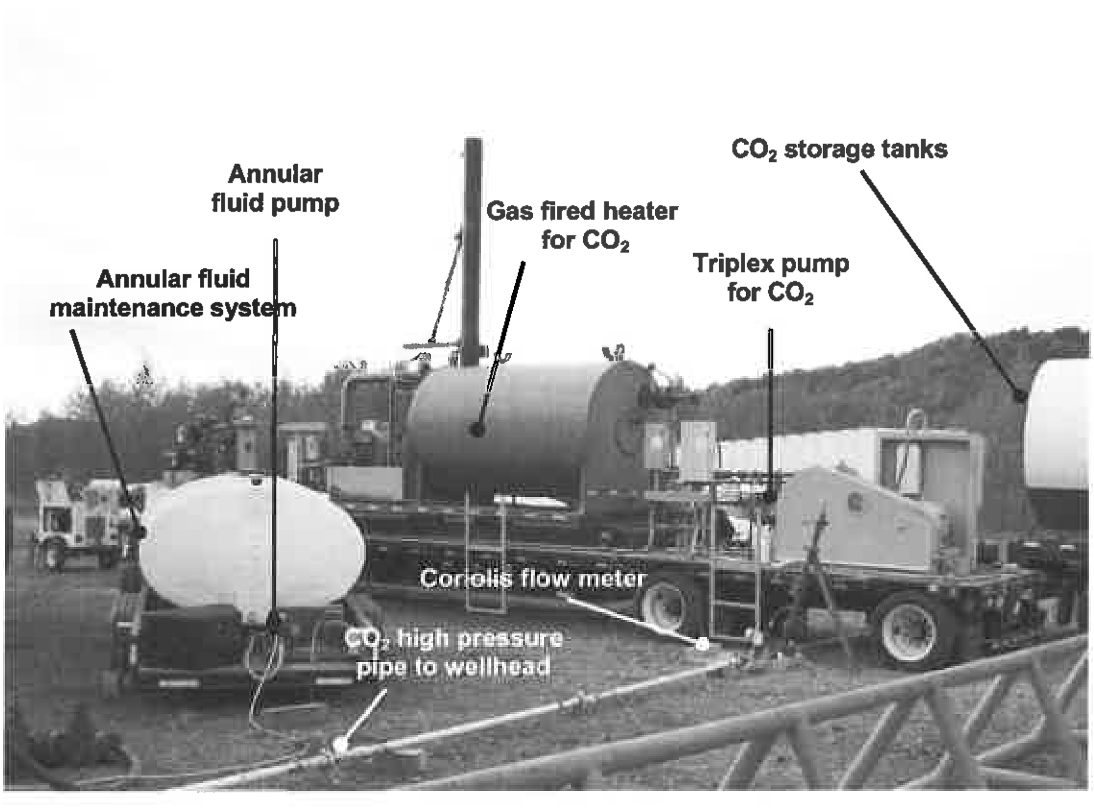


Figure 6-2. CO_2 Injection Setup at the R.E. Burger Power Plant
(To the left is the trailer-mounted annulus fluid injection and maintenance system and in the background is the Praxair CO_2 injection trailer which includes the heater and high pressure CO_2 pump.)

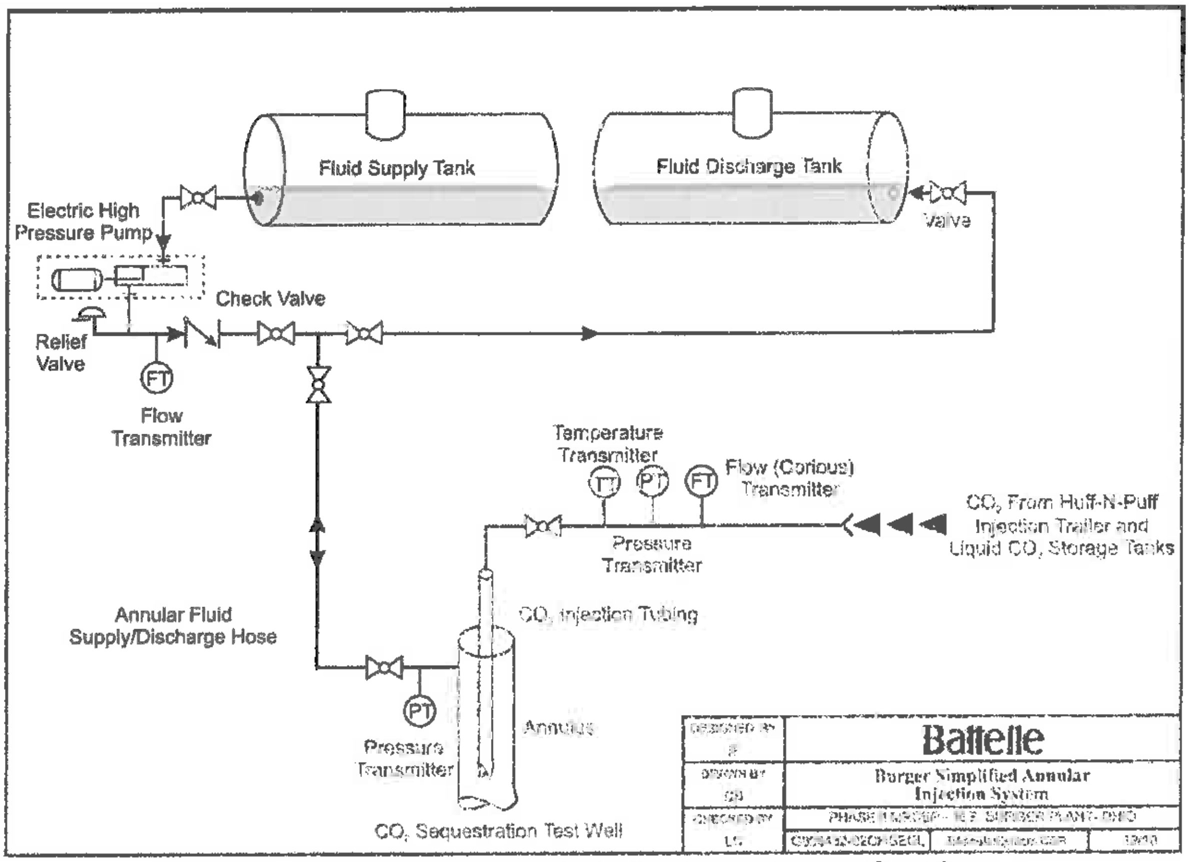


Figure 6-3. Annular Monitoring and Injection System Process Flow Diagram

7.0 MONITORING

The objective of monitoring is to assess the status of CO_2 from the delivery system to the storage reservoir, including injection and storage of the injected CO_2 in the deep geologic reservoir. Monitoring technologies for CO_2 sequestration were reviewed and a subset of options was selected based on the proposed injection system specifications and geologic setting. Because this was a limited injection test with a single injection well, monitoring options are somewhat limited. Consequently, much of the monitoring was focused on assessing hydraulic response in the reservoir, vertical distribution of CO_2 in the injection targets, and health and safety.

A fundamental portion of monitoring the test was focused on the injection system. The objective of this monitoring is to ensure that the injection process and equipment are operating properly during the test. This effort also tracks basic parameters of the tests such as injection pressures, flow rates, and physical properties of the injection fluid.

Monitoring items are described in more detail as follows:

7.1 System Flow Monitoring

The volume of CO_2 injected was monitored at the delivery system with an inline flow meter connected along the supply pipeline. Flow rates were continuously recorded at the compression facility and logged at 15-minute intervals, or equivalent. The flow meter also provided continuous metering of CO_2 temperature and pressure to allow calculation of density. Flow monitoring was required by the UIC permit and the data were also used to track injection volume as well as for hydraulic analysis.

7.2 Hydraulic Monitoring

Pressures were monitored at several locations to provide information about the injection operations. This was also required by the UIC permit and the data were a primary input to the hydraulic analysis.

Pressure measurements within the injection tubing reflect how effectively the fluid is being transmitted into the target rock formation. Any changes in the injection zone, such as a scale buildup in the well or far-field restriction in the reservoir, may be revealed by a gradual increase in injection pressure. In addition, any compromise in the well integrity may be reflected by a sudden change in pressure.

For the R.E. Burger site, options allow for pressure to be monitored at the following locations:

- Injection tubing at the wellhead
- Injection well bottomhole injection zone
- Injection well interannulus wellhead (differential)
- Downhole zone below packer (if applicable).

Pressure measurements were tracked at the wellhead injection tubing and the interannulus with a pressure gauge and recorded with a continuous data logger at 1- to 10-minute intervals. A downhole gauge was placed through the injection tubing to record pressures in the injection zone. This gauge was be "soft-mounted" with a cable and was retrievable to obtain the recorded data. A similar retrievable downhole gauge was installed below the packer to monitor pressure in this zone. The interannulus pressure was monitored with a wellhead pressure/temperature logger.

The pressure data also were used with shut-off valves to ensure safe operating conditions. For example, if the reservoir fracture pressure was approached, the injection of the CO_2 to the reservoir was stopped. Similarly, if the regulated differential pressure above and below the packer was not being achieved, the well was shut in.

In addition to pressure, temperatures were monitored as an indicator of the effects of the CO_2 injection. The injected CO_2 will have a lower temperature than the rocks and fluids in the target formation. Continuous temperature monitoring was performed downhole in the monitoring well, if possible. The temperature of the CO_2 was also logged at the pipeline and/or wellhead.

7.3 Wireline Monitoring

An initial run of a pulsed neutron capture tool was performed in August 2008 for the purpose of collecting baseline data. The tool makes measurements of the formation capture cross section, called sigma. Different chemical elements have different sigma values, allowing for a determination of the rock fluid chemistry. For example, the sigma value for chlorine is very high and helps to compute salinity. Assuming that the rock matrix was not affected by the injection, a repeat pulsed neutron capture log would show a lower sigma value in zones that were saturated with CO_2. Due to the low injection rates and amounts injected in this test, a repeat log was not completed.

7.4 Health and Safety Monitoring

Borehole leakage has been identified in CO_2 storage research as a potential route for leakage. To address this risk, an array of atmospheric monitoring sensors was installed near the injection wellhead during the injection period. These sensors were programmed to sound an alarm if dangerous conditions (>0.5% CO_2) exist due to CO_2 release from the injection system.

7.5 Quality Assurance/Quality Control Plan

Field and laboratory procedures followed established quality assurance/quality control (QA/QC) protocols in association with the monitoring. System monitoring gauges were calibrated to standard pressures before installation. In addition, duplicate gauges were installed in the downhole portion of the well. Calibration checks on wireline equipment were run with each logging run with the control parameters provided with the logs. In addition, multiple logging runs were completed at selected intervals. All wireline logs were examined by field operators and comments provided for inconsistencies. Well indicator sensors were calibrated prior to installation and compared to wellhead measurements. Field equipment were calibrated prior to brine sample collection and recorded in instrument logbooks. All sample analysis followed established laboratory QA/QC protocols.

8.0 Test Results and analysis

The overall injection plan for the R.E. Burger site was to test three CO_2 sequestration targets through a sequential injection procedure. Based on the hydraulic analysis of injection potential for the injection targets, a flexible plan was developed that will allow injection within multiple units. The objective of the testing was to assess injectivity and CO_2 behavior within the deep saline formations. Figure 8-1 shows a flow diagram for the reservoir testing program.

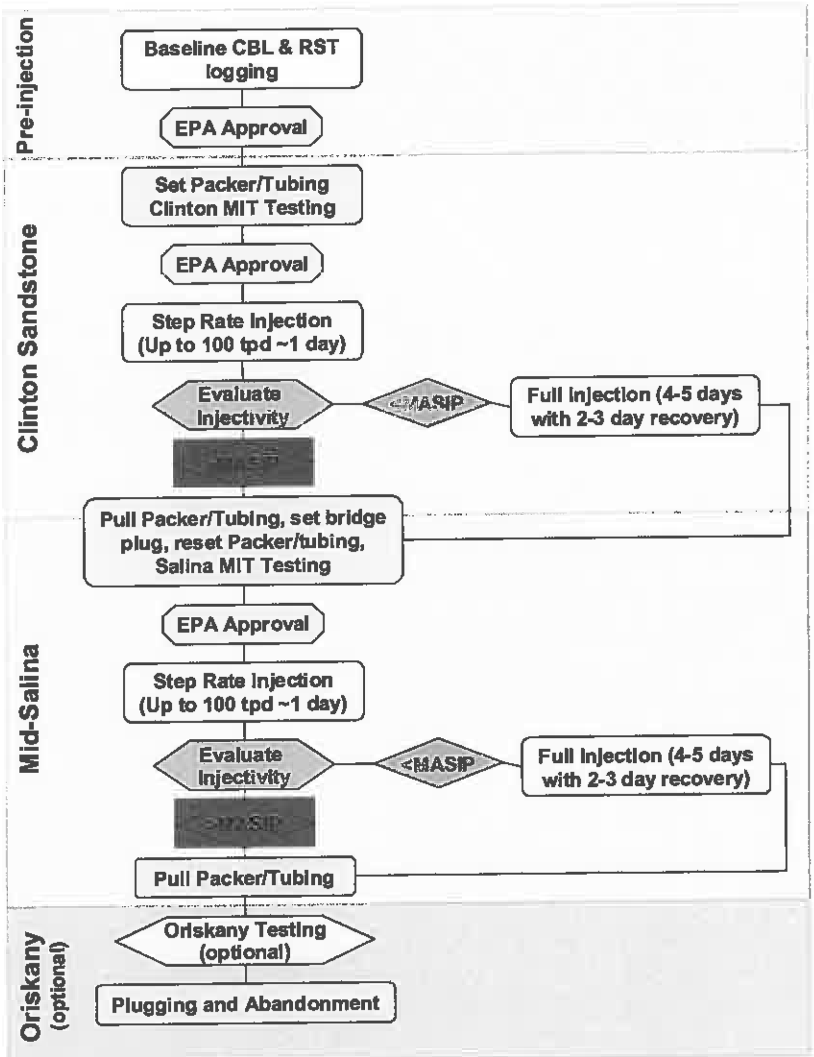


Figure 8-1. Flow Chart Outlining Injection Procedure

8.1 Injection Testing Field Work

A series of injection tests was completed in the Clinton, Salina, and Oriskany Formations. The testing started in the deepest formation (Clinton) and moved upward to the shallower formations. Most testing utilized CO_2, but some tests were completed with acid solutions during well treatment activities. In general, surface flow and bottomhole pressure data were the main criteria used to analyze tests.

Clinton Sandstone. Testing of the Clinton Formation was conducted between September 25-28, 2008 (Table 8-1 and Figure 8-2). Three attempts were made at injecting CO_2 into the formation (on September 25, 26, and 28). In addition to the attempts at CO_2 injection, the well was stimulated with acid on two separate occasions (September 27 and 29). During each attempt of injection (both CO_2 and water/acid), injection and formation pressures quickly increased even with relatively low injection rates of 8 tonnes per day of CO_2 and water/acid (<2 bbl/min). In each case, the upper regulatory pressure limit was reached within 3 hours of starting injection.

Table 8-1. Clinton Formation Testing

DATE	ACTIVITY	DESCRIPTION	FORMATION
09-25-08 (1)	CO_2 Injection	• Duration: 3.25 hr • Flow rate: 0.12 bpm • Amount Injected: 24 bbl	Clinton
09-26-08 (2)	Step-Rate Test w/ CO_2	• Duration: 11 min • Flow rate 0.053 bpm • Amount Injected: 0.59bbl	
09-27-08 (3)	Acid Injection	• 500 gal of 20% HCl followed by 500 gal of 15% HCl	
	Step-Rate Test	• Duration: 2.25 hr • Flow rate: 0.2-2 bbl/min	
	Pressure Falloff Test	• Duration: 2 hrs	
09-28-08 (4)	CO_2 Injection	• Duration: 30 min • Flow rate: 8 tonnes/day	
09-29-08 (5)	Acid Injection	• 500 gal of 15% HCl	

Example Clinton CO_2 Injection Testing. Figure 8-3 shows the sequence of injection testing in the Clinton Formation. It took about 2 hours to fill the injection tubing with CO_2. Based on initial bottomhole pressures of 775 psi, there was 1,800 ft of fluid in the well before testing started. Once injection started, surface injection pressure increased rapidly to 2350 psi, while flow rates decreased to less than 0.24 bpm. Pressure falloff was monitored for 45 minutes, with about 100 psi drop-off at surface and in the bottomhole gauges. Another short injection was started, but surface pressures rapidly increased again over 2000 psi. Pressure falloff after this test showed another gradual decline. A final injection was attempted up to pressures of 2400 psi, near the maximum allowable surface injection pressure.

In general, it appears there was minimal flow into the formation during testing. Most of the pressure response in the well likely reflects wellbore storage phase due to compression of the CO_2 column within the borehole. Consequently, it is not possible to complete analysis of pressure response. Overall, it appears there may be potential to inject into the Clinton at rates of 0.12 to 0.24 bpm for short periods of time (less than 1 hour).

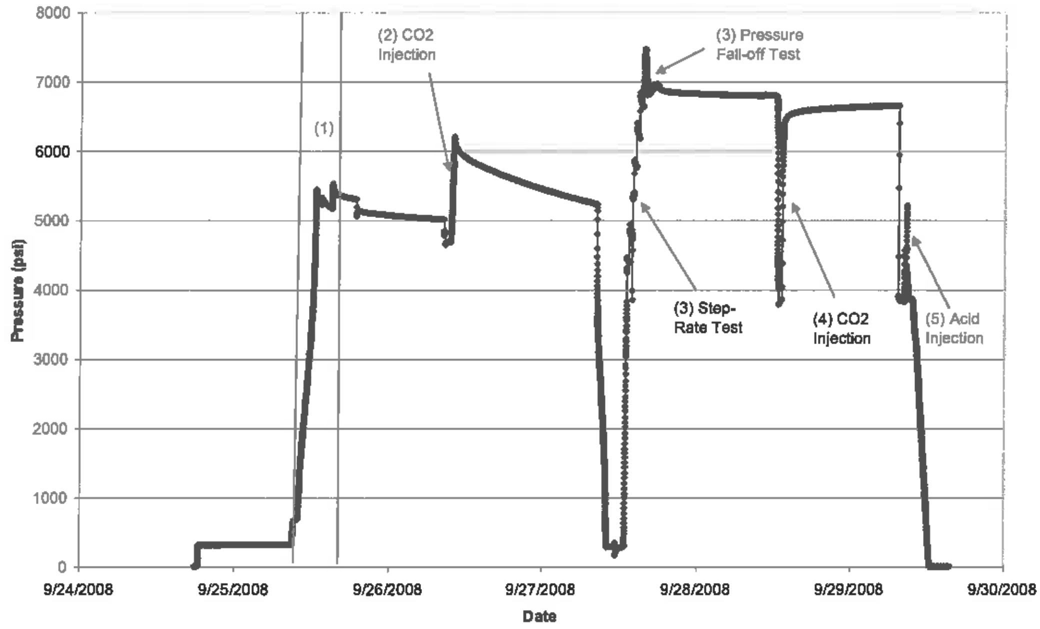


Figure 8-2. Downhole Pressures for CO_2 Injection in the Clinton Formation

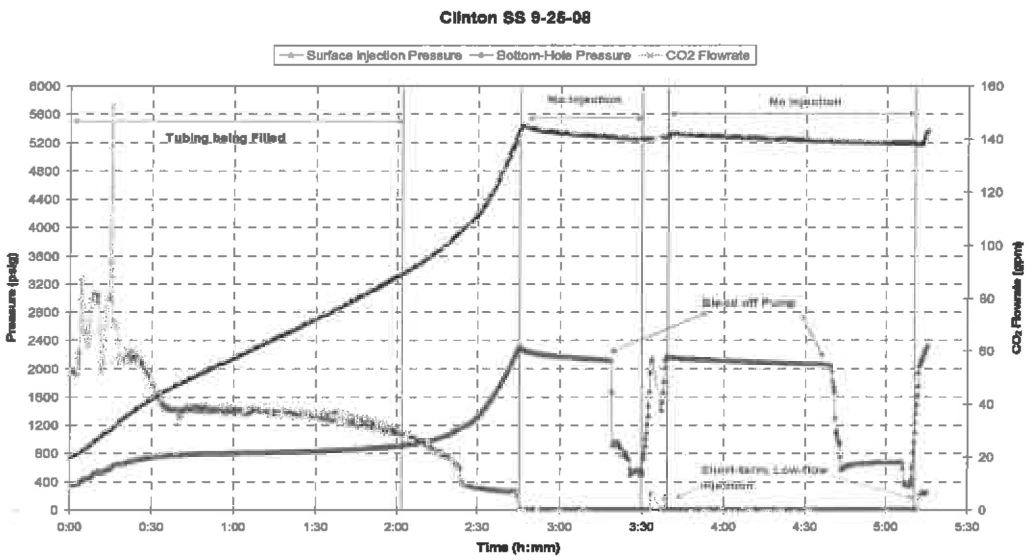


Figure 8-3. Test Sequence in the Clinton Formation

Salina Formation. Much of the initial injection work on the Salina Formation was performed to stimulate the well with acid. Due to concerns regarding the corrosion of the pressure monitoring gauges, they were not installed in the well until most of the stimulation work was completed, after October 17.

On October 1, the tubing and annular space were pressured to 1,000 psi. After the pressures in the tubing and casing were established at 1,000 psi, the tubing pressure was increased in 500 psi increments. The flow rate was held constant at 0.2 bpm during the pressure increase test. After the desired pressure was achieved, the pressure falloff was measured before increasing the pressure again.

Well stimulation activities were performed on October 2 using acid injection. In addition, injection testing was performed during the stimulation. Initially, the annulus pressure was increased to 1,000 psi. After the annulus pressure was increased to 1,000 psi, the tubing pressure was increased to 2,000 psi. The tubing pressure was then increased approximately 500 psi every 15 minutes up to a final pressure of 4,000 psi. After the desired pressure level was achieved, the pressure decrease was measured. The typical pressure loss over the 15 minute monitoring period was 500 to 700 psi.

On October 7, a step-rate injection test was performed on the Salina Formation using fresh water in order to determine the fracture pressure of the reservoir as required by the UIC permit. After establishing appropriate annular pressure, fresh water was pumped into the well at a rate of 0.2 bpm. Over a period of approximately 6 minutes, the pressure increased to 4,597 psi when the formation began to fracture. Following the fracture of the formation, the flow rate was increased over time. However, only a small amount of fresh water was stored at the site, and the flow steps were limited in time. Table 8-2 displays the pressures that were measured at each flow rate.

Table 8-2. Measured Pressures at Each Flow Rate

Time	Flow Rate	Starting Pressure	Final Pressure
8:56 AM	0.2 bpm	4,600 psi	4,600 psi
9:16 AM	0.25 bpm	4,600 psi	4,670 psi
9:30 AM	0.5 bpm	4,670 psi	4,750 psi
9:35 AM	1.0 bpm	4,750 psi	4,860 psi
9:47 AM	2.0 bpm	4,860 psi	5,220 psi

After the step-rate test was completed, the well was shut in and the pressure falloff was monitored. The pressures measured over time are presented in Table 8-3.

Table 8-3. Pressures Measured Over Time

Time	Pressure
0 min	4,880 psi
5 min	4,855 psi
10 min	4,843 psi
15 min	4,839 psi
30 min	4,832 psi

Following the injection of the fresh water, the well was shut in and the pressures were monitored. Table 8-4 presents the pressure levels in the well after shutting in the well.

Table 8-4. Pressure Levels

Time	Pressure
0 min	4,830 psi
5 min	4,828 psi
10 min	4,824 psi
15 min	4,824 psi
30 min	4,820 psi
12 hours	4,040 psi

Table 8-5 summarizes acid treatment work. Universal Well Services pumped 1,000 gallons of 28% hydrochloric (HCl) acid into the well. The first 80 gallons of acid was pumped in the well at a rate of 0.2 bpm. At a flow rate of 0.2 bpm, the tubing pressure was 4,500 psi. After 80 gallons of acid was pumped into the well, the pumping rate was increased to 1 bpm until 500 gallons of acid was pumped into the well. The tubing pressure was 4,850 psi while the acid was being injected at 1 bpm. The final 500 gallons of acid was pumped into the well at 2 bpm with a tubing pressure of 5,330 psi. The acid was displaced into the formation with approximately 600 gallons of fresh water.

On October 11, during acidization to remove possible skin effects, 130 perforation balls were dropped into the well in a stream of 28% HCl solution. Over the course of the operation, 2,000 gallons of acid was pumped into the well and approximately 2,000 gallons of water was pumped into the well. Both the acid and water were pumped into the well at a rate of 1.9 bpm.

On October 16, multiple zones of the Salina Formation were stimulated again with the injection of acid. The first zone (6,720 to 6,780 ft) was stimulated with 500 gallons of acid. During injection, the acid was displaced with water at a rate of about 1.5 bpm. Tubing pressures during injection quickly increased from 0 psi to over 4,900 psi within approximately 15 minutes and remained at approximately 4,850 psi throughout pumping.

Five hundred gallons of acid was also used to treat the second zone (6,890 to 6,840 ft bgs). Injection was started at a rate of 0.4 bpm. At the initial injection rate, the wellhead pressure equaled 4,760 psi. Over a 5-minute interval, the flow rate was increased from 0.4 to 1.5 bpm. At a flow rate of 1.5 bpm, the wellhead pressure was 5,100 psi.

The perforations from 6,830 to 6,890 ft were isolated and treated as a third zone. The initial injection rate was set at 0.25 bpm, resulting in a tubing pressure of about 2,200 psi. Shortly after starting injection, the flow rate was increased to 0.5 bpm. After about 10 minutes of pumping at 0.5 bpm, the tubing pressure increased to approximately 4,000 psi. Following injection, the pressure decrease was monitored. After 10 minutes, that pressure decreased from 4,000 to 3,300 psi.

The final zone (6,900 to 6,985 ft bgs) was treated with acid, with a step-rate injection test. Each injection period lasted approximately 5 minutes, with 5 minutes of pressure monitoring between each period of injection. The initial injection rate of 0.8 bpm produced pressures of 3,000 psi at the end of the injection period. After 5 minutes of monitoring, the pressure decreased to about 1,800 psi. Another period of injection was conducted at a rate of 0.8 bpm with pressures increasing to 4,000 psi after 5 minutes. The pressure decreased to 3,000 psi during the 5-minute period of no injection. The third injection phase was conducted at 0.9 bpm, and the pressure increased to about 4,400 psi after 5 minutes of pumping. Pressure decreased from 4,400 psi to about 3,800 psi after 5 minutes. The final pumping period was performed at an injection rate of 1.6 bpm. After 5 minutes of pumping, the wellhead pressure increased to 4,700 psi. The pressure decreased to about 4,000 psi after 5 minutes of monitoring.

On October 18, CO_2 injection into the Salina Formation was attempted (Figure 8-4). The pump was initially set at 10% capacity. During pumping, the pressures in the tubing gradually rose as did the temperatures in the CO_2 heater. The heater turned off on two separate occasions as a result of overheating. Throughout the day, the tubing pressures continued to increase. After 7 hours of injection, the wellhead pressure increased to 4,100 psi. The system was shut down at this time. The total amount of CO_2 injected into the well was about 30 bbls. The tubing/well volume equals 24 bbls; therefore, about 6 bbls of CO_2 was injected into the formation. The flow rate during injection was about 0.18 bpm, which equaled about 49 metric tons/day.

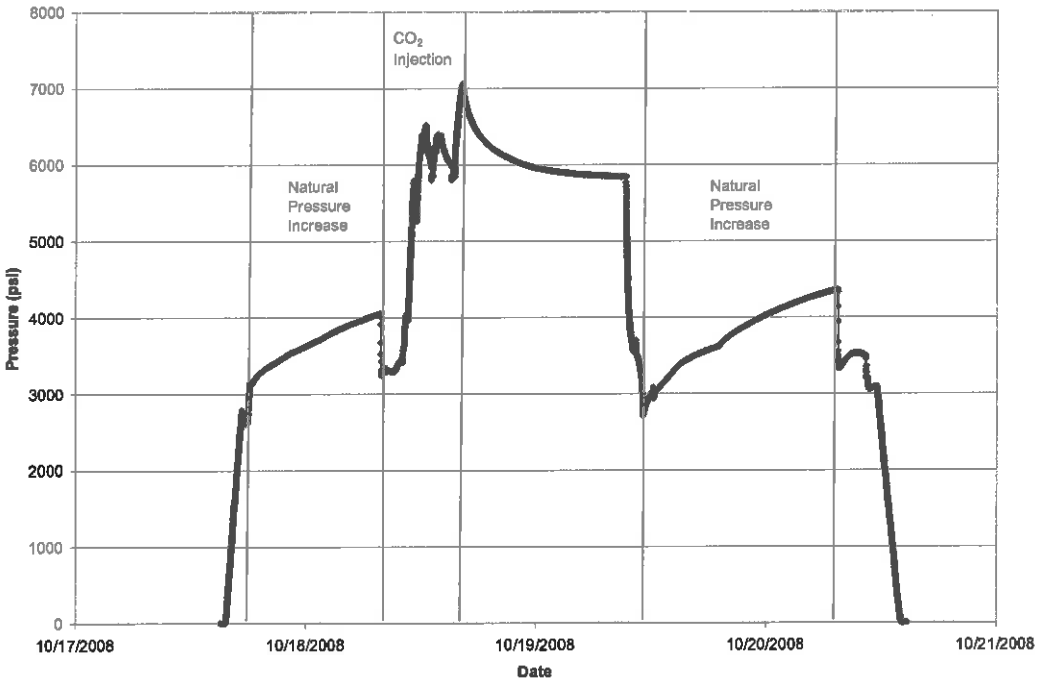


Figure 8-4. Downhole Pressures for CO_2 Injection in the Salina Formation

Example Salina CO_2 Injection Testing. Figure 8-5 shows the test sequence in the Salina Formation. Several injection tests were completed at intermittent pumping rates because the injection pump system would overheat at lower injection rates. Initial injection resulted in a surface injection pressure buildup to over 3,200 psi with CO_2 flow rates of less than 0.24 bpm. A subsequent injection period where the injection rate was gradually stepped up resulted in more pressure buildup past 3,200 psi, even at flow rates less than 0.12 bpm. A final injection test was completed up to surface injection pressures over 4,400 psi at fairly steady CO_2 flow rates of 0.12 bpm. Bottom hole pressures for this test were up to 7,100 psi, which equates to a pressure gradient over 1.0 psi/ft at the injection zone of 6,734 ft. However, no formation breakdown pattern was present in the pressure response.

Overall, high injection pressures and low flow rates were observed in the Salina Formation. Hydraulic analysis predicted injection rates approaching 50 tonnes per day for the Salina at pressures less than 2000 psi; in actuality, injection rates of less than 20 tonnes per day were not sustainable at twice that pressure. There were no pressure response curves that could be analyzed. No formation breakdown pattern was observed in pressure monitoring data, even at the high injection pressures.

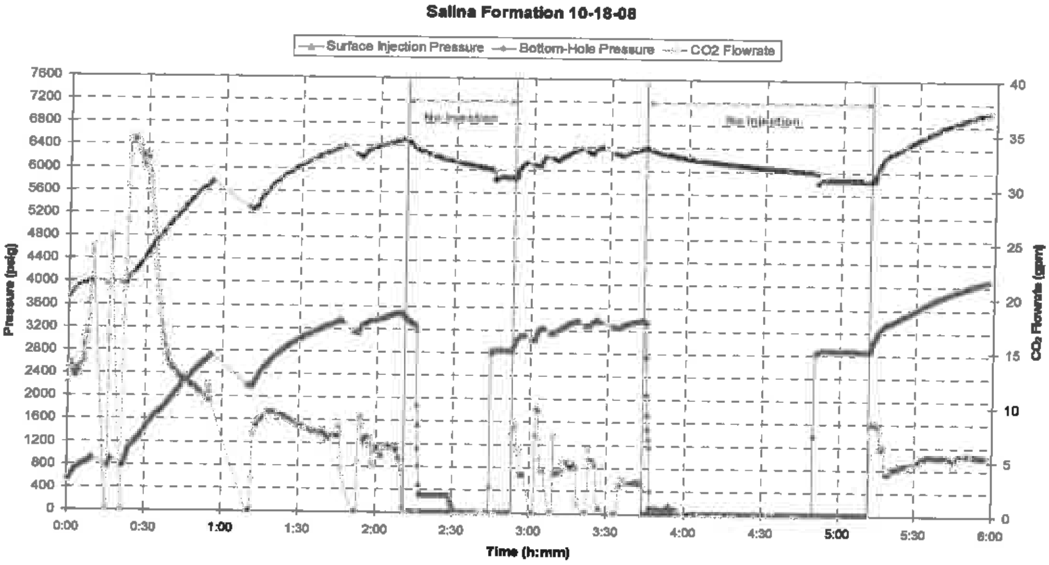


Figure 8-5. Test Sequence in Salina Interval

Oriskany Sandstone. On October 23, an evaluation of effectiveness of the acid stimulation was performed at the beginning of the testing on the Oriskany sandstone. Pre-acidization brine injection was completed by injecting brine at a rate of 0.2 bpm. Within 17 minutes, tubing pressure at the wellhead increased to 2,000 psi. After reaching a pressure of 2,000 psi, the well was shut in, and the pressure decrease was monitored for 19 minutes. The pressure decreased from 2,000 to 1,300 psi. Again, the well was pressured up to 2,000 psi, which only took 5 minutes during the second injection. Pressure was monitored for 34 minutes, and the pressure decreased to 1,400 psi.

Following the baseline brine injection testing, 1,000 gallons of 28% hydrochloric acid was pumped into the well at a rate of 0.2 bpm. This rate was continued for 2 hours, 45 minutes. For the first 2 hours, the wellhead maintained pressures below 2,000 psi. After 2 hours the pressure increased to 2,000 psi, and a pressure break was observed. After 2 hours 45 minutes of pumping into the well, the flow rate was increased to 0.5 bpm, and the pressure increased to 3,200 psi. The well was pumped at 0.5 bpm for 70 minutes and the pressures remained at 3,200 psi.

The post-acidization brine injection test was performed on October 24. Injection was performed at a constant rate of 0.2 bpm. After 49 minutes, the wellhead pressure was 2,000 psi, injection was stopped, and the pressure fall-off was monitored. Only limited pressure fall-off information was gathered because the gauge on the pump truck needed to be disconnected in order to be repaired. Over an 18 minute period, the pressure decreased from 2,000 to 1,100 psi.

After the pump truck was repaired, approximately 1,000 gallons of water was pumped into the well to displace the acid spotted at the perforations. The pump rate was 0.2 bpm throughout the injection, and the pressures remained below 2,000 psi (1,800 to 1,900 psi). After 1,000 gallons of water was injected into the well, the injection rate was maintained at 0.2 bpm, and the pressure increased to 2,700 psi. The water injection rate was increased to 0.5 bpm, and pumped at 0.5 bpm for about 10 min with pressure increasing to 3,100 psi. Again, the rate was increased to 1 bpm near the end of stimulation with pressure increasing to 3,700 psi. After pumping was stopped, the instant shut in pressure was 3,640 psi.

On October 26, a short-term injection of CO_2 was conducted to evaluate the pressure response. CO_2 was injected at a rate of 0.23 bbl/min until well head pressure increased to 2,500 psi (approximately 20 minutes after starting injection).

On October 27, well stimulation occurred with 1,000 gallons of 28% hydrochloric acid with perforation balls. Approximately 700 gallons of acid was pumped into the well, when the perforation ball gun began to leak. The system was shut down for approximately 2 minutes while the system was switched from acid to water. After pumping 1,000 gallons of water, the system was shut down to remove the perforation ball gun from the injection stream.

A second stimulation was performed on October 29. A total of 300 perforation balls (7/8 inch, 1.3 specific gravity) were dropped in the well. After 13 minutes of pumping acid at a rate of approximately 1.5 bpm (a total of 1,000 gallons of 28% hydrochloric acid), pumping was switched to brine injection to displace the acid. The brine flow rate was approximately 3.1 bpm. The brine injection lasted about 10 minutes and approximately 1,300 gallons of water was injected into the well. The pressure during brine injection was approximately 4,800 psi. Following the brine injection, the wellhead pressure was monitored to measure the rate of the decrease. Over a period of 40 minutes, the pressure decreased by 1,500 psi (from 3,800 to 2,300 psi).

On October 30 and 31, injection of CO_2 into the well was attempted. The objective of the testing on these days was to determine if CO_2 could be pumped into the well at a reasonable flow rate (>20 tonnes/day) while maintaining a wellhead tubing pressure below 2,000 psi on October 30 and less than 2,500 psi on October 31. Initial injection rates were relatively low at approximately 0.25 bpm until the desired pressured limit was approached. The flow rates were then reduced to maintain pressures below the limit. Once the flow rate had been reduced to less than 20 tonnes/day with pressures exceeding the limits, the tests were concluded.

8.2 Well Test Analysis

As described in the previous section, a series of injection tests was completed in the test well. Many of these tests provided information on the reservoir properties such as fracture pressure and general injection potential. To further examine reservoir behavior and quantify permeability, the post-injection pressure falloff curves from specific test intervals were compiled and analyzed. These pressure falloff curves generally provide a better idea of overall reservoir behavior than injection or step-rate tests, which can be irregular due to inconsistent injection rates, CO_2 phase behavior, and other factors.

Due to injection difficulties, this analysis is more of a field check on results. Rigorous test well analysis requires long periods of constant injection, followed by a falloff observation period, usually half the injection period. Because injection was difficult to sustain, the injection rate was variable and fairly low. As such, this analysis may be considered more of a field check on results.

Pressure data were obtained from downhole pressure/temperature loggers installed in the injection interval. The loggers included quartz transducers with a pressure range of 13 to 6,000 psi, accuracy of 0.03% full scale, and inconel housing. The injection zone was isolated by a packer assembly. Flow rates were metered at the surface with the CO_2 delivery system. After injection, the well was shut in at the surface and pressure falloff was observed.

Pressure falloff curves were identified for the three rock formations tested:

- Clinton/Medina Formation: two pressure falloff test on September 25, 2008
- Salina Formation: two falloff test on October 18, 2008
- Oriskany Formation: one falloff test on October 30, 2008.

These falloff intervals were selected because they exhibited a reasonable falloff curve shape and were preceded by a relatively steady period of injection. Figure 8-6 shows the Clinton/Medina test sequence examined. The first falloff test followed an initial injection period of 21 minutes at an average rate of 7.5 gpm. The next test followed a low flow injection period of 8.5 minutes at an average rate of 0.03 bpm. Figure 8-7 shows the Salina test sequence. The first falloff period followed an injection period of 58 minutes at an average rate of 0.17 bpm. The second Salina falloff period followed an injection period of 54 minutes at an average rate of 0.079 bpm. The Oriskany falloff followed a period of 69 minutes at an average injection rate of 0.25 bpm (Figure 8-8).

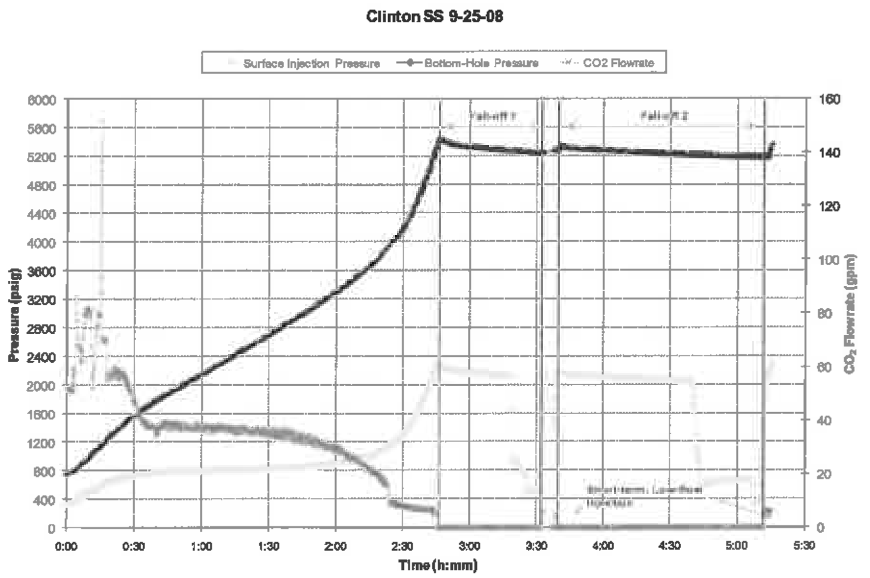


Figure 8-6. Injection Sequence in Clinton/Medina Analyzed for Pressure Falloff

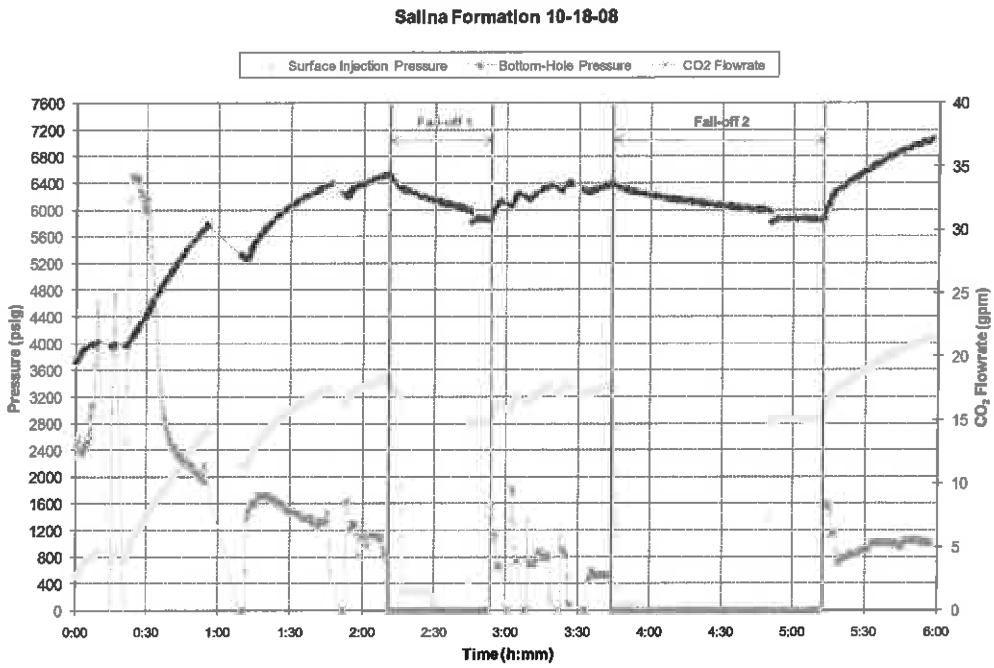


Figure 8-7. Injection Sequence in Salina Analyzed for Pressure Falloff

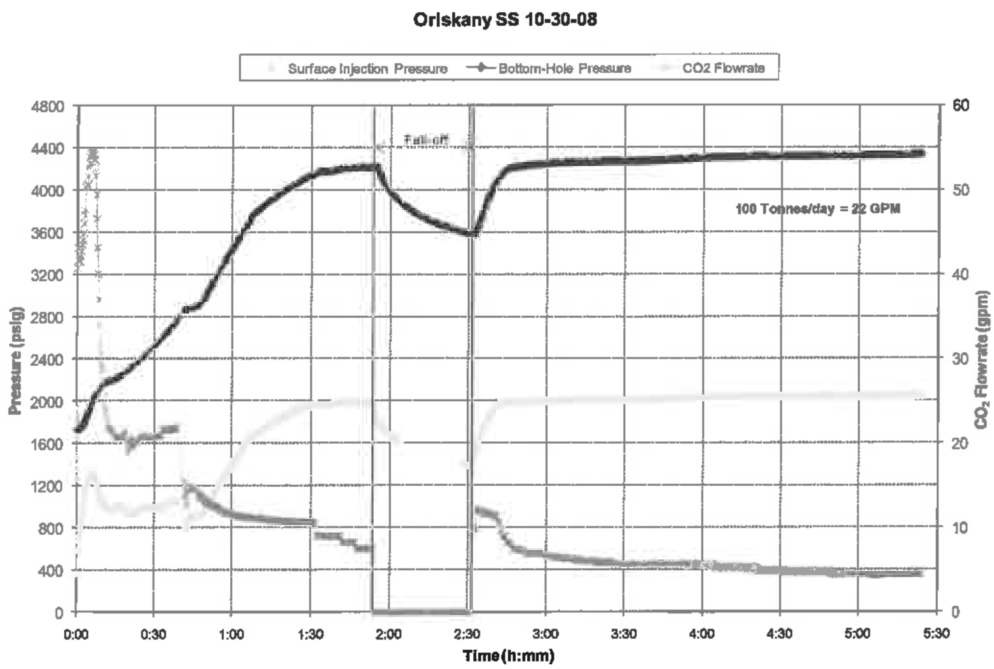


Figure 8-8. Injection Sequence in Oriskany Analyzed for Pressure Falloff

Falloff curves were analyzed with log-log diagnostic and Horner plots. These methods have been established to analyze reservoir production tests for oil and gas wells as well as injection wells (Horner, 1951; Earlougher, 1977). Figure 8-9 shows curves for each plot. As shown, the log-log diagnostic test can help delineate wellbore storage, transition period, and radial flow in the reservoir. The Horner plot shows pressure versus Horner time, which approaches 1.0 at the end of the falloff period (as such, the time scale is reversed). This plot may be used to estimate reservoir permeability.

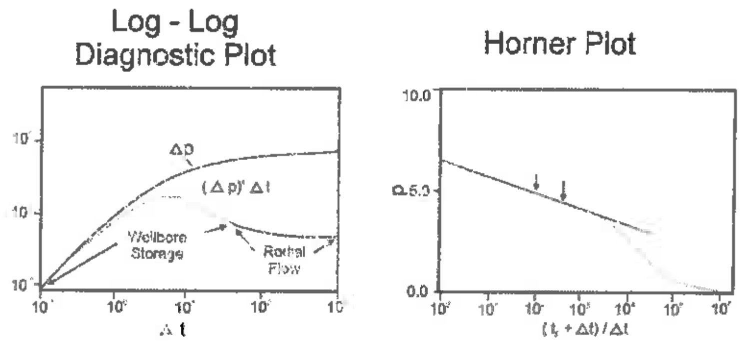


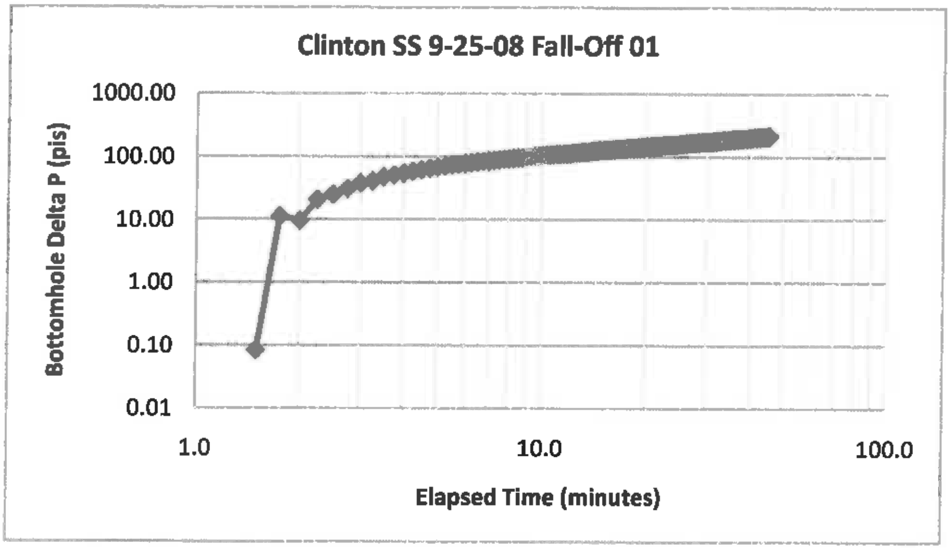
Figure 8-9. Typical Log-log Diagnostic and Horner Plot for Well Test Shut-in Analysis

Plots for the Clinton 01 falloff test are shown in Figure 8-10. The diagnostic plot shows gradual plateau pressures. However, the Horner plot suggests that only the borehole storage and initial transition period were observed. Figure 8-11 shows well test plots for the Clinton 02 falloff test. This test shows a similar pattern as observed in the first test.

Well falloff test plots for the Salina 01 period are shown in Figure 8-12. Figure 8-13 shows well test plots for the Salina 02 falloff test. Similar to other tests, the plots appear to show mainly a borehole storage period. However, it appears that the falloff pressure progressed further into the transition period between radial flow and borehole storage. Regardless, it is difficult to interpret the response curve. This test shows a similar pattern as observed in the first test.

Figure 8-14 shows the well test plots for the Oriskany falloff test. The diagnostic plot shows a gradual plateau in reservoir pressures. The Horner plot suggests that mainly the borehole storage and initial transition period were observed.

In general, the response curves suggest that mainly borehole storage was encountered during the pressure falloff tests. It did not appear that radial flow was observed during the pressure falloff after injection. Consequently, no quantitative analysis was possible to estimate reservoir permeability. Longer pressure recovery observation periods may have allowed for collection of more data that would have indicated radial flow in the reservoir. However, these falloff tests would likely have taken significant time (up to several hundred hours), because of the generally low permeability environment.



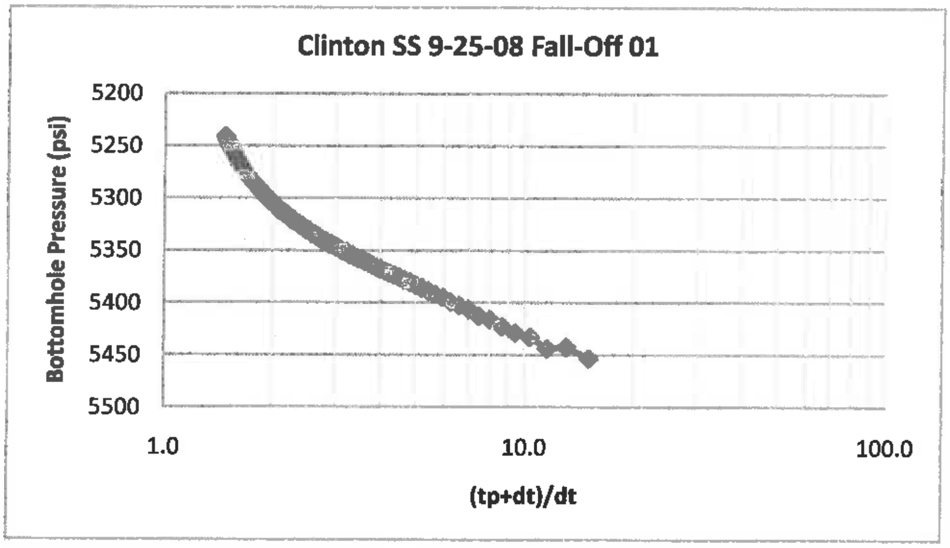
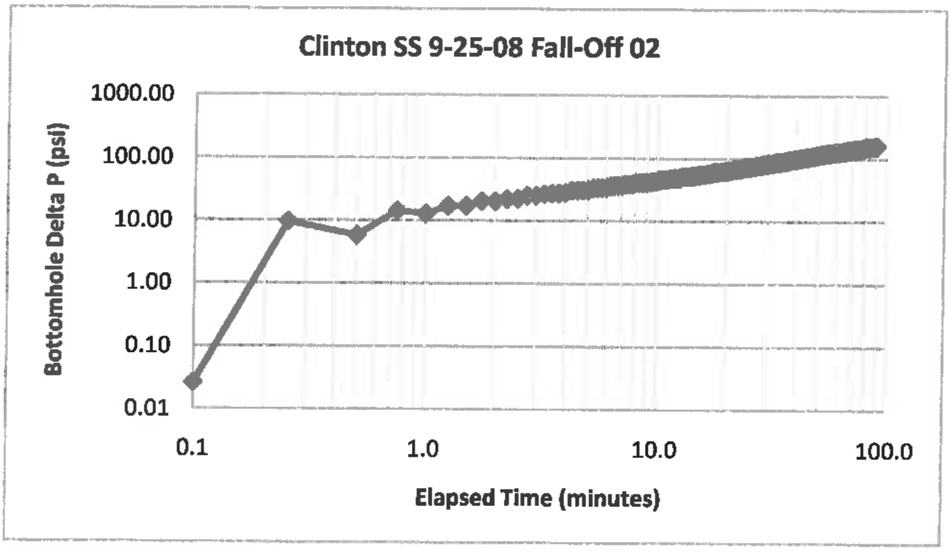


Figure 8-10. Log-log Diagnostic and Horner Plot for Clinton Falloff 01



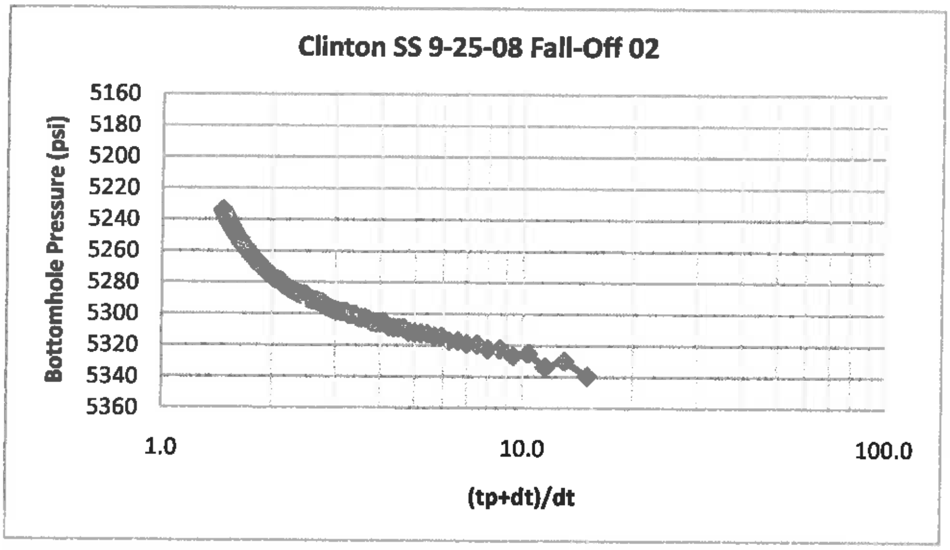
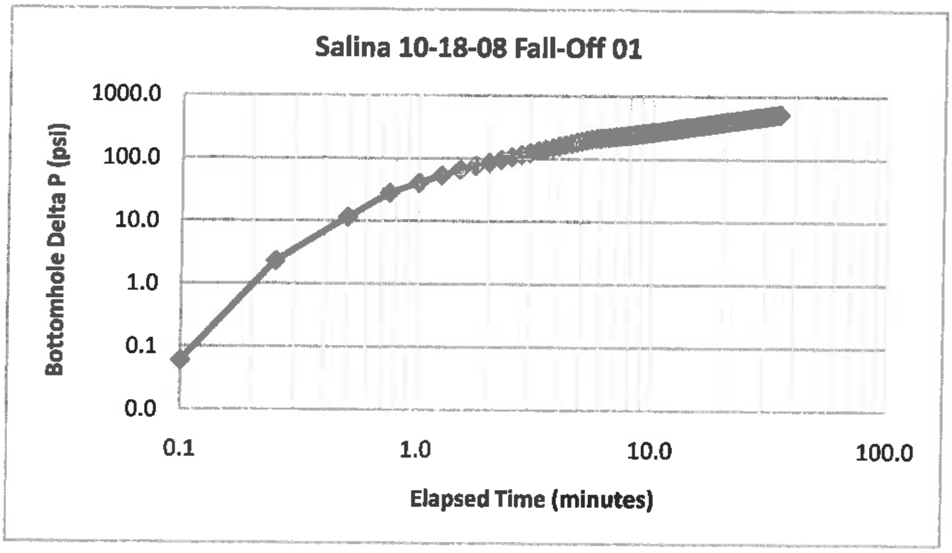


Figure 8-11. Log-log Diagnostic and Horner Plot for Clinton Falloff 02



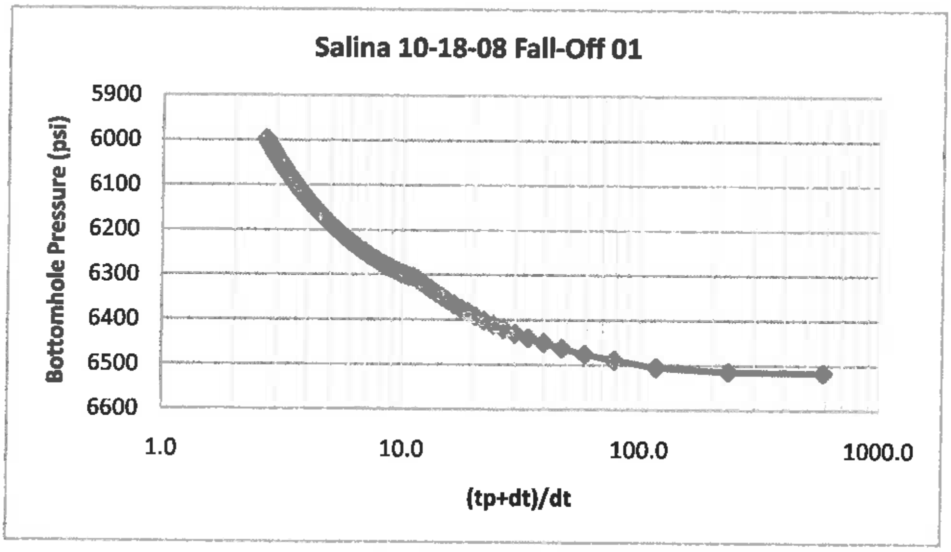
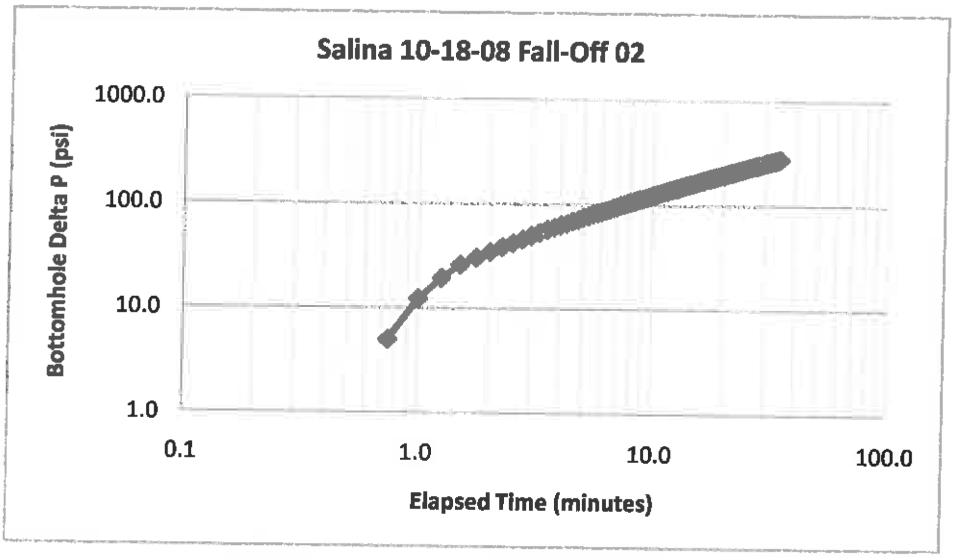


Figure 8-12. Log-log Diagnostic and Horner Plot for Salina Falloff 01



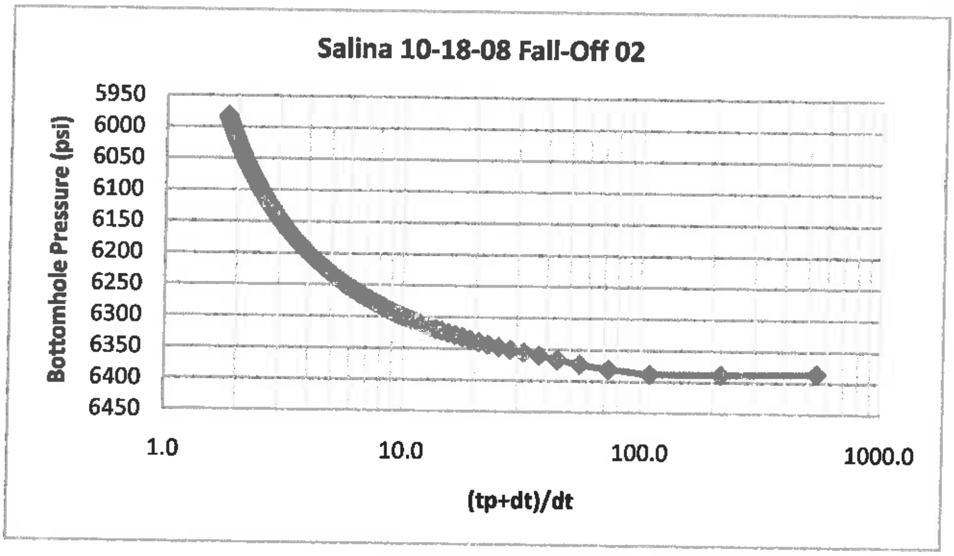


Figure 8-13. Log-log Diagnostic and Horner Plot for Salina Falloff 02

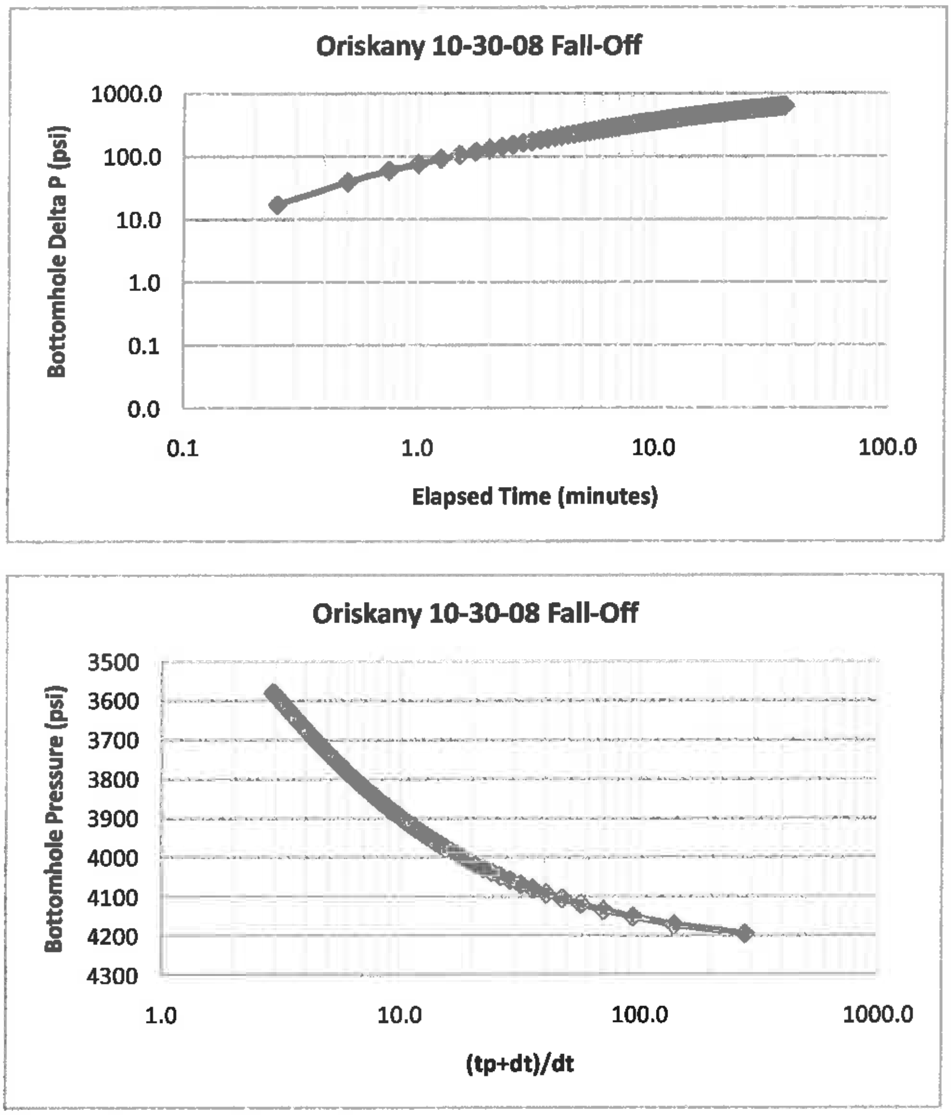


Figure 8-14. Log-log Diagnostic and Horner Plot for Oriskany Falloff

While pressure falloff curve analysis was not possible, some qualitative analysis of the well tests was performed to determine the character of the three different formations and the various well treatments applied to the well. Figure 8-15 shows pressure falloff observed for all of the tests analyzed. In general, the Oriskany formation appeared to show the steepest pressure falloff curve, suggesting it had the highest reservoir transmissivity.

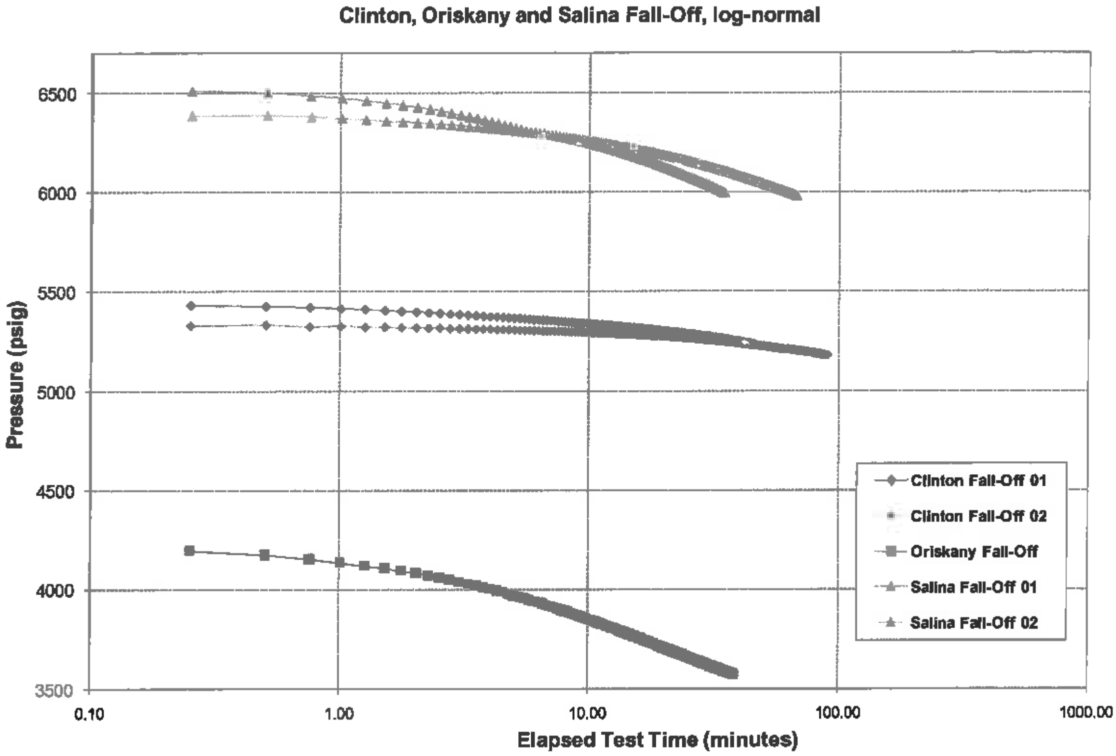


Figure 8-15. Semi-log Plot of Pressure Falloff Curves

9.0 OUTREACH

The overall goal of the outreach program is to lay a foundation for potential future deployment of carbon sequestration from the perspective of public awareness and perception. It is integrally linked to the scientific and regulatory efforts. Outreach activities are designed to:

(1) Identify and communicate early with stakeholders at all levels (local, state and national) to ensure that they are fully aware of the need and potential benefits of the project, as well as planned field activities at each stage of the project

(2) Establish and maintain the project's credibility through open communication with these stakeholders.

(3) Help the technical research team understand the perspectives of the stakeholders and identify potential issues that would need to be addressed if this new technology was deployed on a large scale.

Each demonstration site involves formation of an outreach team, identification of stakeholders, proactive engagement with these stakeholders in a variety of ways (telephone calls, briefings, one-on-one discussions and public meetings) and development of informational materials, including establishment of an interactive web site. At the R.E. Burger site, the outreach team included both outreach and technical staff members from the entities involved in the research including Battelle and FirstEnergy. AJW Associates, an outreach consulting organization, also assisted in the effort. Regular conference calls among team members were convened to ensure that activities were coordinated and on track.

9.1 Outreach Plan

An outreach plan was developed to link outreach activities to technical activities as the research project progressed. The purpose of the plan was to ensure that the partners involved in the test were coordinating with each other in conducting outreach activities aimed at building a solid foundation of public support for this test and for the longer-term concept of geologic sequestration. As each field test was conducted, several key points of interaction with the public were identified as the technical project progressed: announcing the test location and initiating site activities (seismic testing, if applicable, and drilling); applying for an injection permit; injection activities; and project closure. In effect, outreach planning and implementation can be viewed as a series of plans that are tailored to the particular technical stage of the project. For the R.E. Burger Power Plant project, these technical stages, or periods, and dates were identified as follows:

- Period 1: Selection of project, seismic survey, drilling and core sampling (June 2005 - February 2007)
- Period 2: Submission and approval of the injection permit (January 2008 – September 2008)
- Period 3: Injection (September 2008 – November 2008)
- Period 4: Well closure and research (Spring 2009)
- Period 5: Dissemination of Results (Summer 2009)

The plan used a systematic approach for identifying and interacting sequentially with stakeholders and gradually building up the necessary information base. To guide and ensure coordination of activities, the Outreach Team used a summary matrix as a working document for planning, coordinating, implementing and following up on interactions with the various stakeholder groups during the five phases. Each plan included the following elements:

- Time frame
- Stakeholder group
- Outreach objective for each stakeholder group
- Activities
- Needed materials/logistics
- Allocation of responsibility to individual team members
- Follow up

Key components or activities and lead responsibilities were:

- Development of informational materials describing the project in layman's terms and providing contact points in the local area (Battelle and AJW). Materials included fact sheets, project snapshots and graphics and exhibits used for public meetings
- Providing project-related information on the MRCSP Web site (Battelle and AJW)
- Ongoing communication with local officials and local residents, especially during the initiation of drilling operations and CO_2 injection testing (FirstEnergy)
- Briefing of key state and federal officials and development of working relationships and open exchange of information with regulatory officials (Battelle and FirstEnergy)
- Press releases, facility tours, and media interviews (joint, coordinated responsibility between Battelle, FirstEnergy, and DOE)
- Briefing and dialogue with national environmental organizations (Battelle).

An example of an outreach planning matrix is presented in Appendix G.

9.2 Information Materials

In collaboration with the site partners, Battelle prepared a series of informational materials that were distributed to the various stakeholders as appropriate and also posted on the MRCSP Web site. Informational materials were developed very early in the project to provide background and basic information on the MRSCP and geologic sequestration, as well as site-specific project information. Outreach materials were provided to the officials and the local public to educate them about sequestration and inform them of plans for field testing in their area. Fact sheets particularly relevant to the project included the following:

- Carbon Dioxide Storage Field Demonstration at FirstEnergy's R.E. Burger Plant: Project Overview (Appendix G)
- About the Midwest Regional Carbon Sequestration Partnership
- Regional Carbon Sequestration Partnerships
- Climate Change
- Carbon Sequestration
- Geologic Sequestration of Carbon Dioxide

- Phase II Carbon Dioxide Storage Field Demonstration: Overview
- Phase II Carbon Dioxide Storage Field Demonstration: The Field Demonstration Plan
- Phase II Carbon Dioxide Storage Field Demonstration: Safeguards.

In addition, the MRCSP Web site included a link to the R.E. Burger site web page where informational materials (e.g., fact sheets, briefing packages, meeting information) could be downloaded. A short video of the seismic survey at the R.E. Burger plant was developed and distributed to the host site and also posted to the MRCSP Web site. Regular updates were provided as the technical activities progressed. A key feature of the Web site is the periodic posting of "snapshots" – a series of photographs, accompanied by a brief summary of site activities that tells the project story graphically and in relatively simple terms.

9.3 Employee and Public Informational Meetings

Outreach efforts with local stakeholders were primarily focused on preparing for public involvement related to permitting at the R.E. Burger site. The draft permit was submitted to Ohio EPA on January 17, 2008, and planning for outreach worked backwards from the expected publication of U.S. EPA's Notice of Availability in May 2008. Ohio EPA required a public hearing; however, the Ohio EPA also encouraged MRCSP to hold its own informational meeting, since the public hearing does not offer any opportunities for questions and answers and informal discussion. Ohio EPA expressed its willingness to participate in the MRCSP meeting.

Battelle worked collaboratively with the host site to identify stakeholders and develop agreement on the types of materials to be prepared and the type of activities to be undertaken for each stakeholder group prior to the meeting (e.g., telephone calls, one-on-one informal discussions, media preparation). This strategy proved effective in facilitating discussion and agreement with each host site and flexibility in developing activities tailored to each site context.

The outreach team decided to hold informal public informational meetings on March 6, 2008 for employees at the plant in the afternoon and for the public near the site in the evening to provide an opportunity for informal interactions and learning (Figure 9-1). Advertisements were posted by R.E. Burger staff at the appropriate Shadyside locations. FirstEnergy issued invitations to local and state officials and MRCSP partners. Exhibits, fact sheets and handouts on the MRSCP and the R.E. Burger field test were provided. Three Ohio EPA staff participated with displays. Approximately 20 people attended the meeting and were able to talk informally with members of the technical and outreach teams and Ohio EPA. About 60 employees attended the employee presentation and each employee received an informational packet to take home.

9.4 Public Hearing

The Ohio EPA published a notice that the draft permit was available for public review in the local library and in the legal section of the local newspaper (*Martin Ferry News Herald*), with a more "reader friendly" news release state-wide prior to the hearing (Appendix G). They also notified local governments and their citizen advisory list of citizens who have shown interest in previous hearings/Ohio EPA activities.

The public hearing was held on June 24, 2008. At the hearing, the Ohio EPA allowed the MRCSP to feature a display table with handouts. Representatives from Battelle and FirstEnergy attended the meeting to answer informal questions. Approximately 20 people attended this meeting; about six were local citizens and others were policy makers or affiliated with interested companies. The Ohio EPA provided a presentation and an informal question and answer period before holding a formal hearing for the record. A summary of questions raised and lessons learned are included in Appendix G.

Figure 9-1. R.E. Burger Plant Employee Meeting Held on March 6, 2008

9.5 Presentations, Facility Tours, Media Interviews and Press Releases

Presentations to professional groups, facility tours, media interviews and press releases provided a channel for communicating key developments with national (and international), state, and local stakeholders.

Early in the project (February 2006), the MRCSP conducted a briefing in Washington, DC for environmental groups to share information about carbon sequestration activities in the region and the Ohio River Valley Project. Also, regular project briefings were provided by the MRCSP at the annual DOE Partnership Review Meetings and the MCRSP Partners' meetings. These project briefings and presentations are posted on the MRCSP Web site.

The outreach team provided assistance to the Science Media Group (part of the Harvard-Smithsonian Center for Astrophysics) in creating a video for high-school teachers on carbon sequestration, using the R.E. Burger plant experience. The Science Media Group filmed the documentary on geological sequestration at the R.E. Burger site on January 24–25, 2007 and followed up with additional interviews at Battelle's headquarters and the Ohio Geological Survey Core Lab. The documentary is part of a series on energy being produced by Annenberg Media and will be used for educating teachers about sequestration. The video is accessible via a link on the MRCSP Web site or directly at http://www.learner.org/resources/series209.html.

FirstEnergy, Battelle and Powerspan also hosted a visit to the R.E. Burger site on January 30, 2007, which was attended by about 55 people, including DOE's Assistant Secretary for Fossil Energy and the Executive Director of the Ohio Air Quality Development Authority, Mark Shanahan, and FirstEnergy's executive management. The visit included presentations and tours of the site featuring the drilling of the deep geologic injection well being carried out by MRCSP and the ECO multi-pollutant control process being developed by Powerspan.

Press releases and the public meetings resulted in the following news articles specific to the R.E. Burger test, which were posted on the MRCSP Web site:

- "R.E. Burger Plant Selected for Tests", *The Intelligencer Wheeling-News Register*, March 7, 2008 (in response to the MRCSP/FirstEnergy informational meeting held March 6, 2008).
- "More Tests Needed for Carbon Dioxide Proposal", *Akron Beacon Journal*, May 22, 2008 (in response to "Report Released on the Geology of Ohio's Potential Carbon Dioxide Sequestration Site," ODNR press release, May 21, 2008).
- "Permit Sought for Underground Injection of Carbon Dioxide," *Akron Beacon Journal*, May 28, 2008 (in response to "Ohio EPA to Accept Comments about Carbon Sequestration Project," Ohio EPA press release, May 27, 2008).

10.0 Conclusions

CO_2 injection testing was completed at the MRCSP Phase II R.E. Burger test site to explore geologic storage targets in the Appalachian Basin. The project included the following major tasks:

- Preliminary evaluation of geologic framework for CO_2 storage in the area,
- Drilling a 8,384 ft deep test well at the R.E. Burger facility,
- Characterization of deep rock formations with wireline logs and sidewall core testing,
- Completion of the Ohio EPA UIC permitting process,
- Design of a CO_2 injection system and test plan,
- CO_2 field injection testing in the Oriskany, Salina, and Clinton-Medina rock formations,
- Completion of a stakeholder outreach program to inform pertinent stakeholders on the project and CO_2 storage technology in general,
- Site closure of the well, including well plugging and closure monitoring.

The R.E. Burger site was targeted as a Phase II test site for several reasons:

- Its location in the Appalachian Basin, which is a major power generation corridor for the region with relatively little data on deep geology for sequestration.
- The possibility of integrating injection tests with an experimental carbon capture process to be piloted at the R.E. Burger plant by Powerspan as a source of CO_2.
- FirstEnergy's willingness to offer the plant as a demo site and collaborate in performing several key aspects of the project, including, planning, outreach, CO_2 supply, permitting, and monitoring.

Two geological formations, the Oriskany and Clinton/Medina (both sandstones), were identified as the original injection targets at this site. Phase I geological characterization efforts had shown these two formations as being significant possible reservoirs for the region, together comprising an estimated 17% of the region's storage capacity (Carbon Sequestration Atlas). The Mount Simon at 42%, the St. Peter at 17%, and the Rose Run at 9.5% are the only other significant sandstone reservoirs in the region and most of their capacity is in the western part of the region including Michigan, but not in the Appalachian Basin.

The Phase I work also showed that the Oriskany and Clinton/Medina sandstones were variable across the region in terms of porosity, permeability and other characteristics important to defining sequestration potential and not well documented in terms of deep well data.

It was in this context that the R.E. Burger site was chosen for Phase II and was selected as a test site. There was an expectation at the time that not only could a test of 3,000 to 10,000 tonnes be carried out at the site within reasonable cost and time, but that the tests would indicate what the broader potential of these formations was for CO_2 storage in a regional context.

Data from the test well at the R.E. Burger site showed that porosity and permeability of the Oriskany and Clinton/Medina sandstones were on the lower end of what would have been expected for these formations on a regional basis (average porosities less than about 6% and permeability less than 0.1 mD). However, the Salina (at a depth of about 6700 to 7000 ft), a carbonate formation, was found to have porosity and permeability that would cause it to also be considered as a test injection target.

Efforts to align the MRCSP's injection schedule with the Powerspan capture system test were not successful and, in March 2008, a decision was made jointly by FirstEnergy, DOE and Battelle to use the backup option of liquid CO_2 from a commercial source. The Powerspan unit would have supplied 20 metric tons per day of CO_2, which would have required about 7 months to reach the goal of 3000 tonnes of injection allowing for down periods planned for the Powerspan unit. The capacity of the commercial liquid CO_2 system from Praxair was about 200 tonnes per day and plans were made to have the injection rig operable for about a six-week period, implying an expected average injection rate for the 3,000 tonne test injection of about 100 tonnes per day.

Injection testing in all three target zones showed rapid pressure rise at very low flow rates, even less than the 20 tonnes per day that would have been supplied by the Powerspan capture unit. This was especially surprising for the Salina formation. Also surprising was that the fracture pressure found during the step rate test required by permit was significantly higher than would have been predicted by conventional guidelines (more than 1 psi per foot of depth versus the guideline of 0.75 psi per foot).

Predicting injectivity, especially for injection of CO_2 into deep saline formations in a relatively unexplored area like that at the R.E. Burger site, has a higher degree of uncertainty than subsurface injection and production operations like that in the heavily drilled and evaluated oil and gas fields. For instance, hydraulic analysis would have predicted injection rates approaching 50 tonnes per day for the Salina at pressures less than 2000 psi whereas injection rates of less than 20 tonnes per day were not sustainable at twice that pressure. On the other hand, similar predictions for the injection test at the MRCSP Michigan Basin site near Gaylord, Michigan underestimated the injection rates possible within the pressure bounds of the injection permit. As more data become available at any site, the range of uncertainty in these models can be reduced.

10.1 Lessons Learned

Recommendations and lessons learned from the R.E. Burger test include the following:

- Communicate clearly what the expectations for injection are at each of the key stages during the project, especially at the point the site is selected for testing and following the acquisition of downhole data from the test well, but prior to mobilization of the injection equipment.
- Take adequate time during drilling to acquire log and core data to provide a firm basis for expectations. This has to be a tradeoff with the overall cost of drilling and logging the test well, which is a substantial portion of the cost for the overall injection test. However, the geologic knowledge for any area is developed over a period of time as more data become available from drilling of multiple wells and injectivity relationships for different rock types are developed.
- The higher fracture pressures found during testing might have allowed a higher injection pressure for the permit. That would have allowed a wider range of testing conditions, especially injection at higher pressure. However, it is not certain that such higher injection pressure would have led to exponentially higher injection rates. It would also have been useful to try stimulation and fracturing of the rocks to evaluate connection between porous zones. This was not allowed in the UIC permit issued by Ohio EPA and adding it to the permit would have required careful consideration by the regulators for this type of well.

- Characterization methods (rock core tests, wireline logging, geologic logging) may only provide indicators of injectivity. Injection potential needs to be proven with field injection tests.
- Carbonate formations like the Salina need to be evaluated more carefully, as evaporite/salt layers may affect the potential to inject CO_2. These layers may also be a technical challenge for drilling and well completion.
- A well stimulation/hydraulic fracture operation was not completed in the well per Ohio EPA UIC permit restrictions. The formations that were tested are commonly fractured for oil and gas production. Consequently, it may have been possible to obtain better injection results after hydraulically fracturing the well. Given the relatively low injection volumes, well stimulation was not considered during the test design. However, the flexibility to complete a hydraulic fracture operation in the near well bore may be an important consideration for future CO_2 sequestration in the Appalachian Basin.
- This site highlights the value of these smaller, research-oriented tests, which do not involve large capital investment compared to full-scale application.
- An easier mechanism than existing EPA UIC regulations would help facilitate smaller tests.

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APPENDIX A

PRELIMINARY GEOLOGICAL ASSESSMENT OF THE GENERAL AREA

Preliminary Geologic Assessment of the Burger Power Plant and Surrounding Vicinity for Potential Injection of Carbon Dioxide

Prepared for
Battelle Memorial Institute
Columbus, Ohio

By

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June 2006

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B. Listing of core or core analyses of interest.
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PRELIMINARY GEOLOGIC ASSESSMENT OF THE BURGER POWER PLANT AND SURROUNDING VICINITY FOR POTENTIAL INJECTION OF CARBON DIOXIDE

INTRODUCTION

This report, compiled for the Midwest Regional Carbon Sequestration Partnership (MRCSP), is a preliminary feasibility study of the geological sequestration potential for a proposed geologic CO_2 sequestration test demonstration project at the Burger Power Plant located in Belmont County, Ohio. The MRCSP is one of seven regional partnerships funded by the U.S. Department of Energy to investigate the potential for carbon capture and storage in the United States. This partnership, lead by Battelle, includes research institutes and government agencies from the states of Indiana, Kentucky, Maryland, Michigan, Ohio, Pennsylvania, and West Virginia plus several industry partners. In Phase I of the partnership, a regional geologic assessment summarized the subsurface geology of the MRCSP region in terms of potential reservoirs and seals for carbon sequestration (Wickstrom and others, 2005). For Phase II, up to three sites will be proposed within the MRCSP region for field tests in order to evaluate carbon-sequestration methodologies in geologic reservoirs.

Using the Burger Power Plant site for a geologic CO_2 sequestration test project is proposed as part of the MRCSP Phase II sequestration assessment. The objective of this report is to summarize the geology and data availability in the immediate vicinity of the Burger site, and provide also a preliminary characterization of known geologic reservoirs and sealing units for use in further assessment work, developing the test well design, and implementing the various requirements for carbon capture and storage at the Burger site as well as in the acquisition of any underground-injection permit and the subsequent monitoring plan.

The principle investigators for this feasibility study were Mark Baranoski, Ernie Slucher, and Larry Wickstrom of the Ohio Division of Geological Survey (DGS). Additional contributions were made by Kristen Carter of the Pennsylvania Geological Survey (PGS), Lee Avary of the West Virginia Geological and Economic Survey (WVGES).

LOCATION

The Burger Power Plant is located at the southeastern edge of a large flood plain on the west side of the Ohio River at Dilles Bottom, Belmont County, Ohio, on the Businessburg 7.5-minute U.S.G.S. quadrangle (fig. 1). It is approximately four miles south of Shadyside, Ohio and directly across the Ohio River, and southwest of Moundsville, West Virginia. In this report, use of the term "site" refers to the area in the immediate vicinity of the Burger Power Plant.

METHODS

A geologic characterization was conducted for the area within a 20-mile radius of the site, herein referred to as the "AOR" (area-of-review). This included portions of Belmont, Harrison, Jefferson, and Monroe Counties, Ohio, Greene and Washington Counties, Pennsylvania, and Brooke, Marshall, Ohio, and Wetzel Counties, West Virginia (fig. 2). Additionally, because of a paucity of data on deep geologic units, some well data was used from as much as 30-miles distant.

Data used for this preliminary site assessment were acquired from public records at the West Virginia Geological and Economic Survey (WVGES), the Pennsylvania Geological Survey (PGS), and the Ohio Division of Geological Survey (DGS). Available geologic literature, basic geologic maps, and data on coal and coal mines, oil and gas wells, petroleum storage fields, brine solution wells, and core hole records were compiled and analyzed.

Wells in the text and figures are referred to by both lease name and the American Petroleum Institute's well-identification number (APINO). The APINO is a national standardized method for assigning unique identifiers to oil and gas wells. It is expressed as a 10-digit number with the first 2 digits representing the state code, the next 3 numbers representing the county code, and the next 5 numbers representing the permit number.

Stratigraphic terminology used in this report is that currently accepted by the DGS and can be found in Larsen (1998), Riley and others (1993), and Baranoski (in prep). Figure 3 is a stratigraphic chart for strata underlying the Burger AOR adapted from the MRCSP phase I report (Wickstrom and others, 2005).

Presently, 6,257drill holes are on file at the WVGS, PGS, and DGS in the 20-mile AOR. The majority of these were drilled for oil and gas (including coalbed methane). The results of analyses using the well records were constrained because of the age of drilling within this area. Much of the drilling pre-dated modern regulations; thus very little information is available for many of the wells. For instance, only 3,056 of the 6,257 wells in the AOR have a total depth (TD) listed as part of the well record (fig. 4); thus, additional data may exist in company records of current and historic operators in the Appalachian basin on deeper geologic units within the AOR. A listing of all wells within the AOR is attached as appendix A (Excel spreadsheet). Furthermore, very little core or analyses are available within the AOR for rocks below the coal measures (Appendix B) Other subsurface records available in the AOR are either from coal stratigraphic test holes or from wells drilled for brine solution operations.

A dip cross-section was constructed across the AOR (see fig. 4 for location) to illustrate the regional stratigraphy including the potential injection zones and confining units. For graphical clarity, the cross section is split into a shallow section and a deep section and these are presented as figures 5 and 6. Datums used for the shallow and deep sections were the top of the Onondaga Limestone and the Dayton Formation\"Packer Shell", respectively.

Time allowed for this assessment precluded mapping depth and thickness of units via interpretation of formation boundaries and properties from a large number of geophysical logs. In addition, because of the age of many of the wells in this region, many of the wells did not have geophysical logs run in them. Therefore, driller's reported formation depths were used to create two structure (depth below sea level) contour maps on the top of the Berea Sandstone and the Oriskany Sandstone (figures 7-8). Maps created solely from reported driller's tops are prone to error because there is no way to ascertain the validity of the depths for all the wells.

As mentioned, very few wells exist in the AOR that penetrate deeper than the Onondaga Limestone. Therefore, maps for deeper horizons were cut from larger regional maps from the MRCSP phase I geologic report (Wickstrom and others, 2005). It should be pointed

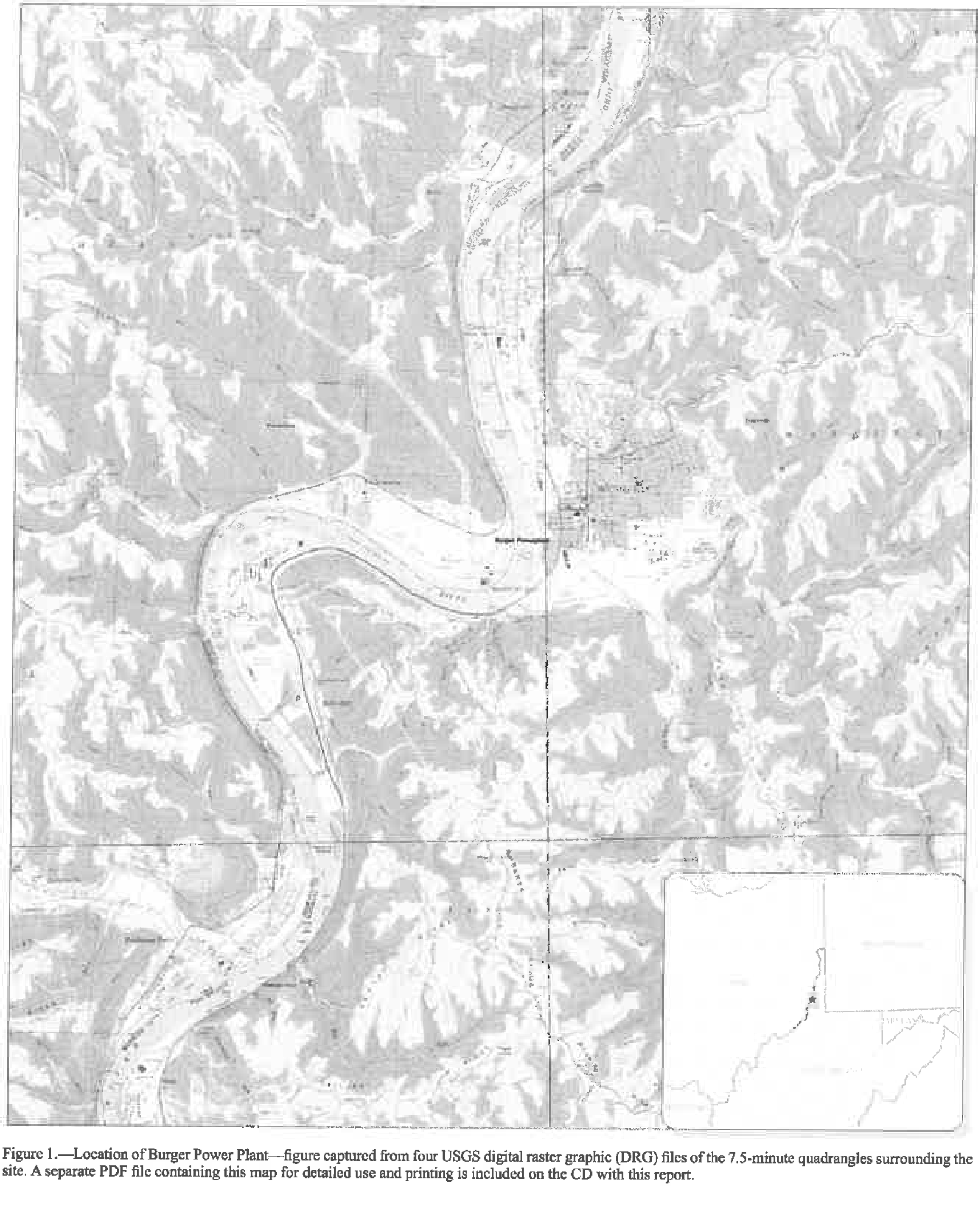

Figure 1.—Location of Burger Power Plant—figure captured from four USGS digital raster graphic (DRG) files of the 7.5-minute quadrangles surrounding the site. A separate PDF file containing this map for detailed use and printing is included on the CD with this report.

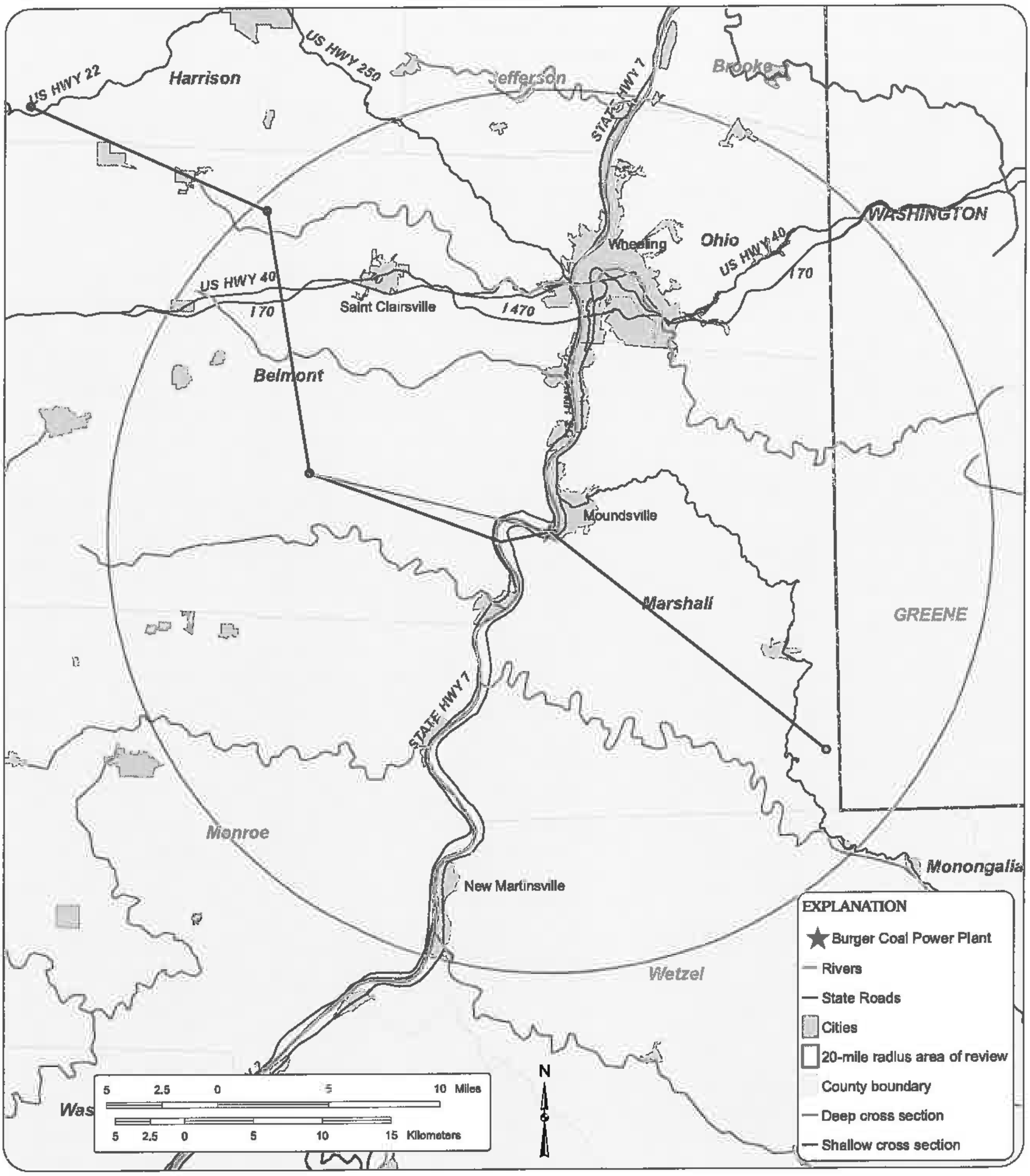

Figure 2.—Map of the Burger site with 20-mile radius area of review (AOR) shown. Line of cross section (figs. 5 & 6). The shallow portion of the cross section contains one control point not used on the deep section.

Regional Correlation and CO_2 Sequestration Characterization of Geologic Units in the MRCSP

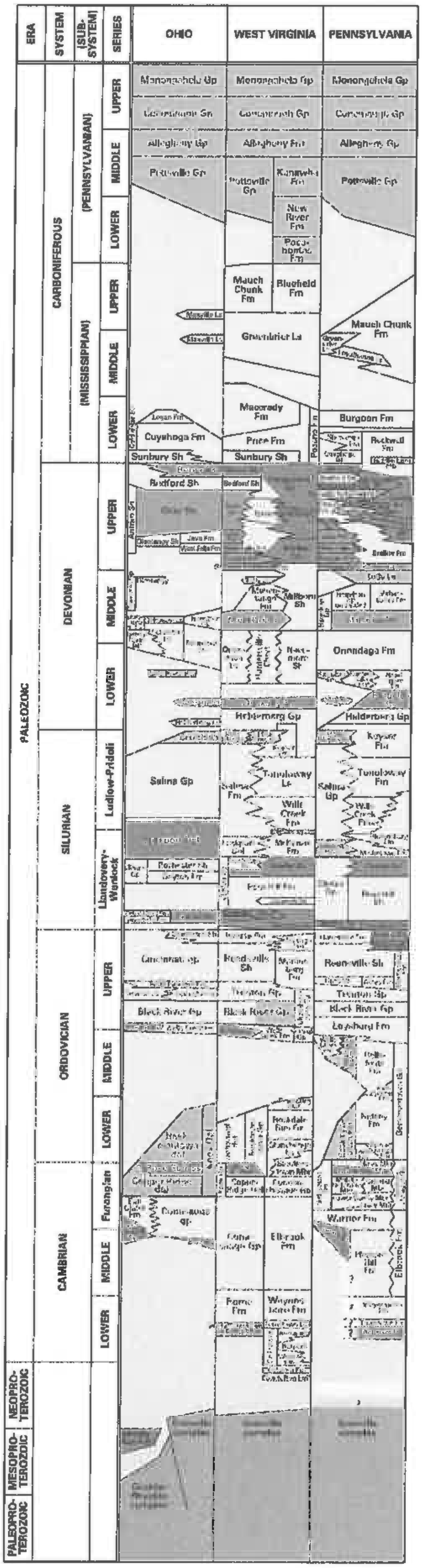

Figure 3.—Stratigraphic correlation and CO_2 sequestration characterization chart of geologic units in Ohio, Pennsylvania, and West Virginia (modified from Wickstrom and others, 2005).

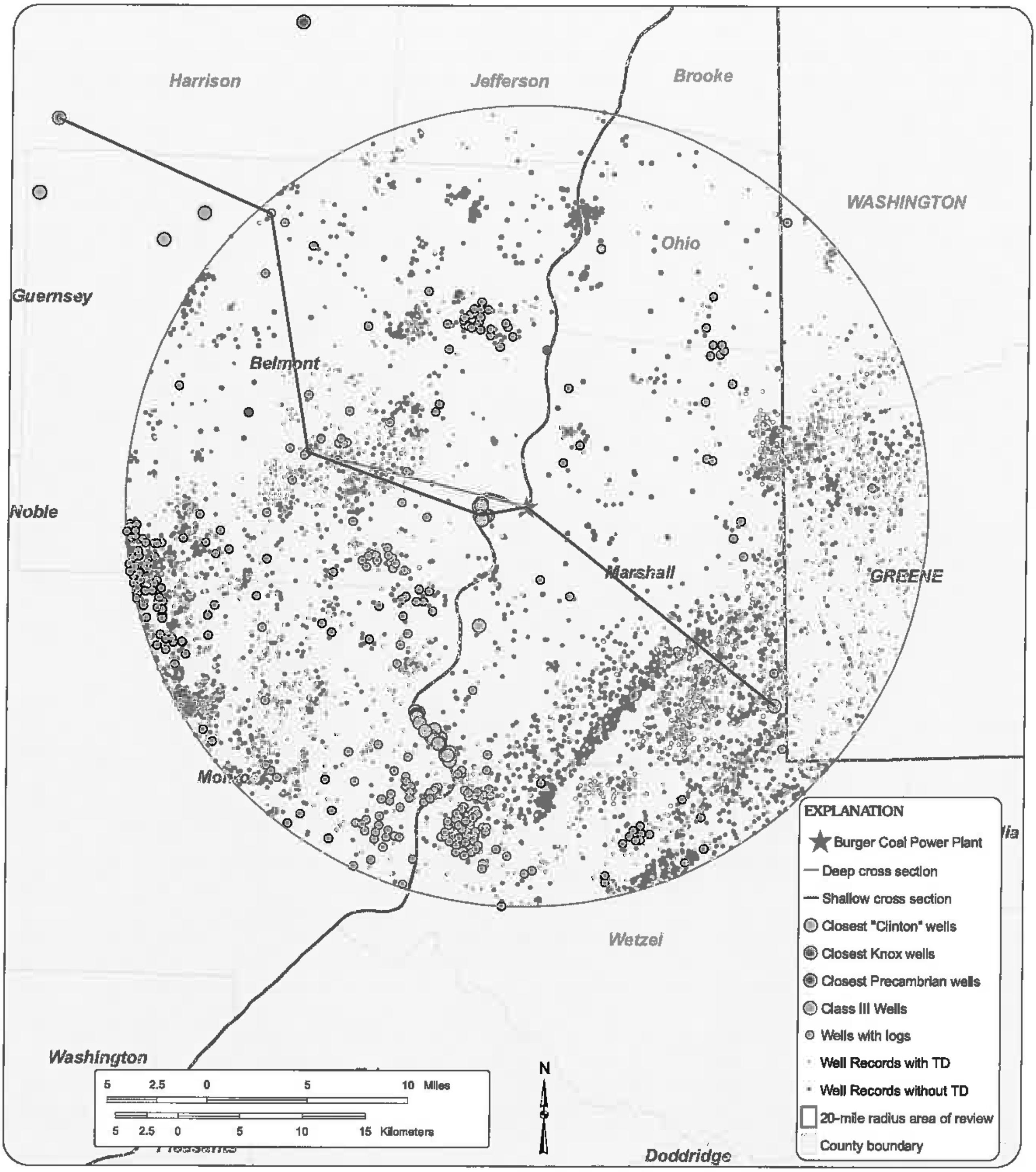

Figure 4.—Map of oil, gas, and solution mining wells located within the Burger AOR. Line of cross section (figs. 5 & 6). The shallow portion of the cross section contains one control point not used on the deep section.

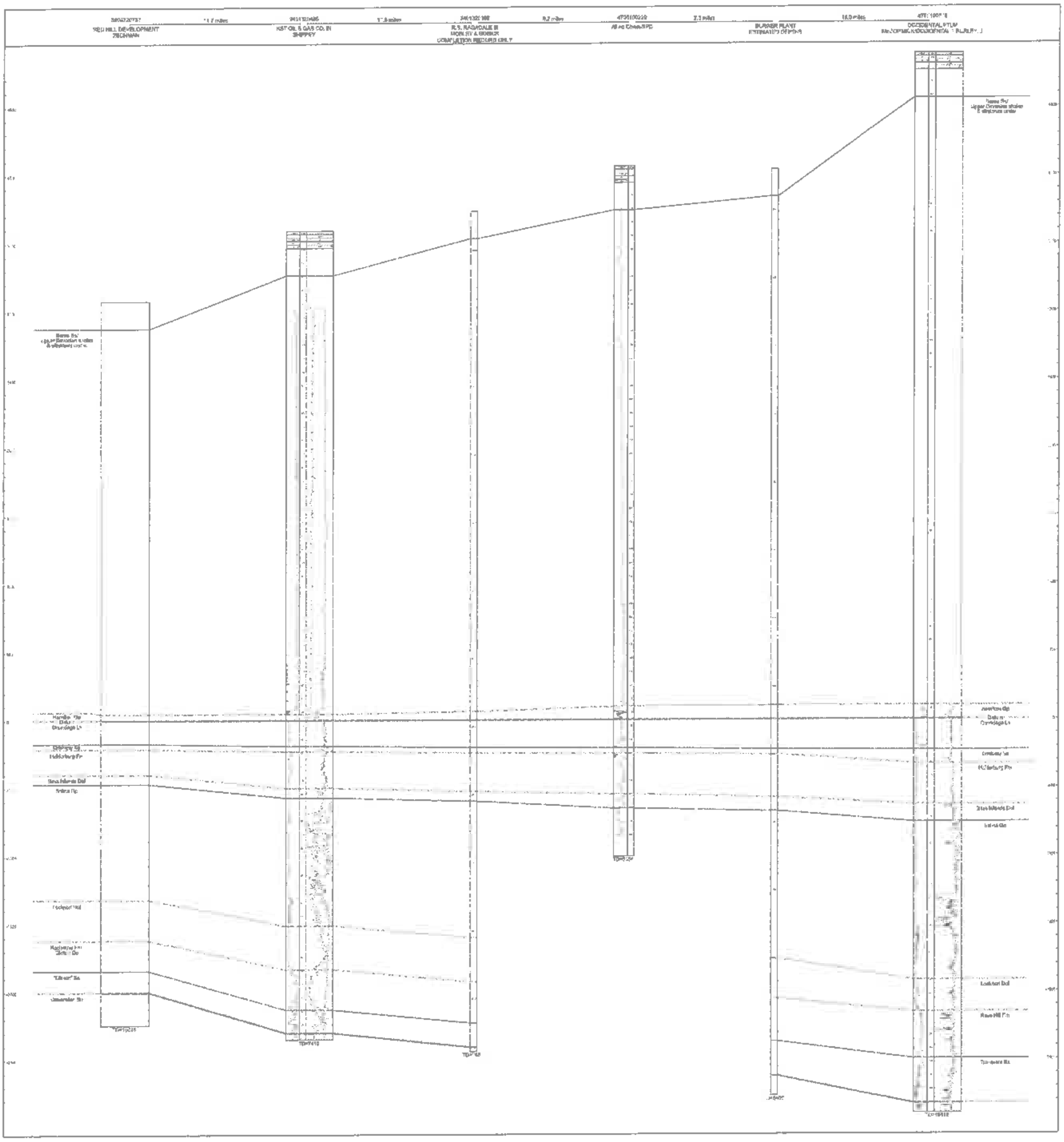

Figure 5.—Stratigraphic cross section oriented northwest-southeast across the AOR showing stratigraphic correlations and geophysical log signatures of shallow geologic units (Queenston Shale thru the Berea Sandstone). Datum is the top of the Onondaga Limestone. See figure 2 for location of line. A separate PDF file containing this cross section for detailed use and printing is included on the CD with this report.

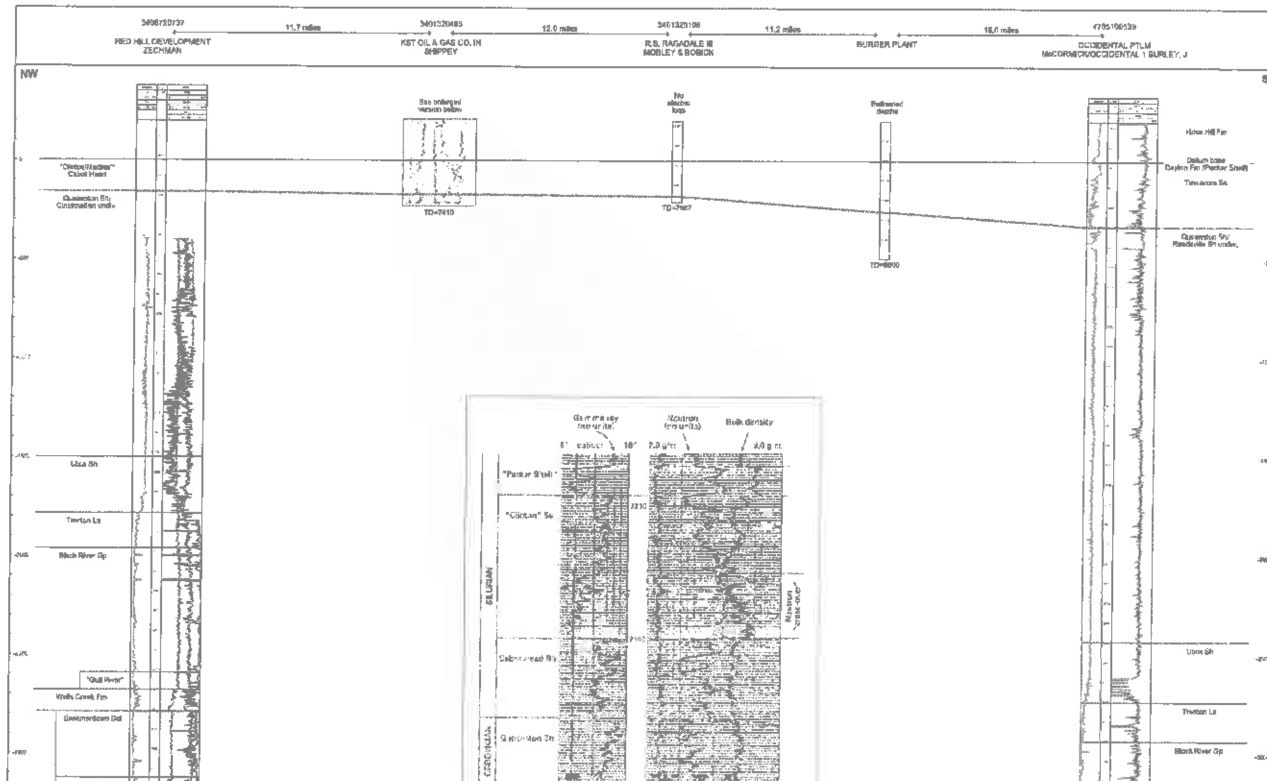

Figure 6.—Stratigraphic cross section oriented northwest-southeast across the AOR showing stratigraphic correlations and geophysical log signatures of deep geologic units (Precambrian thru the Rose Hill Formation). Datum is the base of the Dayton Formation (Packer Shell of drillers). See figure 2 for location of line.location. Inset shows geophysical log from a Belmont County, Ohio well (API no. 3401320485) illustrating gamma ray, density, and neutron curves for the lower Silurian "Clinton-Medina" sandstone and "gas effect" at neutron/density "cross over". A separate PDF file containing this cross section for detailed use and printing is included on the CD with this report.

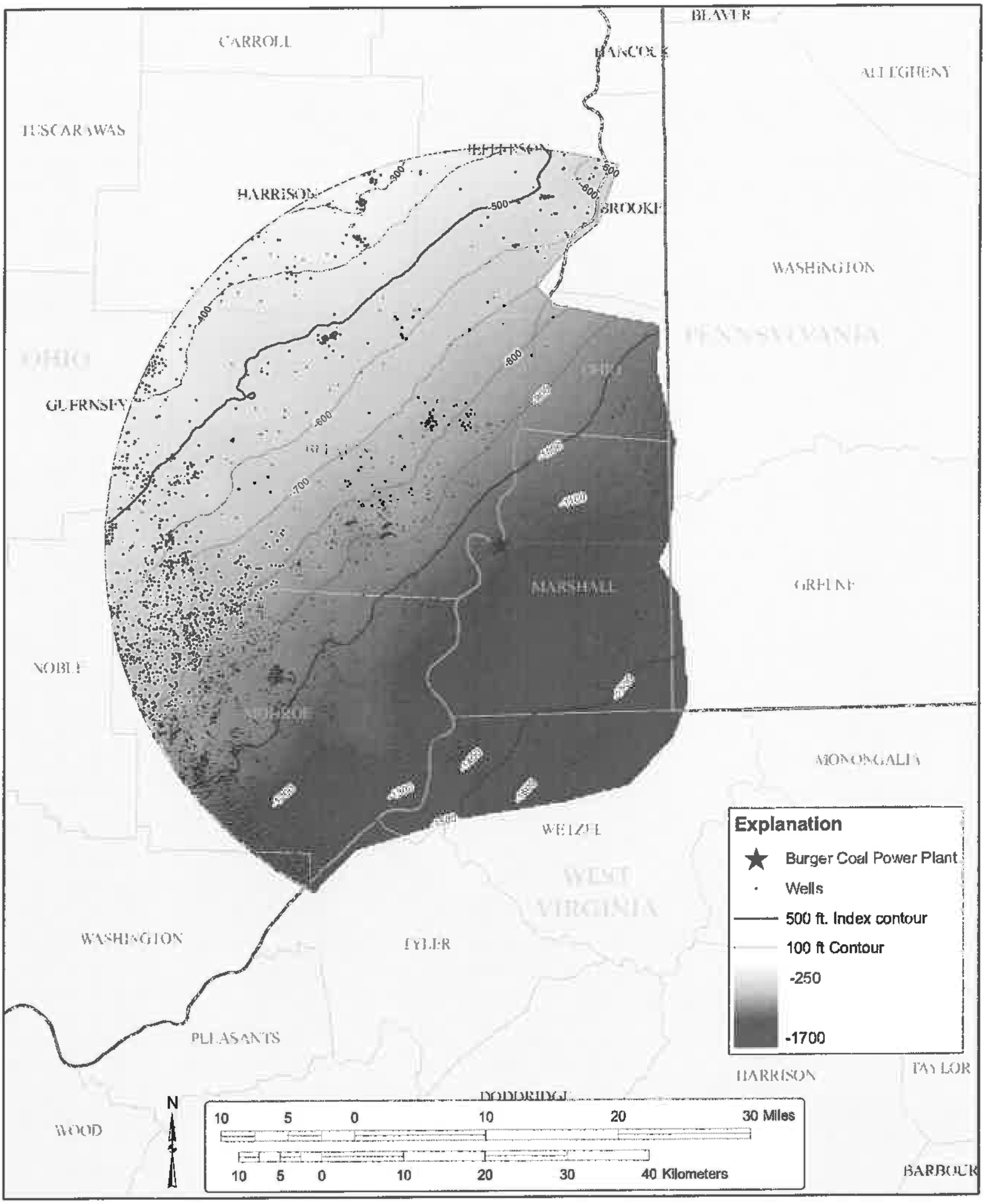

Figure 7.—Structure contour map on the top of the Berea Sandstone within the Burger AOR. Map computer contoured from formation tops taken from driller's records.

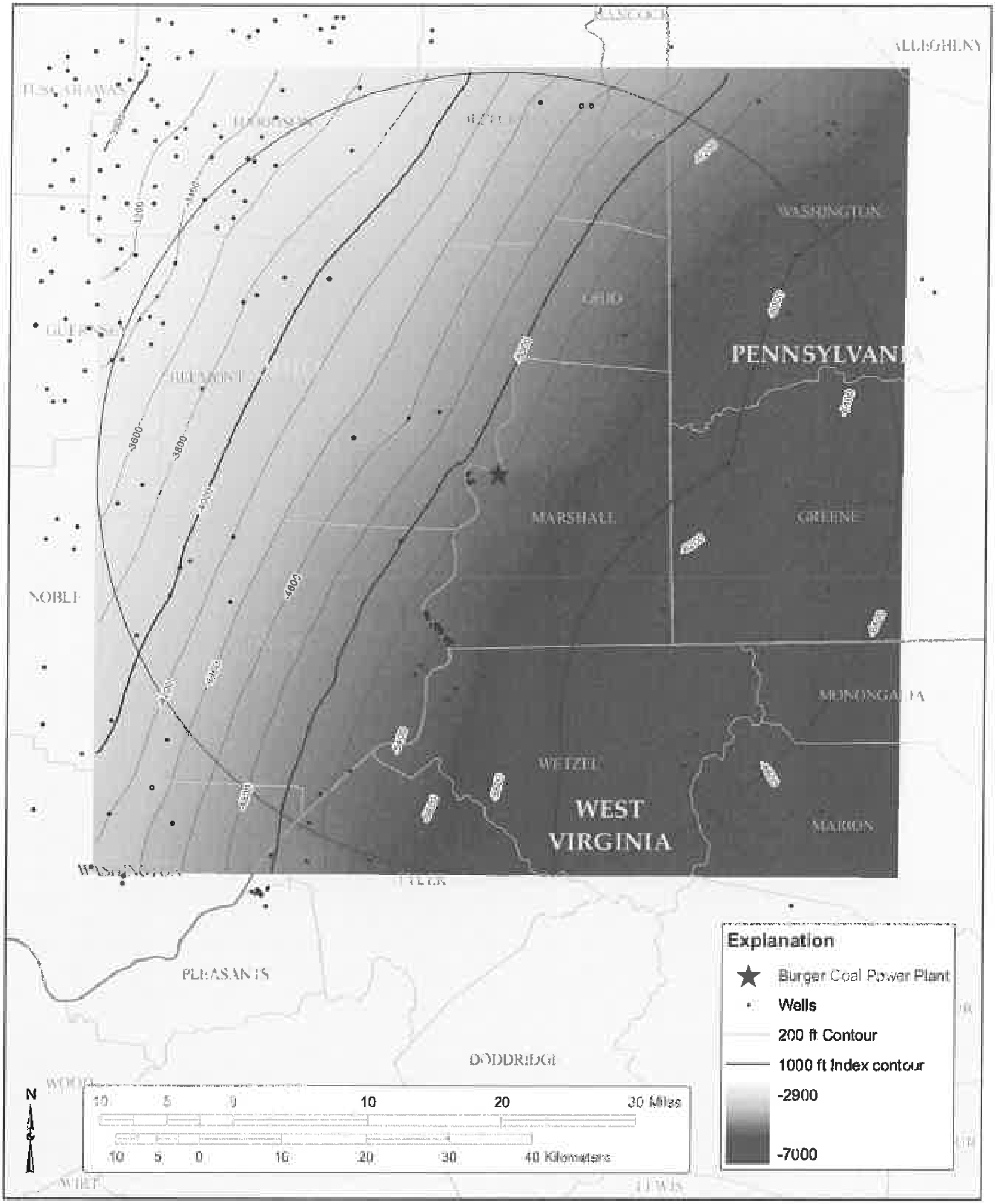

Figure 8.—Structure contour map on the top of the Oriskany Sandstone within the Burger AOR. Map computer contoured from formation tops taken from driller's records.

out that depths or thicknesses at any one point on the computer-generated maps may vary considerably from the actual depth as the maps are best-fit approximations based on grids that are insufficient for site specific accuracy. Thus, the contour maps presented, especially the regional maps, are used only to show general depth and thickness trends not absolute values.

PREVIOUS WORK

No previous detailed deep-subsurface investigations of prospective geologic reservoir and sealing units viable for carbon storage have been conducted for the Burger Power Plant AOR. Several subsurface regional studies of shallow strata (Devonian or shallower) using oil and gas well control have been published (Haught, 1955; Roen and others, 1978; Cardwell, 1979, Schweitering, 1979; Gray and others, 1982; Gas Research Institute, 1989).

Member agencies of the MRCSP team have conducted several geologic investigations over the past 25 years that are of note for the Burger area. The MRCSP Phase I Task Report (Wickstrom and others, 2005) was the source for most stratigraphic data and maps used in this analysis. The Phase I report contains an assemblage of databases and maps depicting the general distribution of the geologic reservoirs and seals in the subsurface of the seven-state MRCSP region.

The Rome Trough Consortium (Harris and others, 2002) investigated the subsurface stratigraphy of sub-Knox group units within, and adjacent to the Rome trough in eastern Kentucky, southeastern Ohio, and northern West Virginia. Included in the final report of the consortium is a database listing the identified tops of geologic units, deep-core descriptions, regional maps of sub-Knox sandstone reservoirs plus information on known hydrocarbon geochemistry in the Rome trough.

The Atlas of Major Appalachian Gas Plays (Roen and Walker, 1996), a comprehensive study of known and speculative gas plays in most portions of the Appalachian basin, facilitated the analyses of some of the geologic horizons in the eastern part of the AOR. One item included in the atlas that may be useful for additional research at the Burger Power Plant are databases on the average geologic and engineering characteristics of each play.

The Eastern Gas Shales Project was a U.S DOE-funded study of the organic-rich Devonian shales in the Appalachian basin (Gray and others, 1982). In addition, this report contains numerous maps on other geologic units—such as the Onondaga Limestone and Berea Sandstone—that may have relevance to the Burger site investigation.

POTENTIAL GEOLOGIC RESERVOIR TYPES

The USDOE has identified several categories of geologic reservoirs for potential CO_2 sequestration (U.S. Department of Energy, 1999, 2004, 2005). Of these categories, four are considered to have potential application at the Burger site. These categories are: (1) deep saline formations, (2) oil-and-gas fields, (3) unmineable coal beds and (4) carbonaceous shales.

DEEP SALINE FORMATIONS

Saline formations are natural salt-water-bearing intervals of porous and permeable rocks that occur beneath the level of potable groundwater. Currently, a number of saline formations are used for waste-fluid disposal in Ohio. Thus, a long history of technological and regulatory factors exists that could be applied to CO_2 injection/disposal. In order to maintain the injected CO_2 in supercritical phase (i.e. liquid), the injection horizons must be at depths of, or greater than, approximately 2,500. Maintaining the CO_2 in a liquid phase is desirable because, as a liquid, it takes up less volume than when in the gaseous phase. One ton of CO_2 at surface temperature and pressure (in gaseous phase) occupies approximately 18,000 cubic feet. The same amount of CO_2, when injected into a formation at a depth of approximately 2,600 feet, will occupy only 50 cubic feet. Sequestration depths of at least 2,500 feet also insure there is an adequate interval of rocks (confining layers) above the potential injection zones to act as geologic seals.

OIL AND GAS FIELDS

Oil-and-gas fields represent known geologic traps (structural or stratigraphic) containing hydrocarbons within a confined reservoir with a known cap or seal. In depleted or abandoned petroleum fields, CO_2 can be injected into the reservoir to fill the pore volume left by the extraction of the oil or natural gas resources (Westrich and others, 2002).

In active oil fields, it has been demonstrated that CO_2 can be used for enhanced oil recovery (EOR). In this process, some of the oil that remains in reservoirs after primary production is recovered by using CO_2 to: (1) repressurize the reservoir and drive the remaining oil to a recovery well (i.e., immiscible flooding at shallow depths), or (2) reduce the viscosity (via mixing/chemical interaction) of the remaining oil and push it to a recovery well (miscible flooding of deep reservoirs). Approximately 70 oil fields worldwide currently inject CO_2 for EOR (U.S. DOE, 2004) thereby demonstrating the effectiveness of this value-added sequestration option. Most existing CO_2-assisted enhanced oil recovery operations are in the western U.S., especially the Permian Basin of west Texas. These fields mainly use naturally occurring sources of CO_2 but recently have been adding anthropogenic sources to their extensive pipeline network. There are no known large, natural-CO_2 sources in the eastern U.S. Having CO_2 available for EOR operations may enable the local oil industry to produce hundreds of millions of barrels of additional oil. Enhanced oil recovery, while sequestering CO_2, could provide a further economic incentive to a long-term sequestration operation at a site such as Burger.

UNMINEABLE COAL BEDS

Unmineable coal beds offer an out-of-the-ordinary option for geologic sequestration because, unlike the previously described reservoir types, CO_2 injected into a coal bed would not only occupy pore space, but would also bond, or adsorb, onto the carbon in the coal itself. The adsorption rate for CO_2 in bituminous coal is approximately twice that of methane; thus, in theory, the injected CO_2 would displace methane, allowing for the potential of enhanced gas recovery (Reznik and others, 1982; Gale and Freund, 2001; Schroeder and others, 2002) while at the same time sequestering twice the volume of CO_2. Because of the adsorption mechanism, concerns of miscibility that occur in oil-and-gas reservoirs are not an issue. Thus, the injection of CO_2 and resulting enhanced recovery of coal bed methane could occur at shallower depths than for depleted oil reservoirs and deep saline formations.

CARBONACEOUS SHALES

Analogous to sequestration in coal beds, CO_2 injection into unconventional carbonaceous-shale reservoirs could be used to enhance existing gas production. As an added bonus, it is believed the carbonaceous shales would adsorb the CO_2 into the shale matrix, similar to the properties of coal, permitting long-term CO_2 storage, even at relatively shallow depths (Nuttall and others, 2005). Sequestration of CO_2 in carbonaceous shales has not been demonstrated and is still in the research stage.

SURFACE AND NEAR-SURFACE SITE CHARACTERIZATION

The proposed site is located in the Little Switzerland Plateau of the Allegheny Plateaus physiographic province (Brockman, 1998). This province is classified as a highly dissected plateau with high relief, and is characterized by topographic relief of as much as 450 to 750 feet, especially along the Ohio River. The elevation of the site is about 640 feet above sea-level while within a mile to the northwest the ridge top elevation is 1,240 feet. Thus relief adjacent to the site is about 600 feet. Also, the site occurs in the Ohio coalfield, a historic area of extensive coal and clay mining since the early 1800s (Slucher and others, in press).

The site occurs well south of the southern limit of the known glacial advance within Ohio (Pavey and others, 1996). Typically, at the base of local hill slopes, valleys and tributaries occur and are filled with many tens of feet of unconsolidated deposits. A waterwell at the site penetrated 85 feet of unconsolidated rock debris before encountering bedrock. These sand and gravel deposits were formerly mined south of the community of Dilles Bottom (fig. 1), however, the depth of the remaining gravel pits is unknown. Generally, in areas of significant topographic relief, and in those areas unaffected by mining, bedrock occurs at the surface, or is covered with a thin veneer (<10 feet) of colluvium. However, extensive areas of unreclaimed and reclaimed strip-mines occur in many areas of the AOR. In areas reclaimed to the original topographic configuration, extensive deposits, many tens to perhaps a hundred feet thick, of amalgamated shale, limestone, sandstone, and other types of rock may exist between the present-day land surface and the rock surface (which denotes the lowest stratigraphic limit by surface mining methods).

The hills immediately north of the site are underlain by numerous underground coal-mines. Mining was for the Pittsburgh coal, which is 5 to 7 feet thick and about 200 feet below the surface in the area immediately north of the site. Most mining stopped once the area of coal extraction reached the margin of the Ohio River floodplain. No records exist of any significant coal mining operations extending beneath the floodplain, and thus, beneath the site (fig. 9). Detailed annual and abandonment maps for the individual underground mines shown on figure 9 are available from the respective state geological surveys.

LOWEST UNDERGROUND SOURCE OF DRINKING WATER

The lowest underground source of drinking water (USDW), as defined (<10,000 ppm TDS) by the U.S. EPA near the R. E. Burger site in southeastern Belmont County is the Pennsylvanian Upper and Lower Freeport sandstone of the Allegheny Group (Vogel, 1982). Based upon Vogel's map (1982), the elevation of the Upper and Lower Freeport sandstone ranges from 300 feet above sea level on the northern side of the AOR to an estimated 500 feet below sea level on the southern edge. At the proposed site, the USDW is approximately 100 feet below sea level (approximately 750 feet deep). While limited domestic supplies of potable water are obtained from these thin Pennsylvanian sandstone beds, larger industrial and municipal water supplies are mostly taken from thick, permeable sand and gravel deposits in valley fill material that is hydraulically connected and adjacent to the Ohio River (Walker, 1991).

REGIONAL GEOLOGIC SETTING

The Precambrian basement complex is the foundation for overlying Paleozoic Era (and younger) rocks of eastern North America. In general terms, the Precambrian complex of the region includes all rocks older than 542 million years, and Paleozoic rocks include rocks less than 542 million years old. A thorough understanding of the geologic structure, character and history of the underlying Precambrian complex is necessary in order to understand the geologic framework of the Paleozoic strata. Therefore, a very general description is provided based on our interpretation of the limited data.

The Precambrian basement complex in this region consists of portions of the Grenville Province, East Continent Rift System, and the Eastern Granite-Rhyolite Province (fig. 10). On magnetic anomaly maps, Grenville Province metamorphic and igneous rocks of high magnetic susceptibility east of the Grenville Front show pronounced positive anomalies against less magnetic rocks of the Eastern Granite-Rhyolite Province west of the Grenville Front (Bass, 1960; Lucius and von Frese, 1988). U/Pb age dates have not been determined for the Eastern Granite-Rhyolite Province or Grenville Province in Ohio. However, regional geochronological investigations outside Ohio indicate the Eastern Granite-Rhyolite Province is approximately 1.3 to 1.4 GA (Van Schmus et al., 1996), and the Grenville Province is approximately 1.0 to 1.2 GA (Culshaw and Dostal, 2002).

The Grenville Province (Grenville Domains) is an extension of the Grenville metamorphic and igneous terrane exposed in southern Canada, and consists of regionally metamorphosed igneous and sedimentary rocks formed during the Grenville Orogeny. The Grenville Province underlies eastern Ohio and adjacent Pennsylvania and West Virginia, and forms the underpinning structure beneath Paleozoic sedimentary cover. The Grenville Province is known to contain numerous fault blocks where it has over ridden the East Continent Rift System in central and western Ohio. However, few deep-seated faults are known within the Precambrian in eastern Ohio (fig. 11). Some Precambrian faulting is noted on the COCORP seismic profile in northern Belmont County (fig. 11), but how far these faults might extend southward is unknown.

Two regional structural features developed on the eastern Laurentian craton, which was the deeply eroded Grenville Province: the Rome Trough (McGuire and Howell, 1963) and the Appalachian Basin (fig. 10). The Rome Trough, which was first described by Woodward (1961) as a "Cambrian coastal declivity," is considered an Early to Middle Cambrian-age failed interior rift (Harris, 1978). The Rome Trough is a regional northeast trending structure extending from southwestern Pennsylvania, where it is termed the Olin Basin (Wagner, 1976), to northern Tennessee and is very prominent on magnetic intensity maps (King and Zietz, 1978). Sparse deep-well data and seismic reflection data correlate to this magnetic trend and indicate the Rome Trough is an asymmetric failed-rift zone with the deepest portion on the NW side (Ryder and others, 1998; Gao and others, 2000). It is thought that the western boundary faults of the trough are located approximately 8 miles southeast of the Burger site (fig. 11). However, there is a possibility that smaller normal

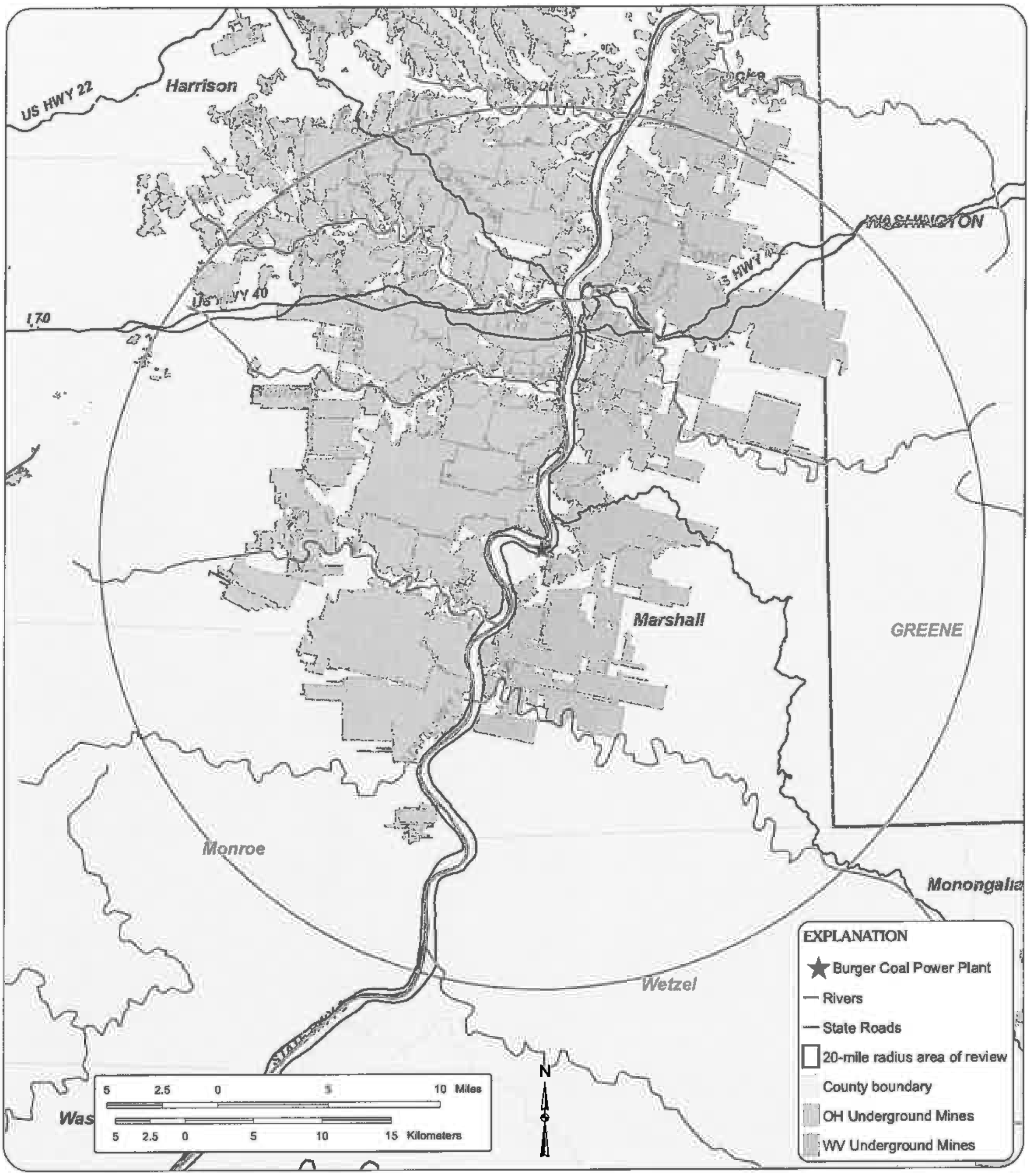

Figure 9.—Map showing the locations of abandoned underground mines within the Burger AOR.

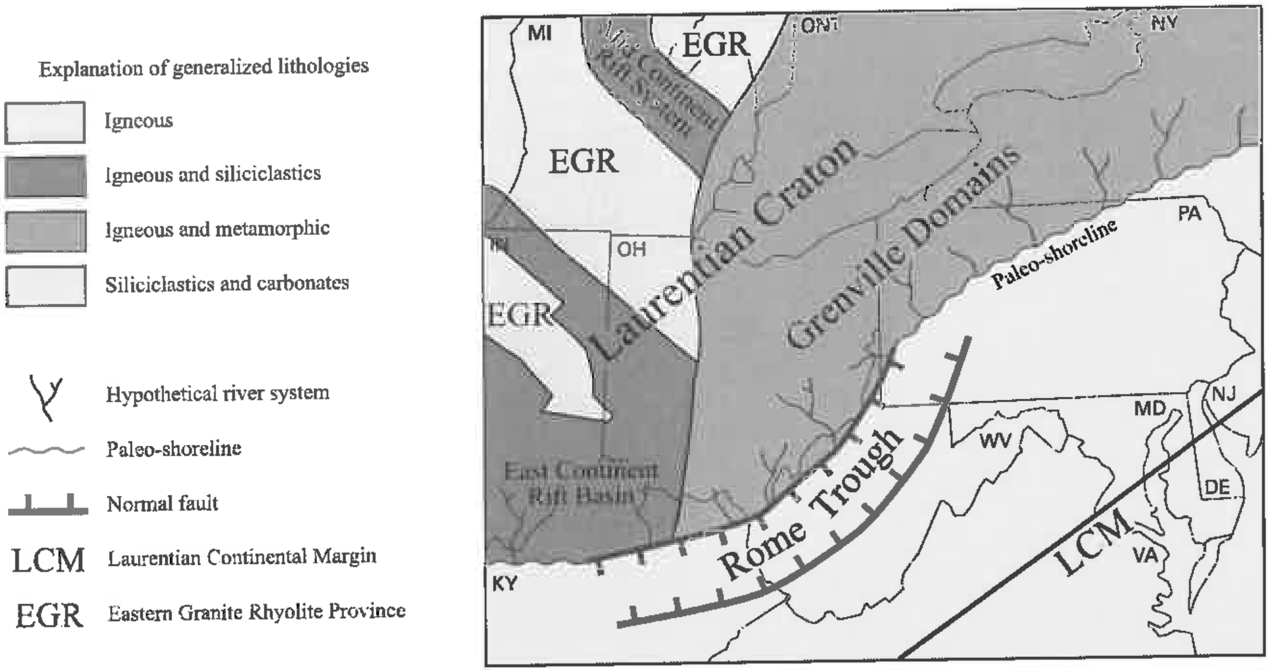

Figure 10.—Map showing the locations of major geologic elements (paleogeography) during early Cambrian time (from Baranoski, in prep).

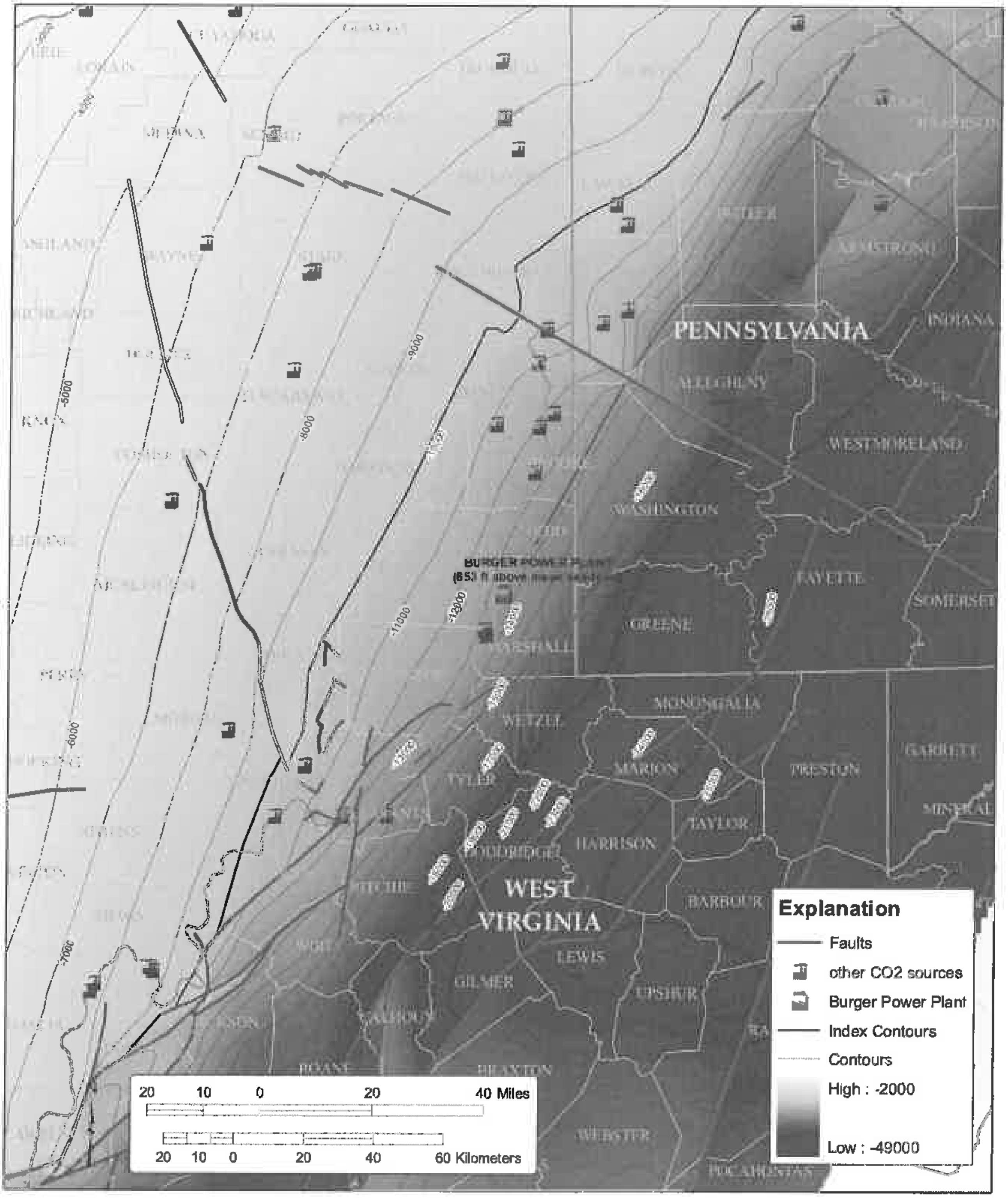

Figure 11.—Structure contour map on the top of the Precambrian unconformity within the Ohio, Pennsylvania, and West Virginia region. Also shown is the location of major (>100,000 tons per year) point sources of CO_2. Map elements taken from Wickstrom and others, 2005.

faults, down to the southeast, parallel to and associated with this system will be found closer to the site, stepping-down to the major border faults.

The Appalachian Basin did not begin to take on its present configuration until after Middle Cambrian time following the major movement of the Rome Trough. The Rome Trough is thought to have controlled, in part, the formation and orientation of the northern Appalachian Basin. The subsidence of the Appalachian Basin culminated with the Alleghenian Orogeny and development of the Appalachian structural front.

PALEOZOIC STRATIGRAPHY AND GEOLOGIC HISTORY

Regional and localized areas of recurrent crustal movement of the Precambrian basement and later regional uplifts, subsidence, and compressional forces affected the distribution, character and thickness of Paleozoic rock units (Beardsley and Cable, 1983; Riley and others, 1993). Thus, knowledge of deep-rooted faulting is salient to deep injection operations. Thickness of Paleozoic Appalachian Basin rock units ranges from approximately 3,000 feet in central Ohio to approximately 14,000 feet in southeastern Ohio, and may reach as much as 45,000 feet in parts of central Pennsylvania. The Paleozoic stratigraphic column of rocks present within the AOR ranges in age from Middle Cambrian to Late Pennsylvanian (fig. 3) representing a range of sedimentary units (carbonates, evaporites, shale, sandstone, siltstone, k-bentonites, chert, coal, etc).

The stratigraphy of the lower and middle Cambrian in the tri-state area (OH-PA-WV) is particularly problematic because of sparse deep-well data and a lack of nearby continuous cores. Another difficulty has been a lack of Cambrian paleontological studies to adequately constrain lithostratigraphic correlations (Babcock, 1994). A recent investigation of all available continuous core and geophysical logs from deep wells in Ohio and adjacent areas has resulted in an updated Cambrian nomenclature and stratigraphy (Baranoski, in prep). The Cambrian stratigraphy and nomenclature as used in this report is from this ongoing project at the DGS and has not been formally published. This recent investigation shows that the Mount Simon Sandstone pinches out in central Ohio, the Rome Formation is not present in southeastern Ohio, and the Conasauga Formation (Janssens, 1973) has been redefined to the Conasauga group (Ryder, 1992; and Ryder and others, 1996). The Conasauga group includes the Maryville Formation (including the "lower unit"), the Nolichucky Shale, and the Maynardville Limestone (fig. 12).

The earliest record of sedimentation within the region is found within the Rome Trough sequence of rocks in West Virginia and Kentucky. Deposition of this sequence began with the lowermost Paleozoic basal sandstone (arkose) in the Latest Precambrian-Early Cambrian time. Rifting of the eastern Laurentian continent resulted in the opening of the Iapetus Ocean (Harris, 1978; Scotese, and McKerrow, 1991). Subsidence of the Rome Trough continued with deposition of the Shady Dolomite and Rome Formation during the Lower Cambrian and continued through Middle Cambrian with deposition of the Conasauga Group. The pre-Knox section of the Rome Trough is older and greatly thickened when compared to the same intervals of the stable cratonic sequence (fig. 13). As much as 10,000 feet of pre-Knox sediments accumulated in the Rome Trough (Ryder, 1992; Ryder and others, 1996).

From latest Precambrian through most of Middle Cambrian time, eastern Ohio and northwestern Pennsylvania remained an emergent area as a stable cratonic platform (fig. 10). During this time, the erosion of the exposed Grenville basement complex in Ohio and northwestern Pennsylvania and West Virginia supplied clastic sediment to the Rome Trough while carbonates dominated east of the trough. Scattered seismic reflection data made available for viewing in Ohio indicates local areas where Cambrian sediments older than the Maryville Formation "lower unit" may be present in structurally low areas. Near the end of the Middle Cambrian, seas had completely transgressed the exposed Precambrian basement complex in Ohio resulting in near shore to marginal marine deposition of Mount Simon Sandstone in western Ohio while marginal marine and marine deposition of the Maryville Formation (Conasauga Group) occurred in eastern Ohio. The Mount Simon Sandstone, which is a 200- to 300-feet-thick, highly permeable, porous quartz sandstone in western Ohio, pinches out and/or is in facies transition with the lowermost part of the Maryville Formation, which is mainly comprised of dolomite, in the eastern portion of Ohio. The presence of significant sandstone within this lower interval in the tri-state area is unknown. Deposition of the Conasauga Group continued into the Upper Cambrian with a minor marine regression represented by Nolichucky Shale clastics and carbonates, followed by a transgression with deposition of the Maynardville Limestone.

Open-marine conditions continued with deposition of the Knox Dolomite. As used in this report, the Knox Dolomite is subdivided in ascending order into the Copper Ridge Dolomite, the Rose Run Sandstone, and the Beekmantown Dolomite (figs. 3 and 12). Minor regressions took place with input of clastics in the "B-zone," and to a greater degree, the Rose Run sandstone.

A major regression took place during the Middle Ordovician with the onset of the regional Knox unconformity. An extensive erosional surface developed on the emergent Knox carbonate platform (Riley and others, 1993). Paleotopography reached a maximum of about 150 feet on the karstic terrain of the Knox Dolomite (Janssens, 1973). Tropical seas returned to the Ohio region and inundated the subsiding Knox platform in the Middle Ordovician. The St. Peter sandstone and Wells Creek Formation represent the next major marine transgression; these units were deposited on the regional Knox unconformity. The St. Peter is a very fine grained, well-sorted, quartz arenite that forms the basal part (where the unit is present) of the Wells Creek Formation. The St. Peter increases in thickness from the stable craton into the Rome Trough (Humphreys and Watson, 1996). The Wells Creek Formation is a dolomitic shale that locally contains beds of limestone and sandy dolomite. In general, the Wells Creek provides a good seal unit above the Knox Unconformity as evidenced by numerous oil and gas pools found within Knox erosional remnants throughout the region. Shallow-marine sedimentation continued through the Middle and Upper Ordovician with deposition of the Black River Group, Trenton Limestone, and the Cincinnatian group of shales and limestones. The clastic sediments of the Cincinnati group were associated with the Taconic Orogeny of eastern North America, whose compressional forces caused a deepening of the seas covering the region.

Marine sedimentation in the region temporarily ceased during Late Ordovician-Early Silurian time as another major regression began and a regional unconformity developed on top of the Cincinnati group. By the end of the Ordovician, the western margin of the Appalachian Basin was delineated by the Indiana-Ohio Platform, and the Cincinnati and Findlay Arches. As Silurian time progressed, repeated fluctuations of sea level flooded and retreated from the coastal lowlands on the western flank of the Appalachian Basin. Silurian-age Tuscarora Sandstone and other clastic equivalents ("Clinton" and Medina sandstones) were deposited in near shore

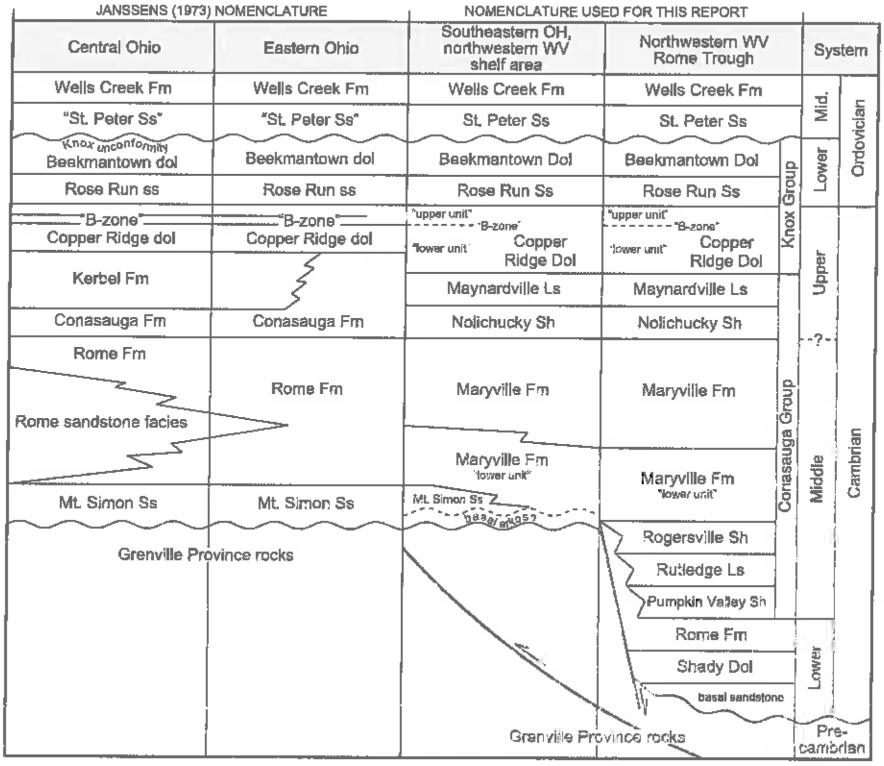

Figure 12.—Stratigraphic correlation chart for the AOR showing details of the Cambrian and lower part of the Ordovician (modified from Janssens, 1973; Ryder, 1992; and Harris and Baranoski, 1996).

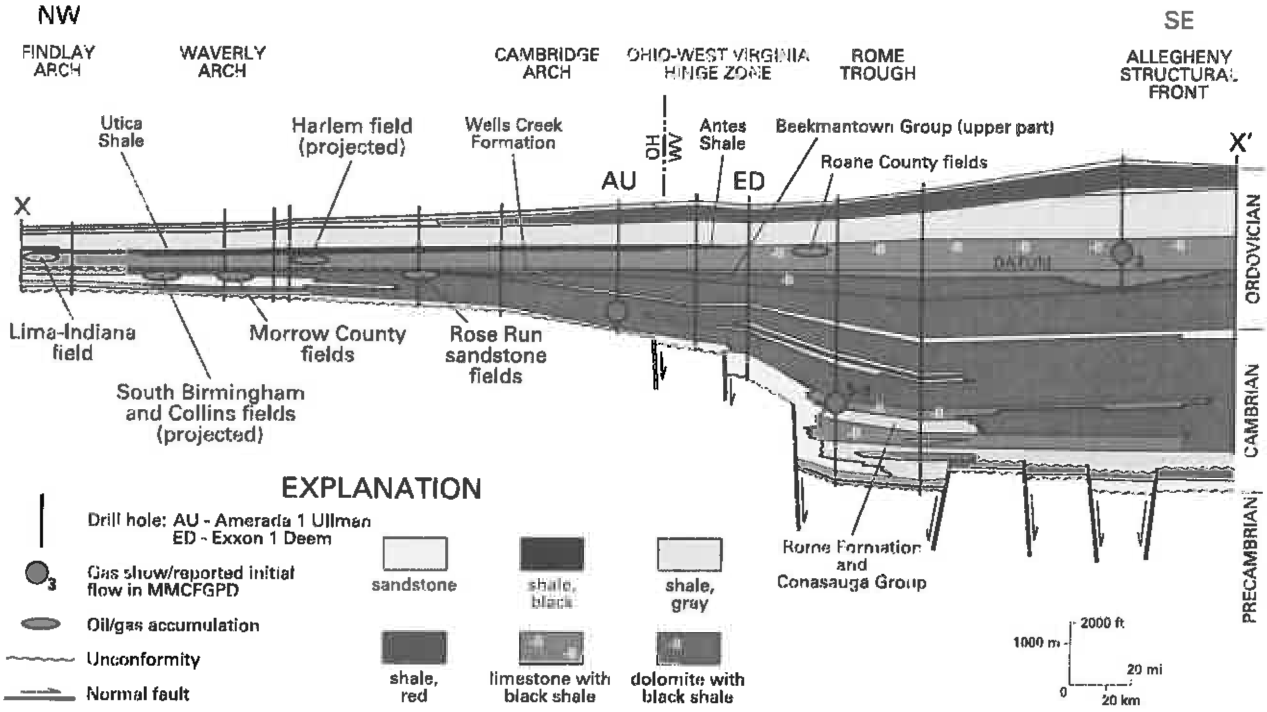

Figure 13.—Stratigraphic cross section from Sandusky County, Ohio, to Pendleton County, West Virginia, showing Cambrian and Ordovician sequences (modified from Ryder and others, 1998).

to marginal marine deposition on this unconformity surface at the onset of another marine transgression. A mixture of clastics and carbonates followed with deposition of the Rose Hill Formation and its equivalents, and the overlying Lockport Dolomite, Salina Group, Bass Islands Dolomite and Helderburg Formation. Another period of regression is marked by an unconformity within Lower Devonian strata, and is followed by a period of transgression and subsequent deposition of the Oriskany Sandstone, overlying Onondaga Limestone, and shales of the Hamilton Group (marking the onset of the Acadian Orogeny).

During the Late Devonian Acadian Orogeny, tropical seas again inundated the region with deposition of the Sonyea, West Falls, and Rhinestreet Formations, and the Ohio Shale in a partially restricted marine basin. The overlying Bedford Shale and Berea Sandstone represent the progradation of gray shales and sandstones over this restricted basin. An Early Mississippian marine transgression resulted in the deposition of the Sunbury Shale. Renewed mountain building in eastern North America with the Alleghenian Orogeny during the Early Mississippian resulted in delta progradation and the deposition of the Cuyahoga and Logan Formations, followed by a minor marine transgression with deposition of the Greenbrier Limestone and equivalents. Continued mountain building to the east resulted in extensive fluvial, clastic deposition including coals with minor limestone accumulations throughout the Pennsylvanian.

DISCUSSION OF POTENTIAL SALINE INJECTION ZONES

Stratigraphic analysis of geologic units deeper than 2,500 feet at the Burger site indicates up to nine deep-saline formations have some level of potential as injection zones (fig. 3). In ascending order these include: the "lower unit" of the Maryville Formation of the Conasauga Group, the Copper Ridge Dolomite – both vugular porosity zones and the "B" zone sand within this unit, the Rose Run sandstone, the Beekmantown Dolomite, the "Clinton" Sandstone, the Lockport Dolomite, the Bass Islands Dolomite, and the Oriskany Sandstone. Unfortunately, although many oil-and-gas wells have been drilled in this AOR, very few wells have been drilled deeper than the Onondaga Limestone (shallower than the Oriskany). Thus, there exists little or no near-field data available for most of the potential saline aquifers at this site. Further, aside from standard geophysical logs, relatively little quantitative data is available for most of these units. Data such as drill-stem tests, step-rate tests, core and core analyses (porosity, permeability, capillary pressure, injectivity testing, etc.), and advanced logging suites, are generally not gathered on Appalachian Basin wells. Therefore, for the purposes of modeling the injection of CO_2 at the proposed site, little data is available within the AOR. This state of data firmly underscores the need to acquire seismic and drill a test well at this location. Once that is accomplished, a more detailed scenario of injection can be developed using actual on-site data from the potential injection horizons and seal units drilled and tested.

CAMBRIAN CONASAUGA GROUP (MARYVILLE FORMATION)

No wells penetrate the Maryville Formation in the Belmont County vicinity. Recent work at the DGS illustrates that the Mt. Simon Sandstone, which is a thick, continuous unit over the entire Illinois and Michigan Basins, pinches out in central Ohio (Baranoski, in prep; fig. 12). Much of this equivalent interval is occupied mainly by dolomite in Eastern Ohio. Wells in northeastern and southern Ohio (e.g. Ashtabula County, Meigs County) contain little or no sandstone within this basal interval, while some wells in central eastern Ohio (e.g. Guernsey County) appear to have appreciable amounts of porous sandstone. The nearest well to the Burger site that has been drilled thru this interval is the Zechman-Thomas Unit well in Harrison County, Ohio (API # 3406720737), approximately 30 miles distant. According to the geophysical logs for this well, it may have encountered about 36-feet of sand in this lower interval. Therefore, while it is possible that some porous sand may be found at this basal Paleozoic position, it remains fairly speculative at the Burger site. Projections from distant wells place the depth to the Maryville at approximately 13,600 feet at the Burger site. At such a depth it is possible that any porosity that may have been present, if sand is present, has been occluded due to pressure solution effects.

The Maryville Formation consists dominantly of dolomite to feldspathic quartz dolomite. The upper portion is light to medium gray, cryptocrystalline to fine and medium crystalline, laminated to irregular, massive bedded, slightly arenaceous dolomite. Glauconite, anhydrite-filled vugs, rip-up clasts, stylolites, shaley discontinuity surfaces, scour surfaces, and bioturbation are locally common. Depositional environments range from shallow subtidal to shallow marine and continental slope. The "lower unit" of the Maryville is feldspathic quartz dolomite to feldspathic quartz sandstone. The "lower unit" is light pink to white and light brown, fine and medium grained, poorly to well sorted, rounded to subrounded, laminated to irregular, massive bedded, feldspathic dolomitic quartz arenite. Trough cross-bedding, fining upwards sequences, anhydrite replacement clasts, shaley discontinuity surfaces, scour surfaces, bioturbation, vertical burrows, trace fossils, and intraformational breccia are locally common. Depositional environments range from near shore and shallow subtidal to shallow marine environments (Harris and others, 2004; Baranoski, in prep).

CAMBRIAN-ORDOVICIAN KNOX GROUP

In eastern Ohio, the Knox Dolomite is subdivided into the Copper Ridge Dolomite, Rose Run Sandstone, and Beekmantown Dolomite in ascending order (figs. 3 and 12). The Knox unconformity records a significant erosional event at the top of the Cambrian-Lower Ordovician carbonate supersequence (Sloss, 1963; Colton, 1970). Thus, the location determines which one of the three units of the Knox are at or near the unconfomrmity surface (figure 14). Within the vicinity of the Burger site, the Beekmantown Dolomite is found at the unconformity surface at a depth of approximately 11,600 feet. Throughout the Appalachian region, this unconformity surface is distinguished by a collection of large-scale karst features. Paleotopographic hills have been recognized, together with sinkholes, caves, intrastratal breccias, solution-enlarged joints, and vugs (Mussman and Read, 1986; Mussman and others, 1988).

CAMBRIAN COPPER RIDGE DOLOMITE

The Copper Ridge Dolomite is the basal unit of the Knox Dolomite (Group). Dolostones of the Copper Ridge range from dense to vuggy. Erosional remnants on the Copper Ridge are the primary reservoir of the large Morrow Consolidated oil-and-gas field of central Ohio. In addition to porosity development at the unconformity, vuggy dolostones may occur at zones deeper within the unit. Vugular porosity zones have been observed unevenly distributed throughout an interval of at least 400 feet in this unit (Shrake and others, 1990). These thick zones of vugular porosity have been encountered in a number of deep wells within the Copper Ridge Dolomite, including

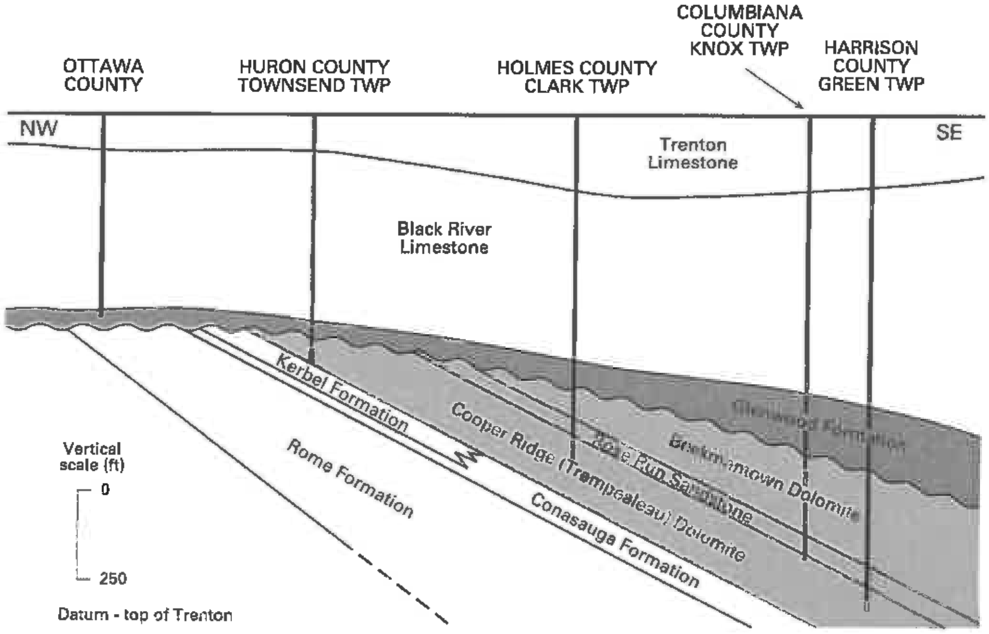

Figure 14.—Diagram illustrating the various units found at the Knox unconformity subcrop traversing from north-central to southeast across Ohio.

the AEP Mountaineer deep test well. Vuggy dolostones of the Copper Ridge have been used as the injection zone in the DuPont WAD Fee well in Louisville, Kentucky for the disposal of industrial waste fluids. The interval of vuggy dolostone is sealed above by dense dolostones of the Copper Ridge. However, it should be cautioned that these porosity zones are not everywhere encountered. Thus, the potential for injection within this zone at the Burger site must remain speculative.

The Copper Ridge Dolomite also contains a siltstone-sandstone unit within the dolomite sequence, typically found 70 to 100 feet above the base of the Knox and referred to informally as the "B" zone. This interval can be as much as 50 feet thick and is composed of glauconitic siltstone, microcrystalline dolomite, and very fine-grained sand with good intergranular porosity (Janssens, 1973). Due to a lack of wells drilled through the Copper Ridge in the Burger vicinity, we cannot be certain of this unit being sandy and porous at this locale. Drilling through the potential reservoir and seal units within the Copper Ridge (and preferably coring) would be required to further evaluate their sequestration potential at this location. Depth to the top of the Copper Ridge at Burger is approximately 12,500 feet (fig. 15).

CAMBRIAN-ORDOVICIAN ROSE RUN SANDSTONE

The Rose Run sandstone occurs within a thick sequence of predominantly shallow-water carbonates that comprise the Knox Dolomite. This sequence has been interpreted to consist of the vertical stacking of various peritidal facies resulting from cyclical sea-level changes on a broad carbonate shelf (Read, 1989; Osleger and Read, 1991; Riley and others, 1993). The Rose Run sands represent low-stand deposits, related to both third-order sea-level falls and short-term sea-level cycles (Read, 1989). Thin-section petrography indicates that the Rose Run sandstone has a continental block provenance with a source in the craton interior to the north and northwest of the project area (Riley and others, 1993). Thus, siliciclastic (sand) deposition in the Rose Run decreases to the south and southeast away from the subcrop (fig. 16).

From a regional study of cores in Ohio and outcrops in Pennsylvania (Riley and others, 1993), monocrystalline quartz and potassium feldspar are the dominant framework constituents in the Rose Run. Polycrystalline quartz and chert generally comprise less than one percent of the sandstone and appear in the more feldspathic samples. Minor amounts (less than one percent) of muscovite and accessory minerals—zircon, tourmaline, garnet, and pyrite—occur locally. Allochems are locally abundant in the Rose Run and include dolostone clasts, glauconite, peloid and dolomitized ooids. Four major cementing agents occurring in the Rose Run include: 1) dolomite; 2) clays; 3) quartz overgrowths; and 4) feldspar overgrowths (Riley and others, 1993). Dolomite is the dominant cementing agent as observed in cores throughout Ohio and Pennsylvania. Five pore textures were observed in the Rose Run, including: 1) intergranular pores; 2) oversized pores; 3) moldic pores; 4) intraconstituent pores; and 5) fractures (Riley and others, 1993). Intergranular porosity is the most abundant porosity type in the Rose Run and appears to be mostly secondary based on corroded grain boundaries. Oversized pores are caused primarily by dissolution of dolomite and feldspar. Moldic pores occur in the more feldspathic samples and have the highest porosities and permeabilities. Intraconstituent pores occur most commonly in feldspar grains and appear to be more common toward the lower portion of the Rose Run. Fracture porosity is the least common porosity type observed in cores, but it may be locally significant in areas adjacent to major fault systems.

Regional structure on the top of the Rose Run sandstone exhibits dip to the east and southeast with strike trending northeast-southwest (fig. 16). Due to a lack of wells drilled through the unit in the Burger vicinity, we cannot be certain of this unit being sandy and

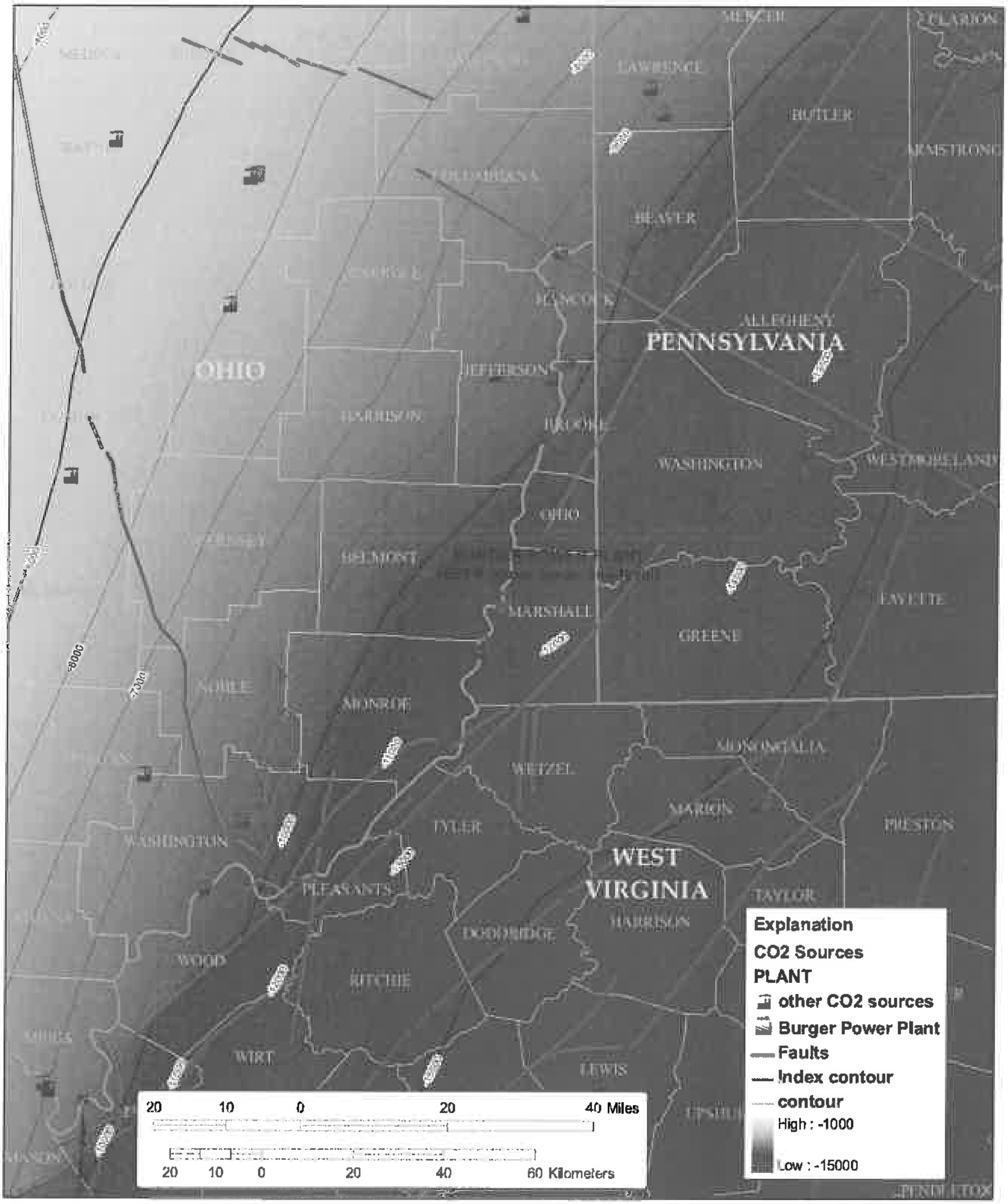

Figure 15.—Structure contour map on the top of the Copper Ridge Dolomite within the Ohio, Pennsylvania, and West Virginia region. Also shown is the location of major (>100,000 tons per year) point sources of CO_2. Map elements taken from Wickstrom and others, 2005.

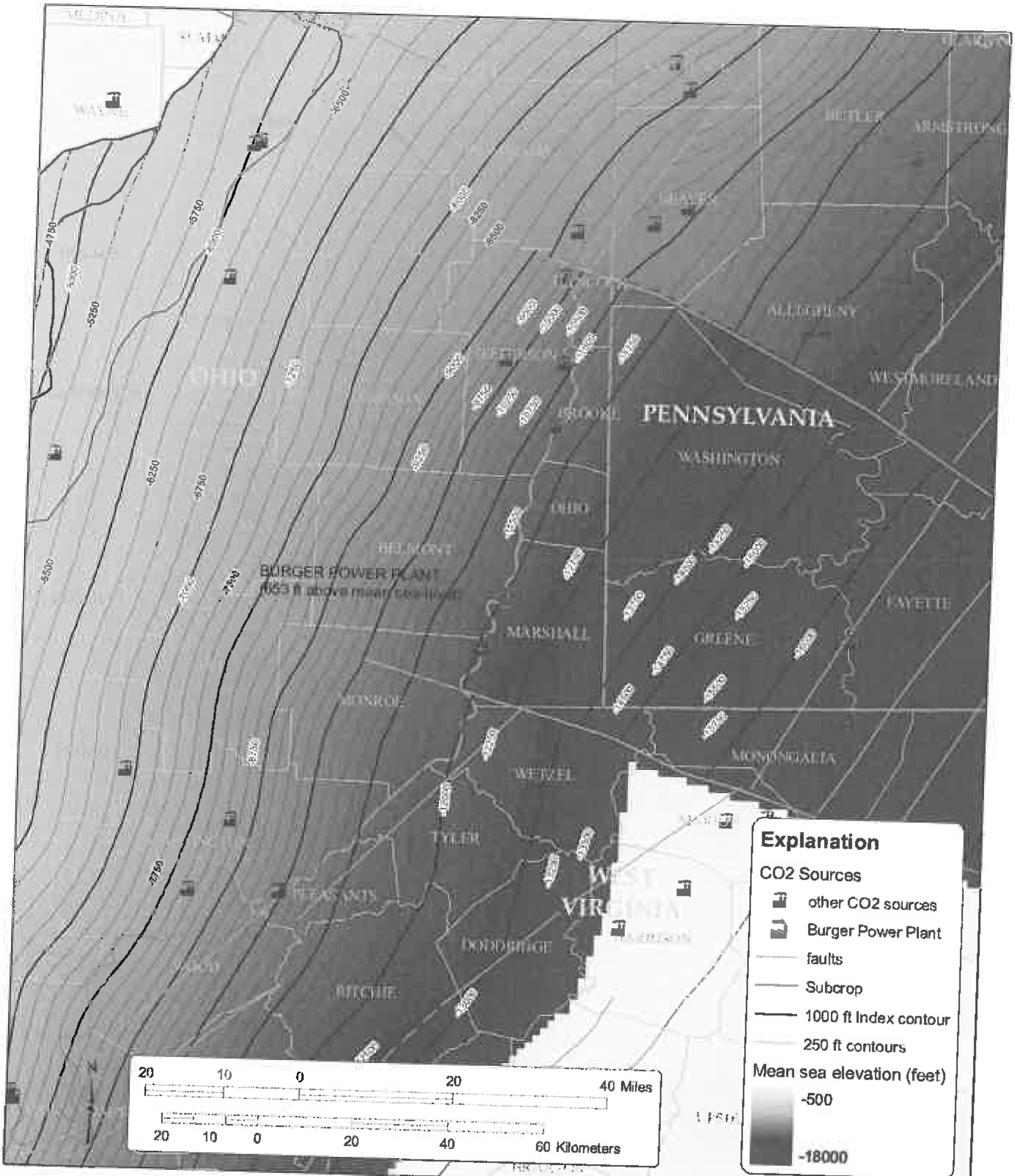

Figure 16.—Structure contour map on top of the Rose Run Sandstone, with area of subcrop delineated. Map elements taken from Wickstrom and others, 2005.

porous at this locale. Drilling through the potential reservoir (and preferably coring) would be required to further evaluate the sequestration potential at this location. The depth to the top of the Rose Run at the proposed site is approximately 12,200 feet.

ORDOVICIAN BEEKMANTOWN DOLOMITE

The Beekmantown Dolomite consists of light- to medium-brown, fine- to medium-crystalline, locally stylolitic, dolomite. Accessory minerals include locally occurring glauconite, chert, pyrite, and quartz. Thin green- to black-shale beds interbedded with dolomite also occur locally. Pervasive dolomitization has been fabric destructive and destroyed much of the original texture and sedimentary structures. The dominant sedimentary structure is burrow mottling; soft sediment deformation and nodular bedding are also observed locally. Vertical stacking of meter-scale shallowing-upward facies that are capped with subaerially exposed surfaces are present in several cores. These subaerially exposed surfaces are associated with scoured erosional surfaces, dessication features, paleokarst collapse features, algal stromatolites, open and mineral-filled vugs, and trace amounts of anhydrite (Riley and others, in prep).

Typically, the Beekmantown has low porosity (less than 2 percent) and permeability (less than 0.1 md) and can thus serve as an effective extra barrier to vertical migration. Locally, however, good reservoir-quality rock with higher porosity (10-20 percent) and permeability (up to 240 md) are present that contain pinpoint and vuggy porosity. These zones of higher porosity are thought to be associated with subaerial exposure surfaces. Good correlation exists between cores and wireline logs in identifying these porosity zones, which have informally been named the "A, B, and C" porosity zones. Porosity types observed in core include intergranular, vuggy, and fracture (Riley and others, in prep).

At the Burger site, the Beekmantown is found at an approximate depth of 11,600 feet.

SILURIAN CATARACT GROUP ("CLINTON" SANDSTONE)

The "Clinton"/Tuscarora sandstone occurs as a sequence of interbedded sandstones, siltstones, and shales. The name "Clinton" is an Ohio driller's term for sands found within the Cabot Head and Brassfield Formations. The rocks are equivalent with the Medina Group and Tuscarora Sandstone interval in Pennsylvania and West Virginia. Lithologically, the individual reservoir beds consist of a white to gray to red, medium- to very fine-grained, monocrystalline, quartzose sandstone (McCormac and others, 1996). The "Packer Shell" is a drillers term applied to the Dayton Formation, a carbonate unit directly overlying the "Clinton" sand and shale assemblage. Because of the variability in the sand packages within the "Clinton" interval, the "Packer Shell" is often used as a surface to map for structure when examining the "Clinton". The top of the "Packer Shell" is found at a depth of approximately 8,100 feet at the Burger site (fig. 17).

Some deep drilling (greater than 7,000 feet) of the "Clinton" has taken place in other parts of Ohio, however, the closest Clinton well to the Burger site is 11 miles to the west-northwest While some deep "Clinton" wells have found sufficient porosity and permeability to consider it a reservoir, others have found the interval to be very tight at this depth.

In some areas the total "Clinton" interval may be up to 200 feet thick (fig. 18), but the effective porosity within the interval will vary widely from a few feet to over 100 feet. The measured log porosities in the net sand intervals may range from 6 percent to 14 percent. The nearest reservoir data for the Clinton-Medina"/Tuscarora sandstone is approximately 36 miles to the west-southwest in Noble County, Ohio where core analyses (from API no. 3412121890) indicate a porosity range of 2.5 to 4.7 per cent and permeability range of less than 0.1 millidarcy (md) to 423 md over a 65-foot interval. Calculated geophysical log porosity from a well in Belmont County is (API number 3401320485) was reported as 6.7% over a 48-foot reservoir of "Clinton-Medina" sandstone. "Clinton" permeabilities are widely variable, average ranges in most fields are from less than 0.1 md to 40 md (McCormac and others, 1996). However, in the Perrysville Consolidated Field (Ashland County, Ohio) recorded average permeabilities of over 100 md, and isolated permeabilities of individual layers in this sequence can have permeabilities in excess of 200 md (McCormac and others, 1996). Due to these lithologic variations within the Medina Group, detailed characterization of this unit for injection potential needs to be performed at each prospective site.

SILURIAN LOCKPORT DOLOMITE

The Lockport consists mostly of Middle Silurian marine dolomites, although areas where the unit is composed primarily of limestone are known to exist. In central and eastern Ohio, portions of the Lockport are often referred to informally as the "Newburg," which represents any significant porosity zone, probably associated with patch reef development, within the Lockport interval (Floto, 1955; Janssens, 1977). Although highly speculative, it is possible that carbonate patchreefs, barrier bars and/or shoals may exist within the Lockport in the Burger area. If such porosity systems are found within the Lockport, this interval could prove to be very significant as a potential CO_2 injection reservoir. Smosna and others (1989) illustrate areas in the Appalachian Basin with known bioclastic deposits, some of which extend into Meigs County, Ohio, and Mason and Jackson Counties, West Virginia. The Burger Power Plant may be along the depositional strike of this trend suggested by Smosna and others (1989). Several class II (brine) injection wells in Ohio have found this interval to be very porous and permeable, with injection rates as high as 260 gallons per minute. However, the porosity and permeability of the unit is highly variable from well-to-well. Thus, until a test well is drilled through this unit, we cannot ascertain its effectiveness as a reservoir at the Burger site. Depth to the Lockport at Burger Power Plant is estimated at 7,400 feet with a total interval thickness of 400 feet.

SILURIAN BASS ISLANDS DOLOMITE

The Bass Islands Dolomite occurs in Michigan, Ohio, and northwestern Pennsylvania as a series of laminated dolostones. It is a local oil-and-gas reservoir in Erie County, Pennsylvania, and in western New York where it occurs as a narrow, 84-mile-long structurally controlled trend (Van Tyne, 1996). Within many wells of eastern Ohio, this interval appears to consist of a carbonate breccia zone, perhaps associated with the Wallbridge Unconfomity (Wheeler, 1963) found at the base of the Oriskany Sandstone position. Where observed as a breccia, this zone has very high porosity and permeability. Several brine-injection wells utilize this zone in Ohio, with reported injection rates as high as 37 gallons per minute. This interval has had very little detailed study in the subsurface of eastern Ohio but may have high potential as a CO_2 injection zone. It is estimated that the Bass Islands will be approximately 6,300 feet deep at the Burger site.

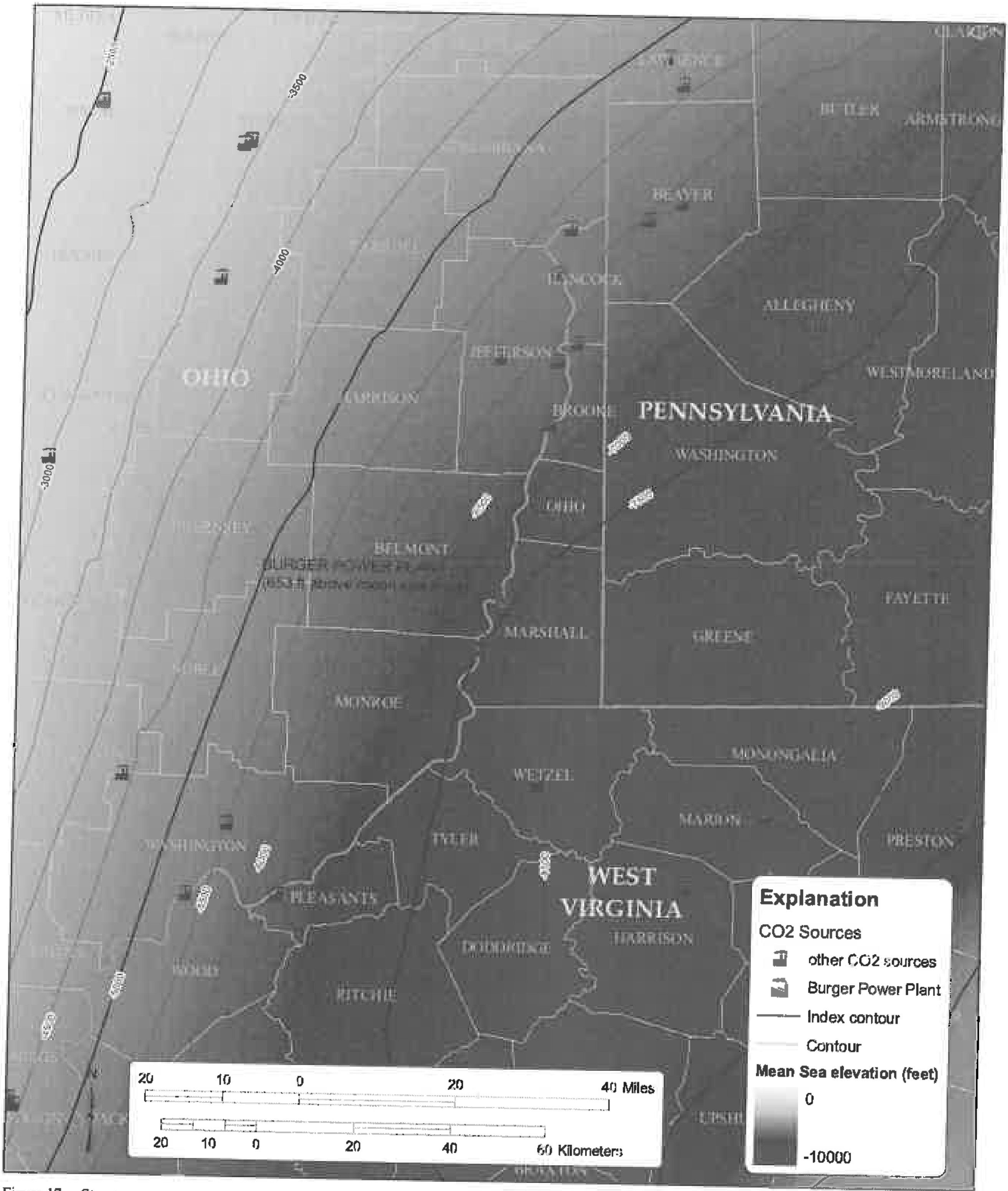

Figure 17.—Structure contour map on the top of the Tuscarora Sandstone and equivalents within the Ohio, Pennsylvania, and West Virginia region. Also shown is the location of major (>100,000 tons per year) point sources of CO_2. Map elements taken from Wickstrom and others, 2005.

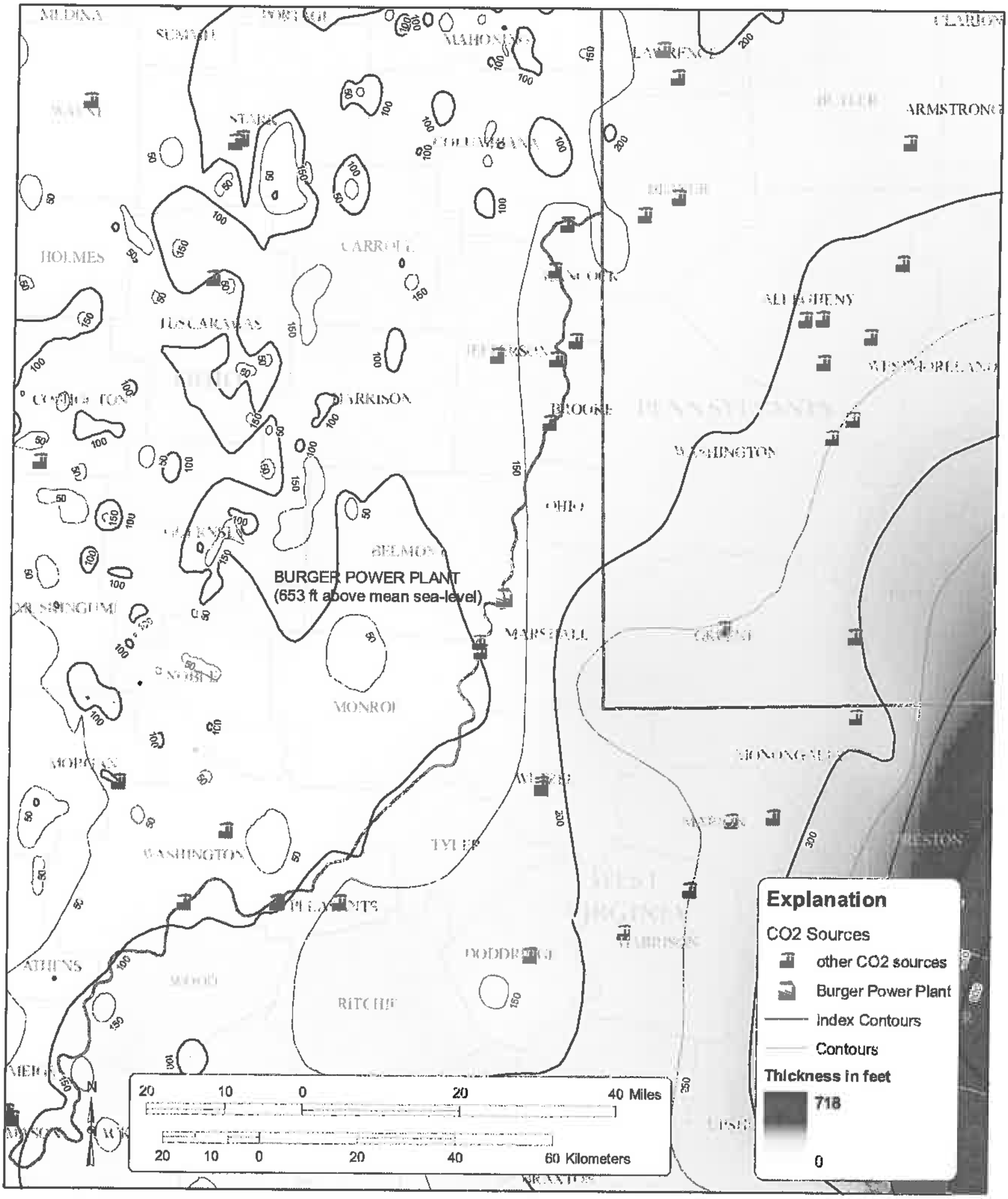

Figure 18.—Isopach (thickness) map of the Tuscarora Sandstone and equivalents within the Ohio, Pennsylvania, and West Virginia region. Also shown is the location of major (>100,000 tons per year) point sources of CO_2. Map elements taken from Wickstrom and others, 2005.

DEVONIAN ORISKANY SANDSTONE

The Oriskany Sandstone represents a major change during Early Devonian deposition in the Appalachian basin. The predominant carbonate sedimentation that originated in the Middle Silurian ceased or slowed, to be replaced temporarily by predominant clastic deposition. The Early Devonian ended with a worldwide regression that resulted in erosion throughout much of North America (the Wallbridge discontinuity of Wheeler, 1963). Thus, the Oriskany Sandstone is an unconformity sandstone overlying the Helderberg Formation and underlying the Onondaga Limestone. Lithologically, this unit consists of well-sorted, white to light gray, and gray-brown, quartzose sandstone (Opritza, 1996). Erosion following Oriskany deposition near the basin margins might have been more extensive than pre-Oriskany erosion—there are large areas of the basin where the Oriskany is thin or absent, for example the "Oriskany no-sand area" in northwestern Pennsylvania (Figs. 19 and 20). This unit is thin or missing in much of eastern Ohio, but steadily increases in thickness to the southeast. At the Burger site, it is thought the Oriskany should be 30 to 50 feet thick (fig. 19) at a depth of approximately 5,600 feet (figs. 8 and 20). Therefore, the Oriskany may prove to be one of the best potential injection horizons available at this site.

The Oriskany Sandstone typically is a pure, white, medium- to coarse-grained, monocrystalline quartz sandstone containing well-sorted, well-rounded, and tightly cemented grains (Fettke, 1931; Gaddess, 1931; Finn, 1949; Basan and others, 1980; Diecchio, 1985; Foreman and Anderhalt, 1986; Harper and Patchen, 1996). Quartz and calcite comprise the most common cementing materials in the formation. In many areas of the basin, the formation contains such an abundance of calcite, both as framework grains and as cement, that the rock is classified as an arenaceous limestone.

The Oriskany Sandstone typically is a tight rock unit except in certain areas affected by fracturing (areas of folding and faulting) or dissolution of cement (generally near pinchout areas). Porosities and permeabilities vary widely across the basin, depending on mineralogy, diagenesis, and amount of fracturing (Harper and Patchen, 1996). Intergranular porosity consists of both reduced primary porosity and secondary porosity due to dissolution of carbonate cements and some grains. While the arenaceous limestones have porosities less than five percent, zones within the arenites can have porosities greater than 20 percent where secondary porosity has been favorable (Basan and others, 1980). Permeabilities in the Oriskany Sandstone range from less than 0.1 to almost 30 md (Harper and Patchen, 1996).

The Oriskany Sandstone has been used for the injection of industrial wastes in several wells in the basin, and for injection of natural gas for gas storage purposes in numerous depleted gas fields. One injection project, a waste disposal well in Pennsylvania, had an injection rate of about 20 gallons per minute at an intake pressure of 1,400 psi during the initial investigation stage (Pennsylvania Geological Survey files). The Oriskany in this well ranged from 5,250 to 5,426 feet. Average porosity and permeability were 5.2 percent and 2.2 md, respectively (Wickstrom and others, 2005).

SIGNIFICANT OIL AND GAS HORIZONS

CO_2-assisted enhanced oil recovery (EOR) is a common procedure for obtaining additional oil from reservoirs in the Permian Basin of West Texas and a growing number of other western U.S. areas. These projects utilize large naturally occurring CO_2 reservoirs as the main feedstock to the extensive pipelines that have been deployed for distribution of the CO_2 (over 1 billion cubic feet of CO_2 per day). Because of CO_2's unique properties, it has proven to be one of the most efficient mediums known for sweeping left-behind oil from a reservoir. There are no known natural CO_2 sources in the Appalachian Basin of comparable size to those used in the Permian Basin. Thus, even though the Appalachian Basin was the birthplace of the oil-and-gas industry, and this area pioneered the early forms of secondary recovery, it has not been able to utilize this very efficient medium to maximize the recovery of hydrocarbons from its reservoirs. As anthropogenic sources of CO_2 are captured and geologic sequestration initiated, CO_2-assisted EOR may become an established practice in the region.

CO_2-assisted EOR projects can be designed as either miscible (the CO_2 is kept at proper pressure to keep the gas in a near liquid form) or immiscible. To maintain the CO_2 at its supercritical state (near liquid), requires the reservoir to be at a depth of approximately 2,500 feet or greater. Miscible flooding projects are more efficient at sweeping residual oil from reservoirs and sequester much larger volumes of CO_2. Immiscible projects are technically feasible for recovering additional oil, but the ultimate fate of injected CO_2 is less certain and of lower volume.

Extensive mining of shallow coal resources, and the ownership of mineral lease rights, has prevented most oil and gas exploration along a large swath of land along the Ohio River near the Burger site for many decades. Much of the shallow oil and gas drilling in the area pre-dates the large underground mining operations of the area. Therefore, as can be seen on figure 21, there is a large area near the Burger site with relatively few oil and gas fields deeper than 2,500 feet as compared surrounding regions. Thus, to take advantage of miscible EOR operations with CO_2 from the Burger plant, will require transporting the CO_2 some distance away from the plant.

The following paragraphs describe the oil fields, by stratigraphic unit, with significant miscible EOR potential in close proximity to the proposed site. Approximately 67 known oil and gas fields occur within the AOR and many of these produce hydrocarbons from multiple geologic horizons; producing depths range from 800 to 7,300 feet, although most production has been shallow (fig. 22, Appendix C).

Three natural gas storage fields are also found within the AOR (fig. 23). The Majorsville-Heard gas field of Marshall County, West Virginia and Greene County, Pennsylvania was activated 1943 for gas storage in the Mississippian Big Injun sandstone (at a depth of 1,640 feet) and the Devonian siltstones and sandstones (at a depth of 2,700 feet) (American Gas Association, 1988; Carter, 2006). The Victory "A" and "B" gas fields of Marshall County, West Virginia are used as storage fields in the Mississippian Mauch Chunk Fm. (at a depth of 2,040 feet) and Mississippian Big Injun sandstone (at a depth of 2,300 feet), respectively. Gas storage fields, with pertinent reservoir data, may serve as proxies for modeling reservoir conditions for CO_2 injection, as they inject and withdraw known volumes of gas at known rates.

The following oil and gas plays are discussed for the AOR: the Lower Silurian-age *"Clinton"*(Cataract Group)/ Tuscarora Sandstone, and Lockport Dolomite, the Upper Silurian-age Salina Group and Bass Islands Dolomite, the Lower Devonian-age Oriskany Sandstone, the Upper Devonian-age black shales, siltstones, and sandstones, the Upper Devonian-age Berea Sandstone, the Lower and Upper Mississippian-age sandstones and carbonates, and the Lower and Middle Pennsylvanian-age sandstones and coal beds (fig. 2). Detailed descriptions of many of these plays are present in Roen and Walker, (1996). Oil and gas plays deeper than the Lower Silurian are not discussed herein, mainly because the clos-

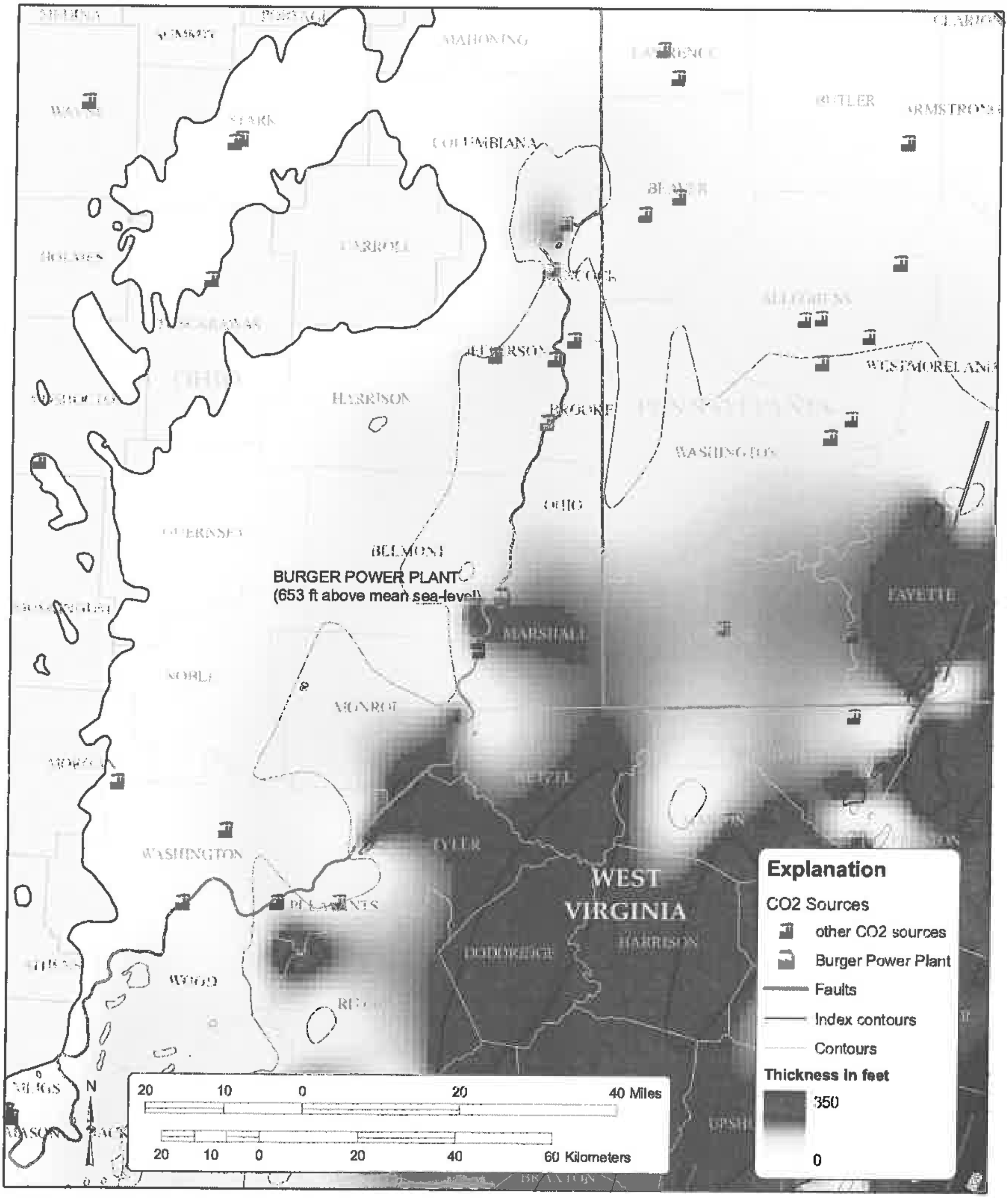

Figure 19.—Isopach (thickness) map of the Oriskany Sandstone within the Ohio, Pennsylvania, and West Virginia region. Also shown is the location of major (>100,000 tons per year) point sources of CO_2. Map elements taken from Wickstrom and others, 2005.

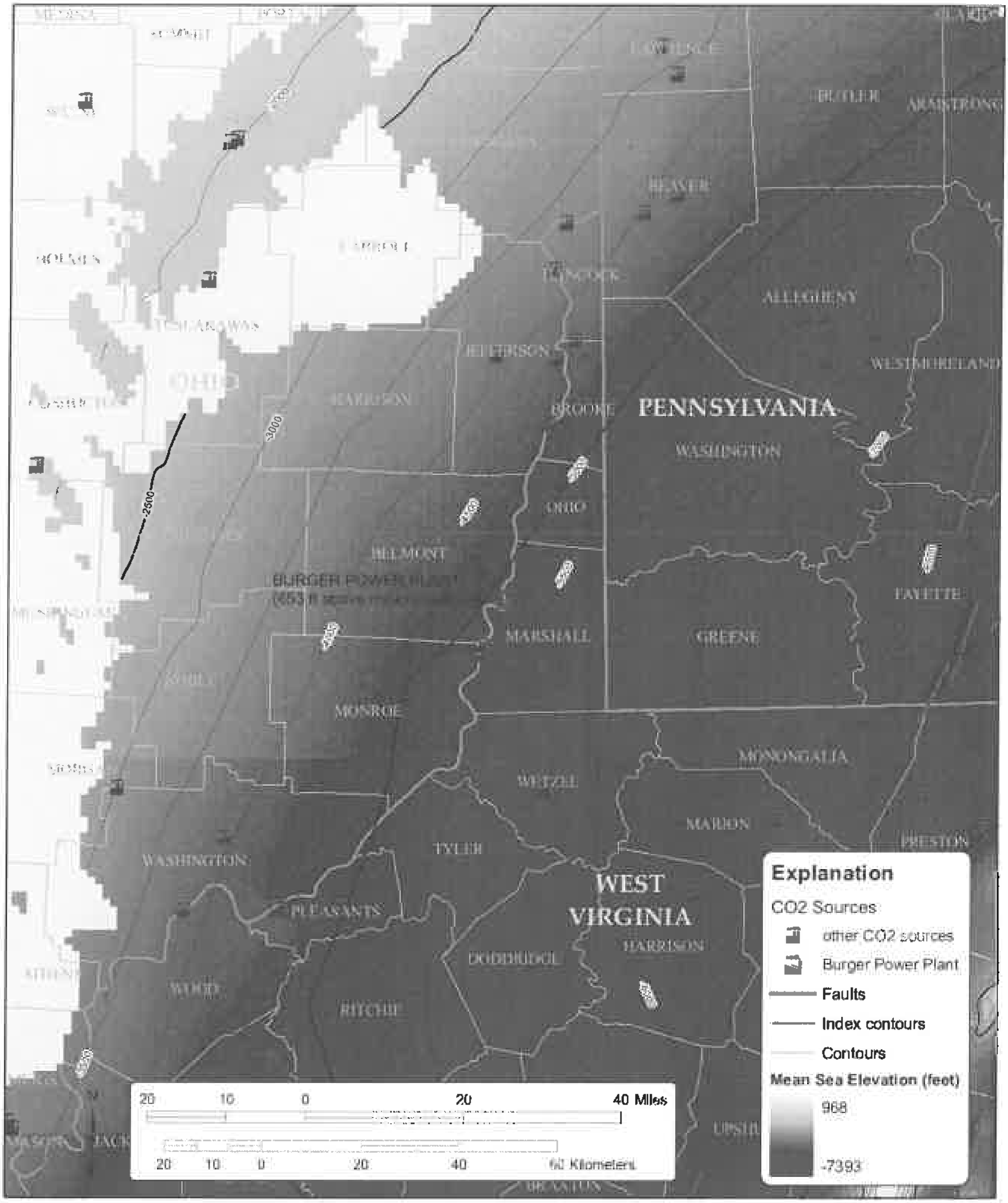

Figure 20.—Structure contour map on the top of the Oriskany Sandstone within the Ohio, Pennsylvania, and West Virginia region. Also shown is the location of major (>100,000 tons per year) point sources of CO_2. Map elements taken from Wickstrom and others, 2005.

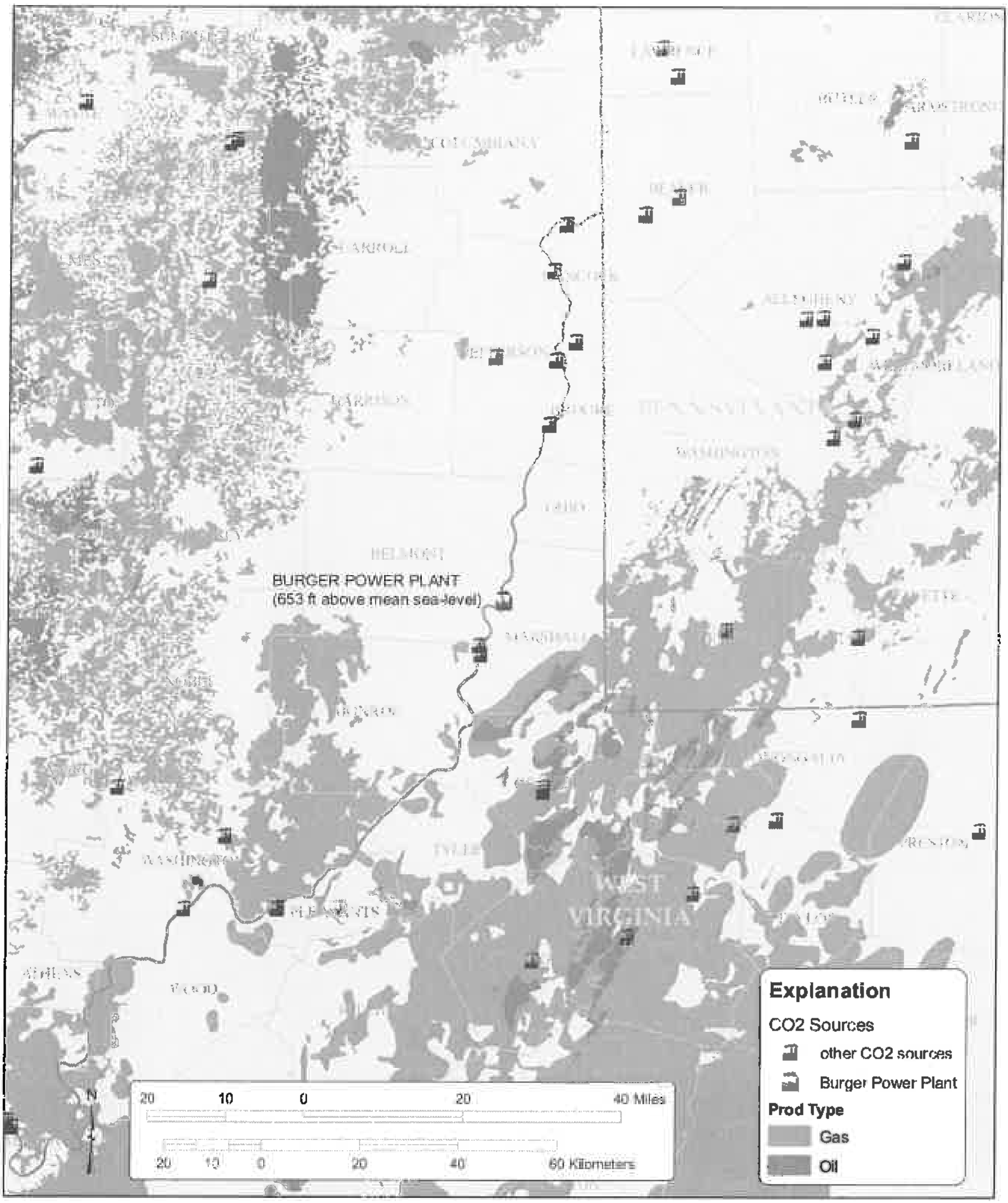

Figure 21.—Map showing the locations of oil and gas fields producing from depths greater than 2,500 feet within the tri-state area.

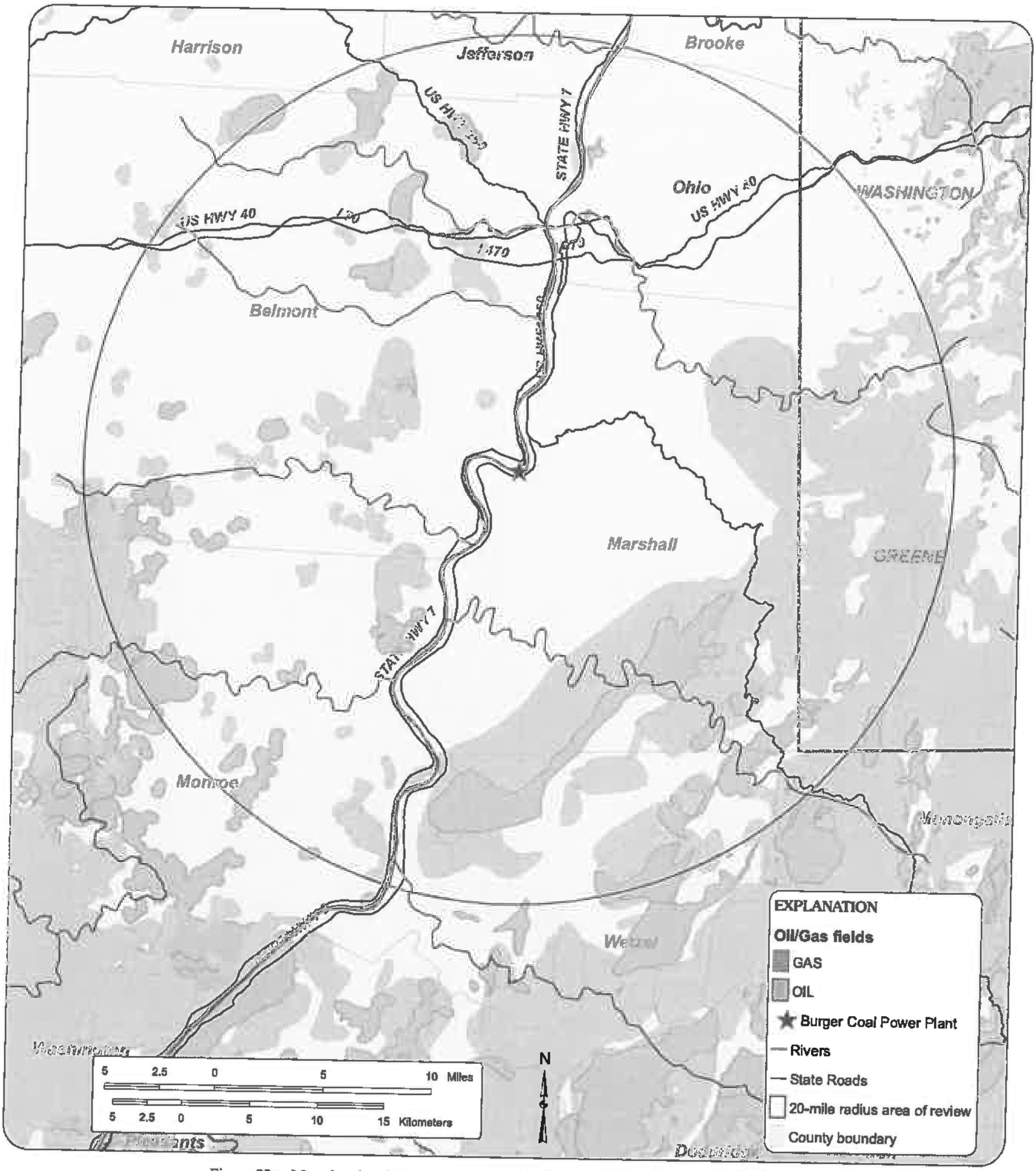

Figure 22.—Map showing the locations of all oil and gas fields within the Burger site AOR.

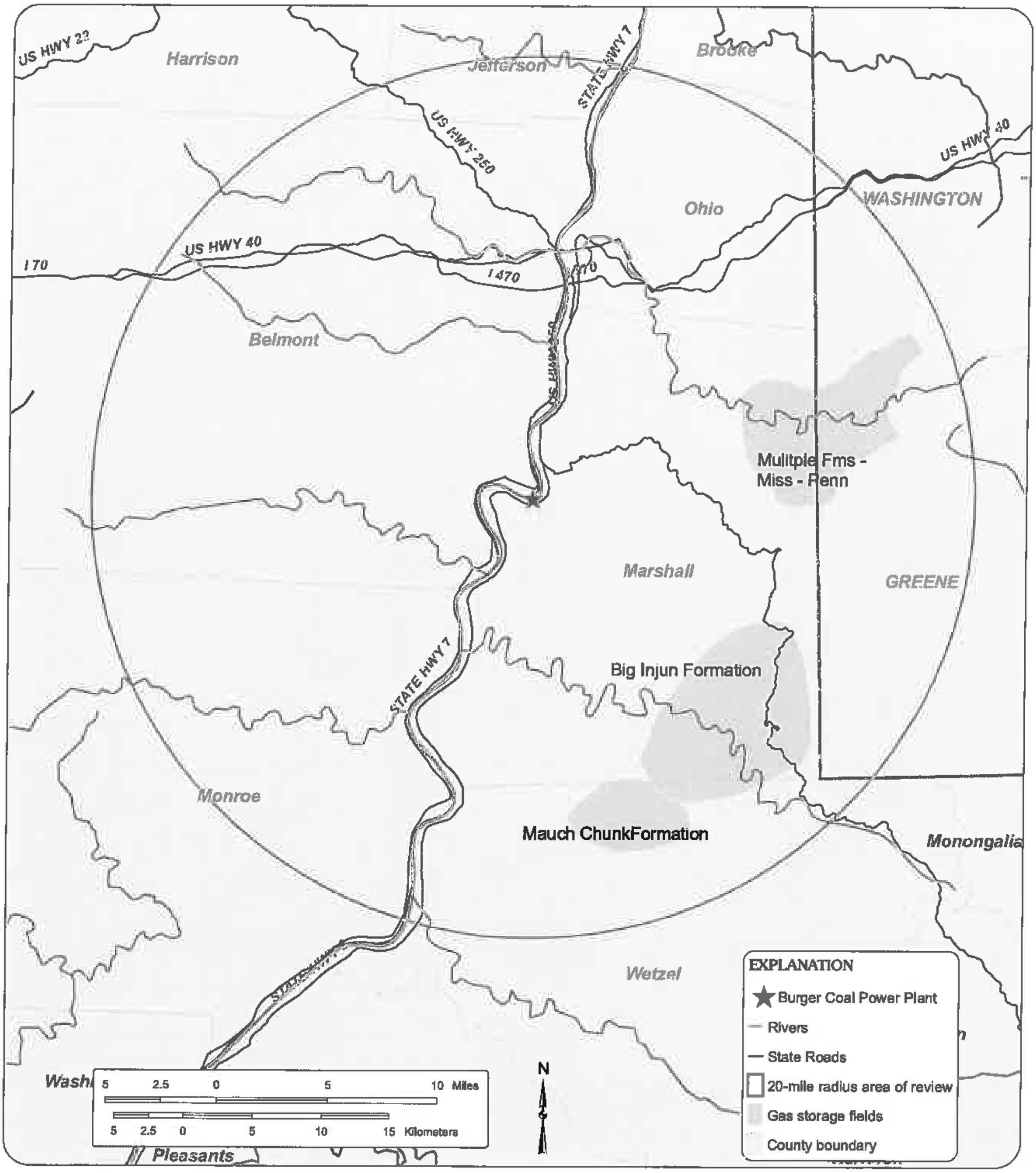

Figure 23.—Map showing the locations of natural gas storage fields within the Burger AOR.

est known production from these deep units is located 50 miles or more from the Burger Power Plant. As discussed earlier, no wells have been drilled to these deep plays near the site; thus, no direct data is available and the plays are poorly understood at this location. However, the potential does exist for deep hydrocarbon production to be discovered in the area from the Trenton Limestone, Black River Limestone, St. Peter Sandstone, the Knox Group, and/or the Conasauga group.

LOWER SILURIAN "CLINTON-MEDINA"/ TUSCARORA SANDSTONE

The Clinton-Medina sandstones have been the most drilled oil–and-gas horizon in Ohio since the 1970s. Ohio has 186 "Clinton-Medina" sandstone fields with approximately 60,000 wells that have produced over 5 trillion cubic feet of gas (tcf) (McCormac and others, 1996), yet no "*Clinton*"/Tuscarora pools or fields are present within the 20-mile radius AOR (fig. 22). Hydrocarbon production (initial production reported @ 100 mcfg; 1 bo; and 2 bw) from the "*Clinton*"/Tuscarora sandstone was reported from one well located 19 miles northeast of the site (API 3401320485). Production history for this well is unknown. Figure 24 shows the stratigraphic correlations using geophysical well logs of the "Clinton-Medina" sandstones across southeastern Ohio. The density logs in figure 24 illustrate a decrease in density (lower porosity) at the eastern end of the cross section. The porosity and permeability of "Clinton-Medina" sandstone reservoirs generally decreases with increasing depth (McCormac and others, 1996). Typically, "Clinton-Medina" reservoirs are hydraulically fractured to enhance available hydrocarbon production. The Burger Power Plant site falls within Ryder and Zagorski's (2003) "basin-centered" trend, which is considered tight reservoir rock and reliant on natural fractures and hydrofracing for economic gas production. Conversely, it might be necessary to hydrofrac the unit to open sufficient permeability for injection operations. It is unclear at this time if artificial fracturing will be allowable in CO_2 injection wells in the region as permit requirements are currently under study.

LOWER SILURIAN LOCKPORT DOLOMITE

Hydrocarbon production from the Lockport Dolomite does not occur within the AOR; the nearest producing area is approximately 100 miles west of the Burger Power Plant site. Noger and others (1996) show a typical producing Lockport patch reef, imaged with seismic reflection data. This under-explored deeper part of the Appalachian Basin warrants examination of this formation using seismic reflection data. The porosity of Lockport reservoirs generally ranges from 4 to 13 percent (Noger and others, 1996).

LOWER DEVONIAN ORISKANY SANDSTONE

The first commercial Oriskany production in the Appalachian Basin occurred in early 1900. Estimated cumulative production for the Oriskany in the Appalachian Basin is 82 billion cubic feet of gas (Bcf) (Opritza, 1996). The nearest Oriskany production is approximately 17 miles east of the Burger site in the Rich Hill pool of Greene County, Pennsylvania (Figure 22). This one well pool was discovered in 2001 and produces at a depth of 7,350. A total of 34 wells have penetrated the Oriskany within the AOR. The nearest reservoir data found for Oriskany sandstone is in Noble County, approximately 44 miles to the southeast of the Burger Power Plant site. Core analyses for API number 3412121561 indicate a porosity range of 1.0 to 6.1 percent and permeability range of less than 0.1 md to 5.3 md over a 17-foot interval. Opritza (1996) shows stratigraphic correlations using geophysical well logs of the Oriskany Sandstone in southeastern Ohio. Thickness of the Onondaga and Oriskany maintains relatively consistent thickness, while the Helderberg and Bass Islands increase in thickness to the southeast. Hermann (1974) describes the Oriskany from a well in Belmont County (API number 3401320129) as a white to clear, fine to medium grained, fossiliferous, silica cemented sandstone, and limestone. The relatively tight cementation reported by Hermann (1974) warrants examination of well samples within the AOR to better characterize the Oriskany as a potential injection reservoir. Depth to the Oriskany Sandstone at Burger Power Plant is estimated at approximately 5,900 feet (figs. 8 and 19) with a thickness of 30 feet (figs. 20). Geophysical log density ranges from 2.60 to 2.70 g/cc for wells within the AOR over a 10 to 100-foot interval. A density porosity electric log from API number 3401320553 well indicates an Oriskany zone 12 feet thick with an uncorrected 6 to 8 percent porosity. This well is located approximately 8 miles northwest of the Burger Power Plant site. The lack of photoelectric logs (PE) makes definitive assessment of quartz sandstone for the AOR speculative. The Oriskany reservoir is thicker with better-developed quartz sandstone in the eastern AOR in southwestern Pennsylvania and adjacent West Virginia. The Oriskany Sandstone is a key horizon for analysis within the proposed test well.

UPPER DEVONIAN SILTSTONES AND SANDSTONES

Hydrocarbon production from Appalachian Basin Upper Devonian siltstones and sandstones began in the 1859 with cumulative production estimated at approximately 20 Tcf and significant volumes of oil (Boswell, 1996) (fig. 25). Fields productive from both Devonian siltstone and sandstone reservoirs are known within the AOR (fig. 25) by such driller's names as "Fifth Sand", "Thirty-Foot", "Gordon", and "Gantz" (these units would be found in the interval labeled as Chagrin Shale on figure 3). The dominant productive area is more than 10 miles southeast of Burger Power Plant in West Virginia. The depleted Majorsville-Heard gas field of Marshall County, West Virginia and Greene County, Pennsylvania was activated in 1943 as a natural gas storage field in the Pennsylvanian Salt sand, Mississippian Big Injun sandstone and the Devonian siltstones and sandstones (American Gas Association, 1988). The deeper Devonian reservoirs are at an average depth of 2,570 feet (American Gas Association, 1988). The Upper Devonian siltstone and sandstones are a complex depositional assemblage, which are distal facies equivalents to the carbonaceous black and gray Ohio Shale deposited to the west. The actual extent, thickness and number of these units are unknown at the Burger Power Plant site. Thickness, porosity, and permeability of the Devonian siltstones varies laterally. Thus, the actual number of prospective Devonian siltstone reservoirs at Burger Power Plant deeper than 2,500 feet is unknown at this time. This interval is of keen interest for analysis within the proposed test well at Burger.

LOWER DEVONIAN BEREA SANDSTONE

In the Appalachian Basin, 151 fields have been discovered productive from the Berea Sandstone and its equivalents with an estimated cumulative production of 1.9 Tcf (Tomastik, 1996). The Berea sandstone produces from 17 pools within the AOR (fig. 26). The nearest reservoir data for the Berea is approximately 30 miles to the north-northwest of the Burger site and indicate a porosity

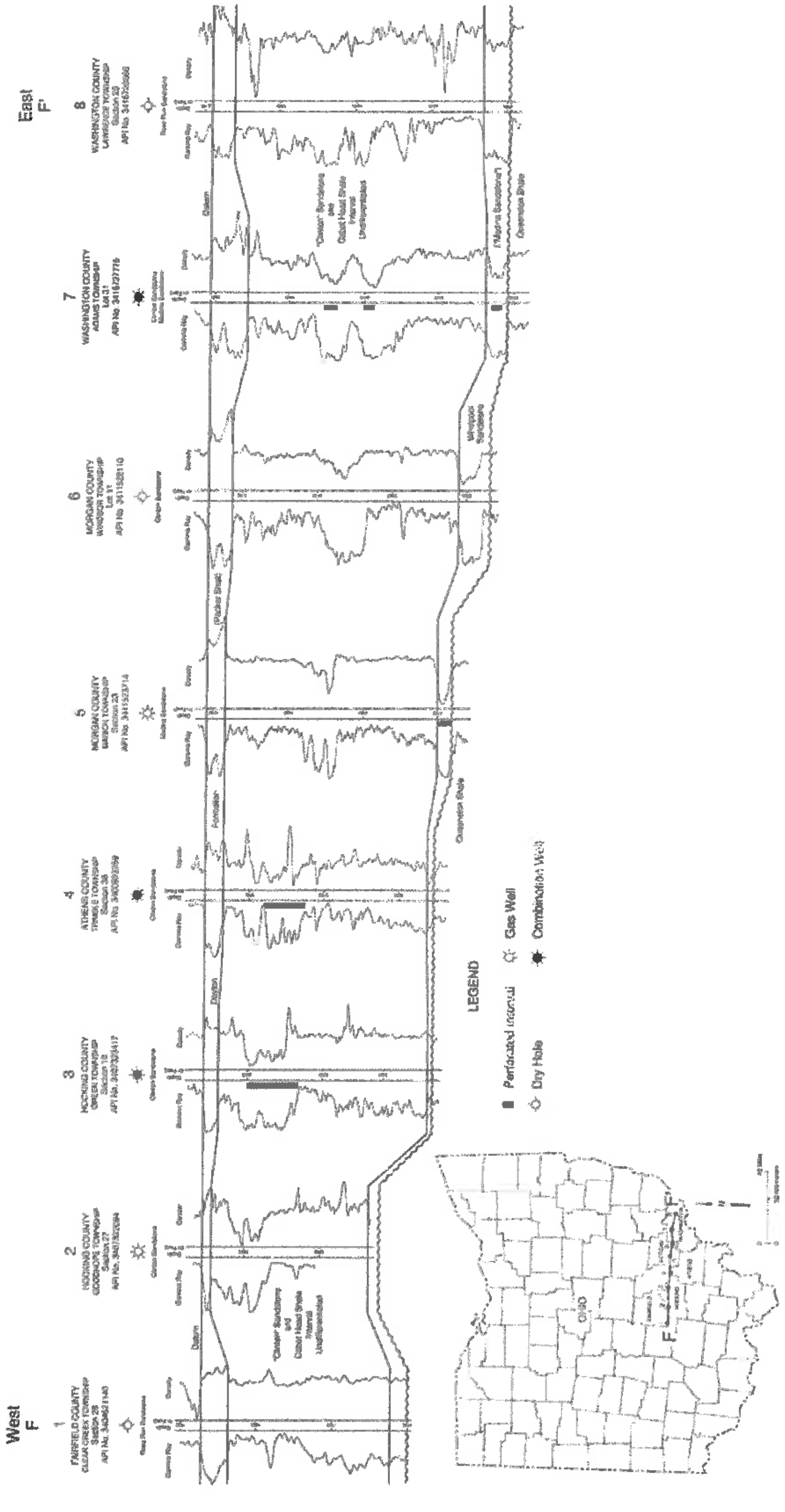

Figure 24.—Stratigraphic cross-section showing the Lower Silurian "Clinton-Medina" sandstone geophysical well log correlations across Sugar Grove and Sharon fields of southeastern Ohio (modified from McCormac, and others, 1996).

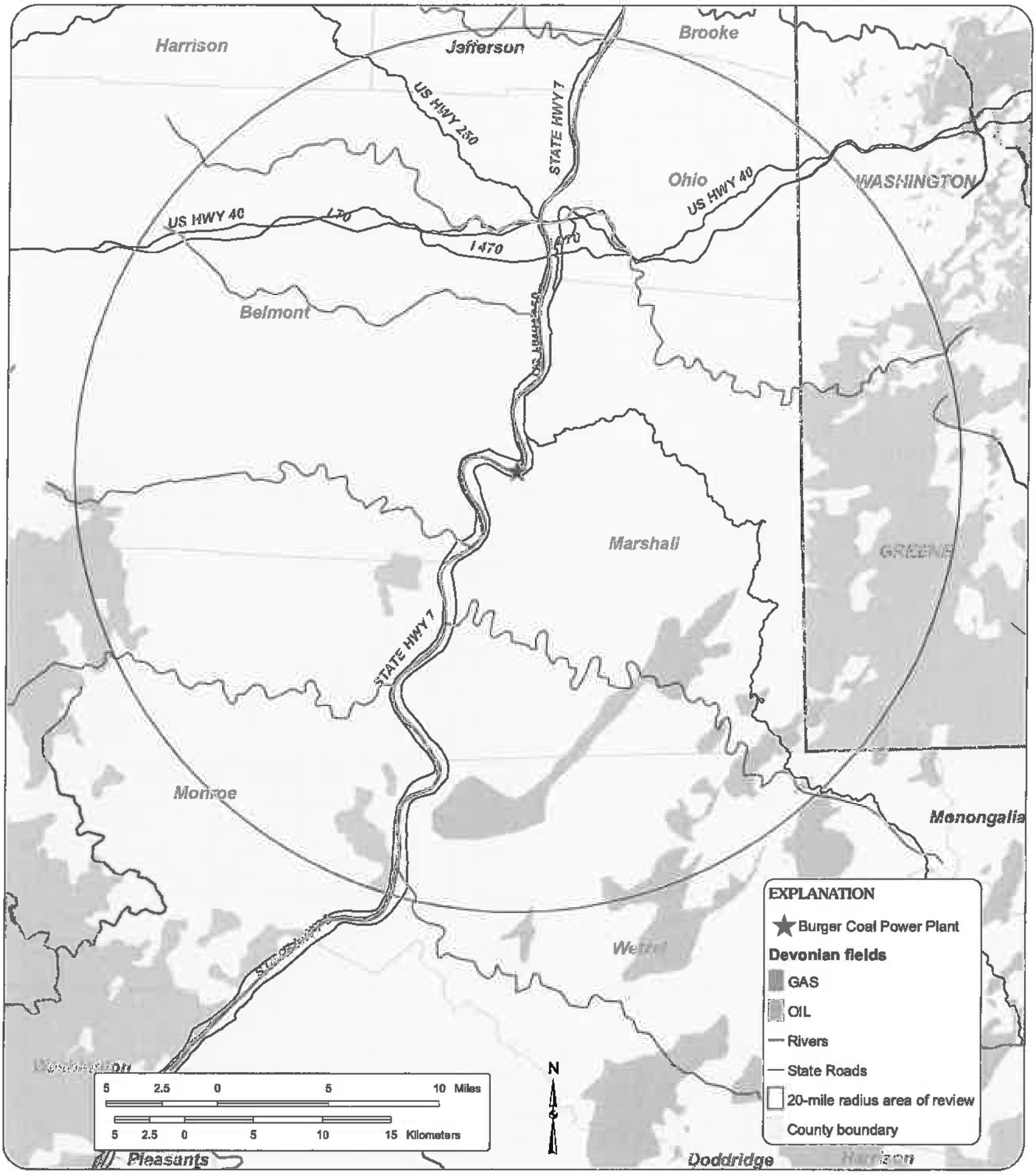

Figure 25.—Map showing the locations of oil and gas fields producing from the Devonian Shales and upper Devonian siltstones and sandstones within the Burger site AOR.

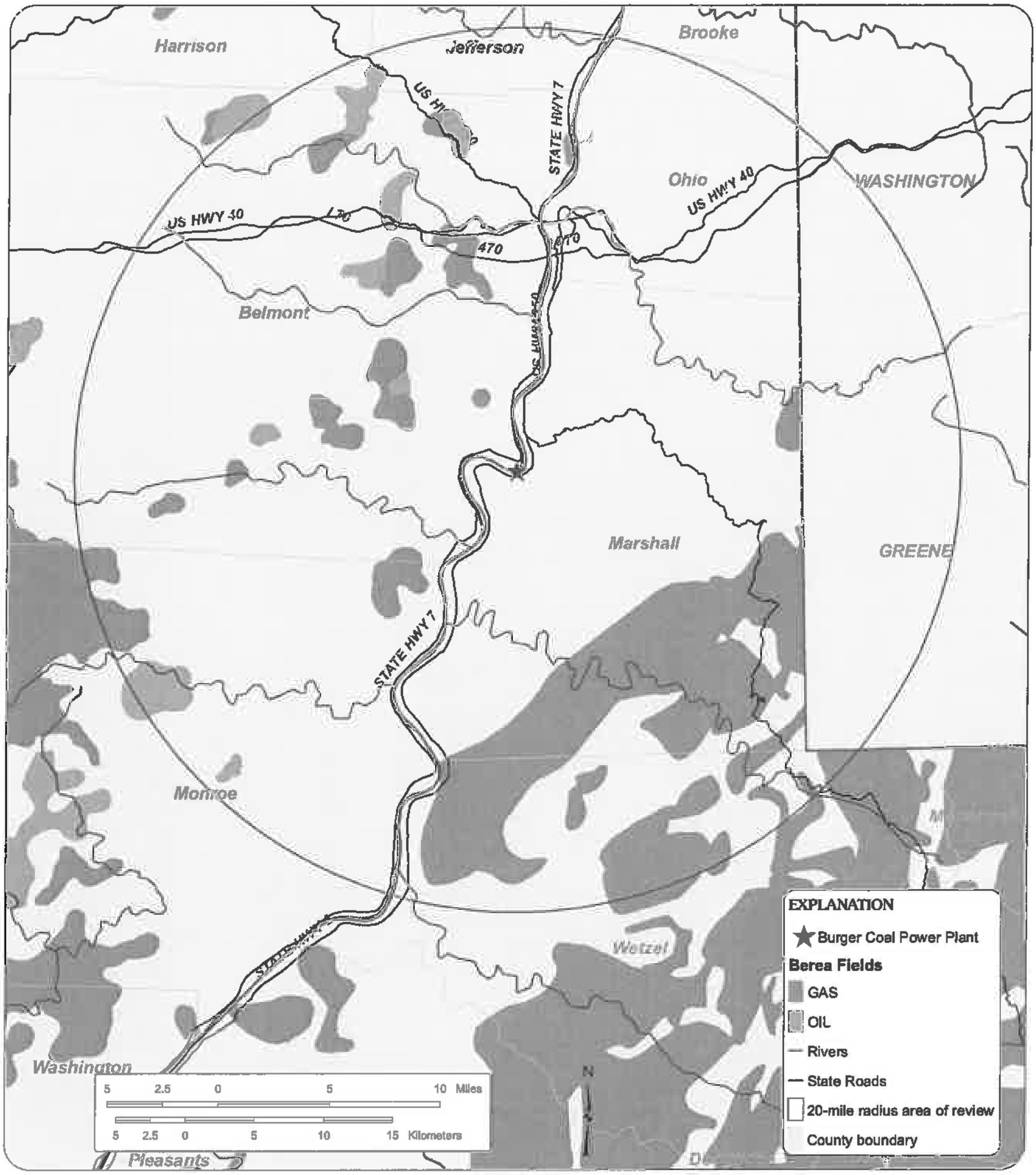

Figure 26.—Map showing the locations of oil and gas fields producing from the upper Devonian Berea Sandstone within the Burger site AOR.

range of 10.1 to 15.4 percent and permeability range of less than 0.1 md to 2.7 md over a 6-foot interval (core analyses from API no. 341212156). Thickness, porosity, and permeability of Berea reservoirs can vary from well-to-well, due to channeling during deposition. Correlation of the Berea Sandstone using geophysical logs alone can be difficult in this portion of the Appalachian Basin due to interfingering of the Berea with low-energy shale deposits. Hence, confusion with younger and older sandstone/siltstone beds may arise, due to a lack of a well-developed Sunbury Shale, which is used as a marker above the Berea. Depth to the Berea at Burger Power Plant is estimated at 1,900 feet (fig. 7) with thickness ranging from less than 10 feet to 20 feet thick. Porosity determined from geophysical logs within the AOR, range from 5 to 12 percent. The Berea is not deep enough for miscible CO_2 injection at this location. It is possible that some Berea oil reservoirs may be candidates for immiscible CO_2 floods.

UPPER AND LOWER MISSISSIPPIAN LIMESTONES AND SANDSTONES

Limited historical production and gas storage from the Lower and Upper Mississippian sandstones is present in the AOR (fig. 27). The Greenbrier/Newman Limestones (Big Lime of Pennsylvania and West Virginia) are prolific producers of natural gas further to the east in West Virginia. Approximately 6,000 wells have hydrocarbon production from 183 fields in West Virginia and 54 wells from three fields in Ohio (Smosna, 1969). Although little production from the Big Injun sandstone is found within the AOR, widespread and prolific hydrocarbon production occurs from the Big Injun in central West Virginia and eastern Ohio, east and north of the AOR. Cumulative production for fields in West Virginia is estimated to be 4 Tcf (Vargo and others, 1996). These reservoirs are mentioned here only to partially explain the large number of shallow penetrations in the area. Depth to the Lower and Upper Mississippian sandstones and Greenbrier/Newman Limestones near the Burger site is too shallow for miscible CO_2 injection.

LOWER AND MIDDLE PENNSYLVANIAN SANDSTONES AND COAL BEDS

Production from the Allegheny Group was first discovered in 1860 (Hohn, 1996). Since then, isolated wells have produced gas in scattered fields in the AOR . Much of this production was encountered while drilling for deeper targets and was commingled. Using an average cumulative of 200 thousand cubic feet of gas (Mcf), the cumulative production for the Allegheny Group in the Appalachian basin is estimated at 181 Bcf (Hohn, 1996). Pottsville sandstones have produced hydrocarbons since the late 1800's in the Appalachian Basin. Of 1,136 Pottsville wells on record in Ohio, 250 have a cumulative production of 20 Bcf, averaging 8 MMcf per well (Hohn, 1996). Figure 28 shows the current and historical production areas from both the Pennsylvanian Allegheny and Pottsville Groups in the AOR. As with the Upper and Lower Mississippian limestones and sandstones these reservoirs are mentioned here only to explain the large number of shallow penetrations in the area.

UNMINEABLE COALS

The tri-state area has had a long and proud history of coal mining, starting at least by 1800. Coal production peaked in Ohio in 1970 with 50.57 million tons produced. In 2004, the state's coal industry produced 23.46 million tons and ranked fourteenth in the nation. Coal-bearing rocks are found in 40 eastern Ohio counties. Belmont County ranks first in the state in all-time coal-producing counties.

It is estimated that three to perhaps as many as five individual coal beds may be present beneath the site that may have sufficient thickness (greater than12 inches) and depth (greater than 500 feet) for consideration as testing targets for enhanced recovery of methane by CO_2 injection. Three of these coals, the No. 6, the No. 5, and the No. 4, most likely will be encountered in the test well. Based on the preliminary analysis of a proposed well sited at a surface elevation of 700 feet MSL, it is estimated the No. 6 coal should occur approximately 820 feet below the surface and be between 24- and 42-inches thick. Analyses of trends in the limited core holes in the AOR suggest the No. 5 and No. 4 coals should occur 30 and 80 feet, respectively, below the No. 6 coal and be in the 12 to 36 inch range in thickness. These data suggest that there is a slight potential for additional coals of sufficient thickness for sequestration purposes to exist below the No. 4 coal in the test well. Rapid facies changes over a lateral distance of only a few hundred feet are typical of rocks in the Pennsylvanian in this portion of Ohio (fig. 29), but particularly so for those occurring below the No. 4 coal. Hence, predicting, or even anticipating, exact lithologic content, especially for something only a few feet thick (as in this case, coal beds) in this part of the geologic section and for a single pilot-project well is uncertain given the nearest control point is a core hole located six miles away.

Ohio is lacking reliable gas-content analyses on most of the coal beds in the state; research on this topic is a high priority at the DGS. However, using conservatively low gas-content values, the DGS estimates the state's producible CBM reserves at 2-5 trillion cubic feet of methane. Although there is currently very limited coalbed methane production in Ohio (all from mine vents), rising natural gas prices have led to growing interest in this energy resource nationally and within the state, and CO_2-enhanced recovery of methane may provide an economic incentive for sequestration of CO_2 sources in coalfields. Coalbed methane drilling and production has seen a sharp increase in both neighboring Pennsylvania and West Virginia since the mid-1990s (fig. 28). It is suggested that the coals underlying the site be fully analyzed via the test well as deep coalbed sequestration (and enhanced methane production) may prove to be an important facet of the portfolio of sequestration options at the facility.

CARBONACEOUS SHALES

The Burger AOR also contains widespread, thick deposits of carbonaceous shales. These shales are interesting in that they are often multifunctional; acting as seals for underlying reservoirs, as source rocks for oil-and-gas reservoirs, and are unconventional gas reservoirs themselves. Both the Ordovician shale and the Devonian shale intervals below the proposed site contain thick sequences of organic shale, however, only the Devonian Shale interval is within economic drilling depths. The suitability of the Devonian shales for CO_2 injection and sequestration has not been demonstrated, but should be considered for additional research at the facility and may have potential to add to the sequestration budget from this plant and others in the near future. Analogous to sequestration in coal beds, CO_2 injection into unconventional carbonaceous shale reservoirs could be used to enhance existing gas production. As an added bonus, it is believed the carbonaceous shales would adsorb the CO_2 into the shale matrix, permitting long-term CO_2 storage, even at relatively shallow depths (Nuttall and others, 2005).

Hydrocarbon production from Appalachian Basin Upper Devonian Shales began in 1821 with cumulative production estimated at approximately 3 Tcf (Milici, 1996). Limited Devonian shale

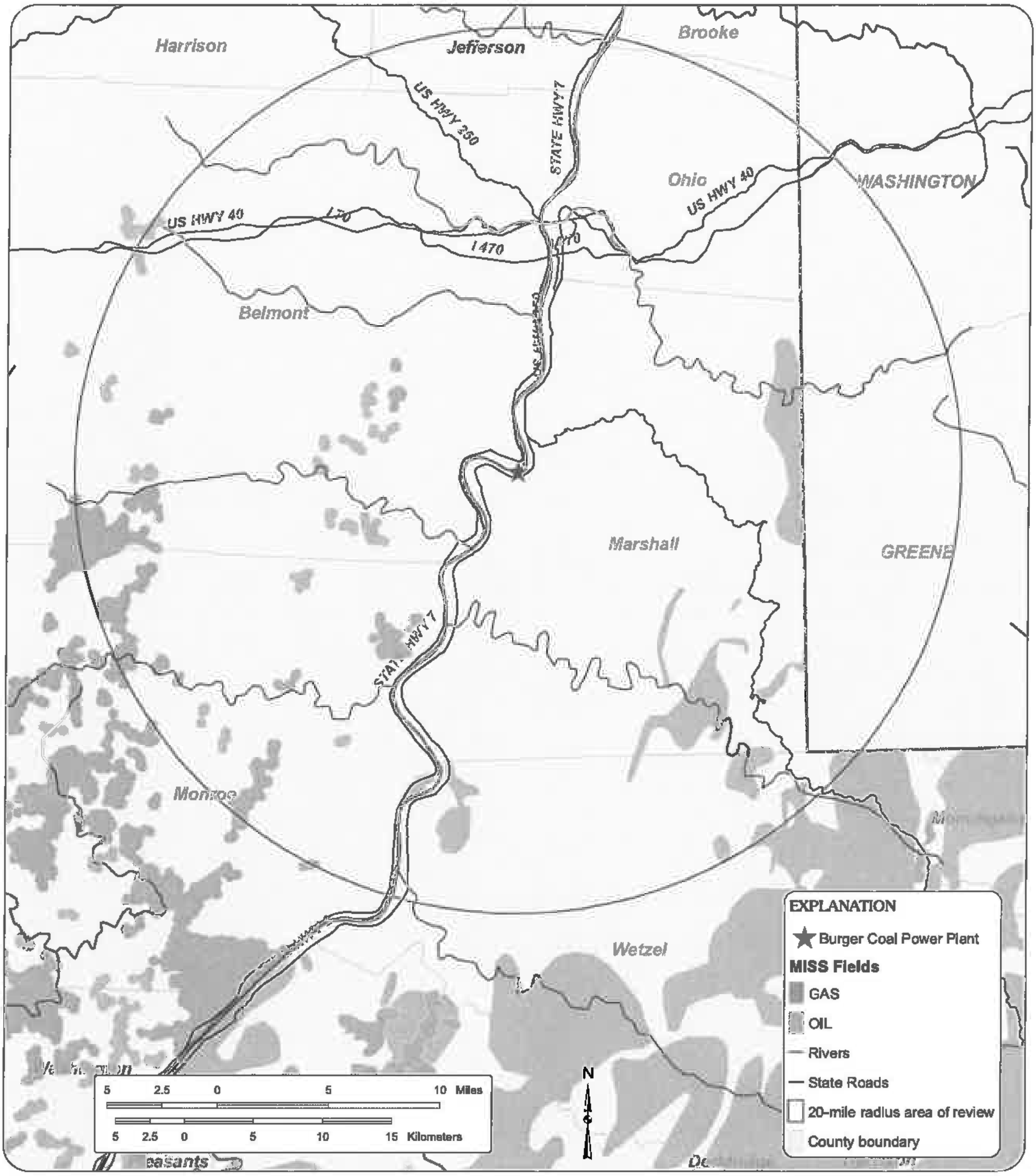

Figure 27.—Map showing the locations of oil and gas fields producing from the Mississippian limestones and sandstones within the Burger site AOR.

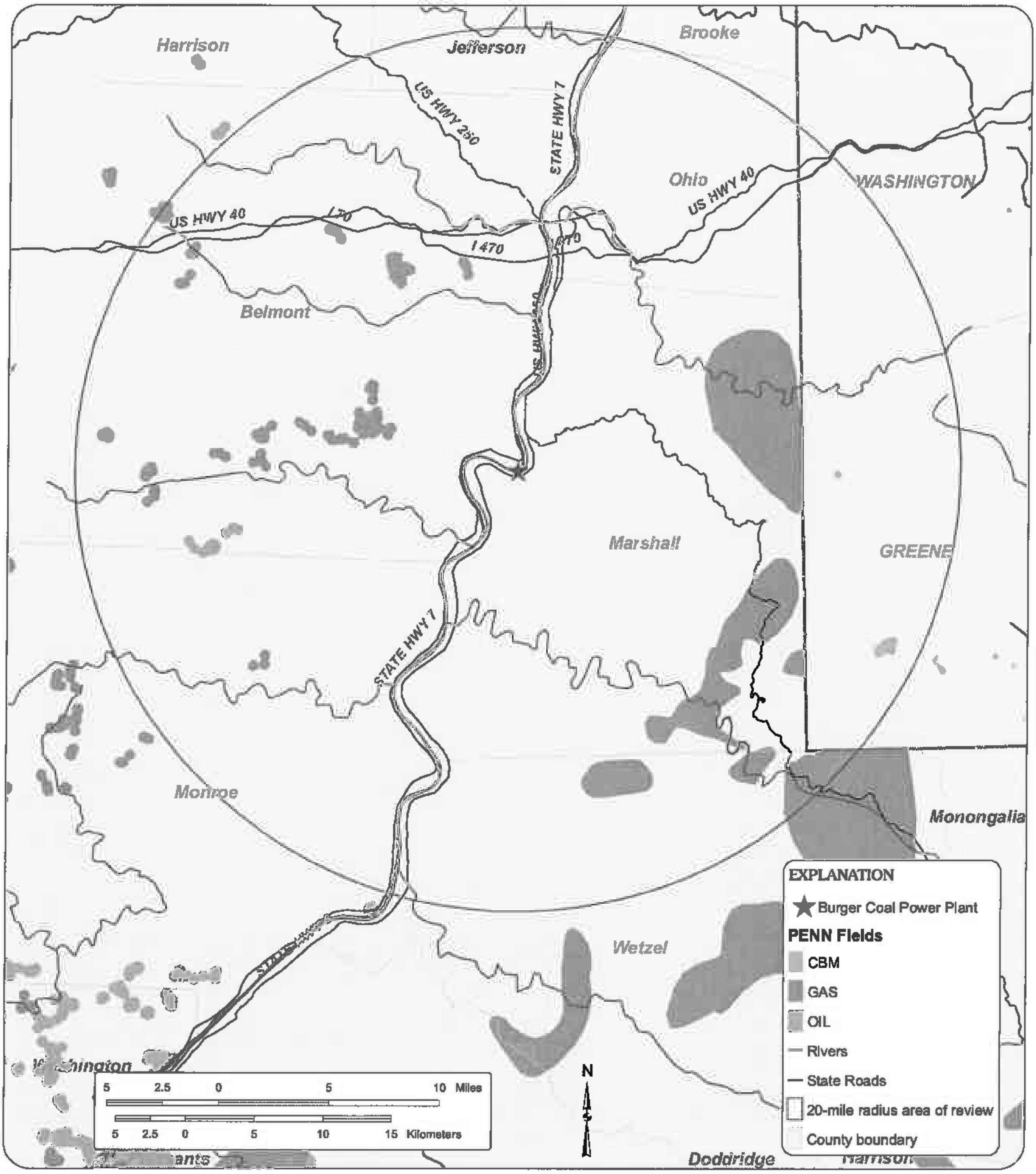

Figure 28.—Map showing the locations of oil and gas fields producing from the Pennsylvanian sandstones within the Burger site AOR.

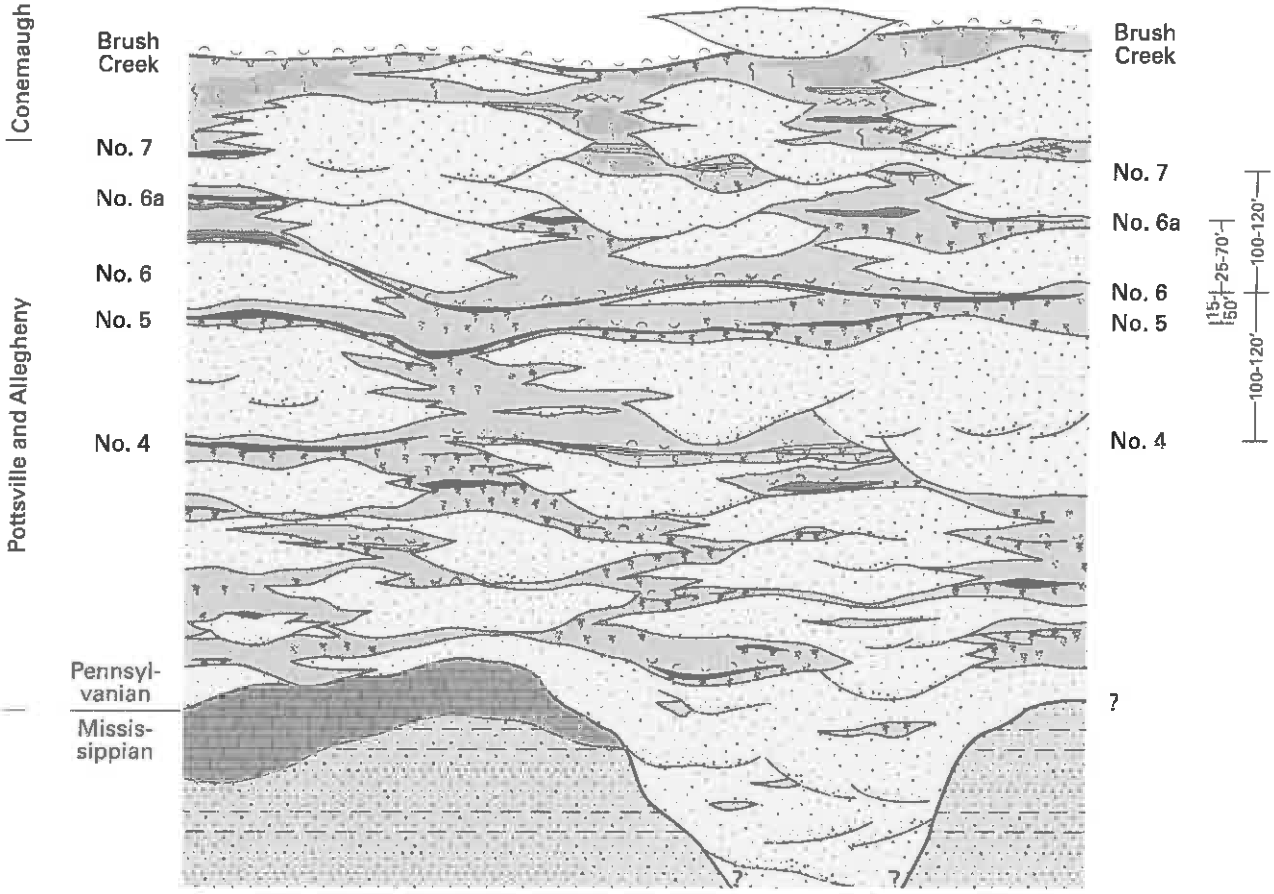

Figure 29.—Schematic cross section of coal-bearing strata near the Burger site illustrating the discontinuous nature of the units and lithologies. Numbered units refer to the numbered coals of Ohio. Right hand column numbers give approximate distance between key coal beds. Surface elevation at the site is approximately 670'. The main coal mined near the site is the number 8 (Pittsburgh), which is found at an approximate elevation of 480' above sea level. The base of the Conemaugh Group (shown in illustration) is approximately 520 feet below the number 8 coal.

production is present within the AOR (figs. 22 and 25). Most Devonian shale wells in the area have been completed using open-hole techniques (without casing and perforations through the pay zones) making it very difficult to know which intervals are the most productive. Also, many of the wells did not have geophysical logs run, thus separating productive black from gray shale and siltstones units in this portion of the Appalachian basin is very difficult. However, we do know that most of the production in this area is from the shallower portions of the Devonian Shale sequence, largely from the gray shales and siltstones. The Devonian black shales within the AOR are very lightly drilled, primarily due to the greater drilling depth. Prospective producing black shale units at the Burger Power Plant site include the Rhinestreet Shale Member of the West Falls Formation; Middlesex Shale Member of the Sonyea Formation; Geneseo Shale Member of the Genesee Formation, and Marcellus Shale Member of the Hamilton Group.

It should be mentioned that the Hamilton Group will likely be problematic during drilling. Lost circulation due to the incompetent, fluid-sensitive shales of this interval is commonly reported. Also, the Hamilton is under-pressured in this region, adding to drilling difficulties. These same characteristics also make the Hamilton a possible injection reservoir.

Depth to top of the Devonian shale at Burger Power Plant is approximately 2,000 feet. Total thickness of Devonian shale at the Burger Power Plant site is estimated at 4,100 feet. Depth to the base of the shale interval (top of Onondaga Limestone) interval is estimated at 5,700 feet. Detailed correlations, sample examination, and log analyses are required to estimate total black shale thickness within the area once the proposed test well is drilled. Reservoir and core data acquisition and analysis for these intervals is suggested for the test well.

CONFINING UNITS FOR POTENTIAL INJECTION INTERVALS

Cap rocks are abundant for all prospective injection reservoirs in the Burger AOR and should, in the absence of well-developed fracture and fault systems, provide adequate sealing to prevent vertical migration of injected CO_2 (figs. 3 and 30). The assumption that tight, impermeable rocks are present in the AOR is based on core analyses and data distant from the Burger Power Plant site, although projecting core analyses for cap rocks long distances is more reliable than delineating prospective reservoirs. Well-developed cap rocks can be generally verified using geophysical well logs, which show low versus high porosity. Cap rocks for speculative injection zones will not be discussed. The reader is referred to Wickstrom and others (2005) for a discussion of deeper seal units (below the Lower Silurian Cataract Group/Tuscarora Sandstone) and regional overview.

Cap rocks above the Lower Silurian "*Clinton*-Medina"/Tuscarora Sandstone include approximately 1,800 feet of tight shale and carbonates of the Clinton Group, Lockport Dolomite and Salina Group carbonates and evaporites (minus cavern development from nearby solution mining). Driller's call the thick carbonates above the "*Clinton*-Medina"/Tuscarora Sandstone the "Big Lime". The Bass Islands Dolomite interval is a cap rock of 400 feet of carbonates beneath the Oriskany Sandstone possible injection reservoir. The Onondaga Limestone, a potential cap rock above the Oriskany, consists of 300 feet of tight to vuggy carbonates, below the Hamilton Group interval. Potential cap rock for the Hamilton and overlying Upper Devonian black shale intervals is variable. Depending on the thickness and extent of Upper Devonian siltstones and sandstones the cap rock for the Devonian shales will range between 1,000 and 2,000 feet of shale and tight siltstone. Cap rocks for Devonian siltstones and sandstones is also highly variable and dependent upon relatively unknown extent and thickness of siltstone and sandstone beds themselves, and an overlying, upward increasingly, complex assemblage of Mississippian and Pennsylvanian shale, carbonates, coal, and sandstone. Estimated thickness of these highly variable lithologies is 2,500 feet. Net effective thickness excluding the USDW is 1,300 feet. Elimination of shallow speculative and possible injection reservoirs effectively either adds reservoirs as buffer zones or potential cap rock to the lower- most prospective injection reservoir. With the "*Clinton*-Medina" as an example as much as 7,400 feet of potential cap rock and buffer zones exists. Actual drilling and core analyses at the Burger site is required to adequately determine rock properties of potential cap rocks. It is suggested that sidewall cores be taken from multiple depths of prospective cap rocks and buffer zones and analyzed for horizontal and vertical permeabilities, and capillary pressure measurements. Thin sections should also be made from these samples and the mineralogy characterized.

STRUCTURAL GEOLOGY NEAR THE BURGER SITE

Depth to Precambrian basement at the Burger site is estimated to be approximately 14,000 feet, based on very sparse deep well control and projecting expected thicknesses of units from the base of the deepest wells near the site. The nearest prospective basement fault to the Burger site is likely to be deep faulting associated with the Rome Trough to the south and east. This faulting is likely to be down to the southeast normal faults with displacement increasing on individual faults further to southeast towards the main border fault of the Trough (fig. 11). So little deep data is available for this area that little can be said with certainty of deep structure. Therefore, the acquisition and analysis of seismic reflection profiles across the immediate area are of vital importance.

Structure contour and isopach maps of various coal beds, and stratigraphic profiles of specific intervals of the Monongahela group in Belmont County by Berryhill (1963) imply a northwest trending structural element may exist in the subsurface of the Burger site. This shallow structure might be indicative of deeper structural elements below the area, so the following paragraphs are included herein for completeness.

Ferm and Wisenfluh (1989) developed a depositional model for Pennsylvanian coal deposits in the Appalachian basin that had a deep structural component as one of the controlling mechanism for lithologic spatial patterns. Moreover, numerous summaries on the structural influence in various coal-forming basins are present in Lyons and Rice (1986). In the AOR, several indirect lines of evidences suggest that the Burger site may occur in an area with a previously unrecognized deep structural element. Data supporting this conclusion include:

1. A northeast-southwest trending, easterly dipping monocline occurs about 2 miles northwest of the site. The monocline is parallel to, and occurs approximately 10 miles south-southeast of a normal fault (downthrown south) mapped in the Pittsburgh coal. Berryhill (1963) discusses another faulted area in the Pittsburgh coal, a northeast-trending graben where the coal is displaced and thickens within the boundaries of the structure. This feature is located approximately 20 miles northwest of the Burger site (see abandoned mine map BT-178 on file at the DGS). Moreover, Berryhill (1963) notes many mine operators

in Belmont Co. report local faulting in the Pittsburgh coal.

2. The Burger site occurs where the south-southeasterly flowing Ohio River makes an abrupt, 130-degree deviation to the northwest. The river then follows this northwesterly trend for about 2 miles and then makes a second abrupt, 165-degree change in course direction to the southeast. This second river diversion occurs where the Ohio River intersects the northeast-trending monocline (see, item 1), a structural feature that may be the controlling element for the second diversion of the river course. The two mile, northwest-trending section of the Ohio River that occurs between these prominent bends of the river, is parallel to several structural irregularities indicated on the structure contour maps of the Pittsburgh coal, that, when aligned, trend northwest-southeast. Interestingly, this trend, when projected northwestward, crosses in close proximity to the graben discussed above (item 1), and aligns with the spillway of Piedmont Lake, a place where surface displacement of the bedrock was reported in the engineering profiles created for construction of the reservoir.
3. Cross and Schemel (1956) mapped a series of northeast-southwest trending synclines and anticlines (Proctor and Loudenville synclines and Martinsville anticline) on the shallow Pennsylvanian strata just several miles south of Burger. These features parallel the monocline and faulting noted in item one.
4. A dome structure with about 50 feet of relief exists on the Pittsburgh coal approximately 7 miles northwest of the site. The dome occurs mostly in the western portion of Mead Township.
5. Changes in the thickness of the Waynesburg coal align with the northwesterly linear trend noted above (item 3).
6. Lithologic changes occur in the vicinity of the northwest-southeast linear trend discussed above. In some areas of Belmont County, the percentage of sandstone in the section increases southwestward of this lineament whereas limestone and other fine-grained lithologic units are prevalent northeast of the lineament. This would suggest, subsurface faulting has occurred along this trend and influenced the distribution of sediments during the Upper Carboniferous.
7. The economic deposits of the Fishpot coal were found only to the south of the linear trend discussed in item 2.
8. Locally, the interval between the Pittsburgh and Fishpot coal expands and is dominated by sandstone south of the linear previously discussed.

The structural grain of the area is typically displayed via an orthogonal joint set with dominant directions be northeast-southwest and northwest-southeast. The above noted structural irregularities may show that shallow deposition and structure is controlled by deep-seated faulting, perhaps the step-down faults associated with the Rome Trough mentioned earlier, which would be expected to be oriented northeast-southwest. Conversely, these irregularities may simply be showing response to local compressional stress associated with a later orogenic event, such as the Alleghenian.

ARTIFICIAL PENETRATIONS

As mentioned above, extensive mining of shallow coal resources has prevented most modern oil and gas exploration within much of the AOR. As a result, deep artificial well penetrations within several miles of the site are rare. An inventory was made of all deep wells in the study region and near the study site. Only 59 wells have been drilled into the Devonian Onondaga or deeper within 20 miles of the site from a total of 6,257 wells reported drilled from public records in Ohio, Pennsylvania, and West Virginia. There are three deep wells drilled deeper than Ordovician Trenton Limestone within 30 miles, one of which drilled into Precambrian basement in Harrison County, Ohio (Appendix A). The closest deep well to the study site is the Occidental no.1 Burley well, 16 miles southeast of the site in eastern Marshall County, West Virginia. The Burley well was drilled to a depth of 16,512 feet into the Cambrian Knox Group. The nearest moderately deep wells are within approximately 2-1/2 miles west of the site, where 13 wells were drilled to about 6,600 feet for Silurian Salina halite solution mining (West Virginia Department of Environmental Protection). The lack of deep well data at the Burger Power Plant site illustrates the need for a deep stratigraphic test prior to attempting reasonable modeling of potential injection reservoirs. Appendix D is a general list of known deep well tests by formation at total depth within 30 miles of Burger Power Plant. The review of artificial penetrations reported to state agencies for the AOR, suggests a minimum of 1,402 wells drilled deeper than 2,500 feet into the Devonian shale.

CLASS I AND II INJECTION WELLS

There are no Class I (hazardous and industrial waste) injection wells within the Burger vicinity. The nearest Class I injection facility is located in Scioto County, Ohio approximately 140 miles from the proposed site.

The locations of nearby Class II (brine) injection wells are shown on figure 30. Two Class II injection wells are found within the AOR. The well in Monroe County, Ohio (API 3411121559) injects brine into the Mississippian "Big Injun" sandstone (Appendix E). The well in Wetzel County, West Virginia (API 4710301415) was drilled to a total depth of 2,360 feet. Although its record does not report the injection zone, the Devonian Gordon Sandstone is the formation at TD.

CLASS III INJECTION WELLS

Class III injection wells are those used for the injection and withdrawal of fluids within the salt solution mining industry. Typically in this region, water is injected via wells into the halite beds of the Salina Group where it acts to suspend the salt in solution, which is then withdrawn via the same or another well. Once at the surface, the water is evaporated from solution to produce the contained salt. Although the Salina Group does not produce hydrocarbons within the AOR, halite beds of this interval have been solution mined in Marshall County, West Virginia within two and one-half miles west of the Burger Power Plant site (figs. 4 and 31). Thirteen wells have been drilled to about 6,500 feet to remove an uppermost halite bed of the Salina. Very little data, other than some well locations, is available on these wells at the West Virginia Geological Survey (Appendix E). Reportedly, the West Virginia Department of Environmental Protection has some additional data on these operations, but it is not in any order, nor is there an inventory of the information. It is suggested that an effort is made to assemble all pertinent available data on these operations prior to permitting injection operations at Burger.

Apparently the area was first drilled for Salina salt production in the early 1950s. A directionally drilled well into the Salina was also reported in Moundsville, WV (French, 1963). This well has not been located via the current data search. The thickness of Salina halite beds solution mined is not known nor is a cumulative volume of produced halite presently available. Thus, adequate modeling of the extent and orientation of cavern development is not possible. It

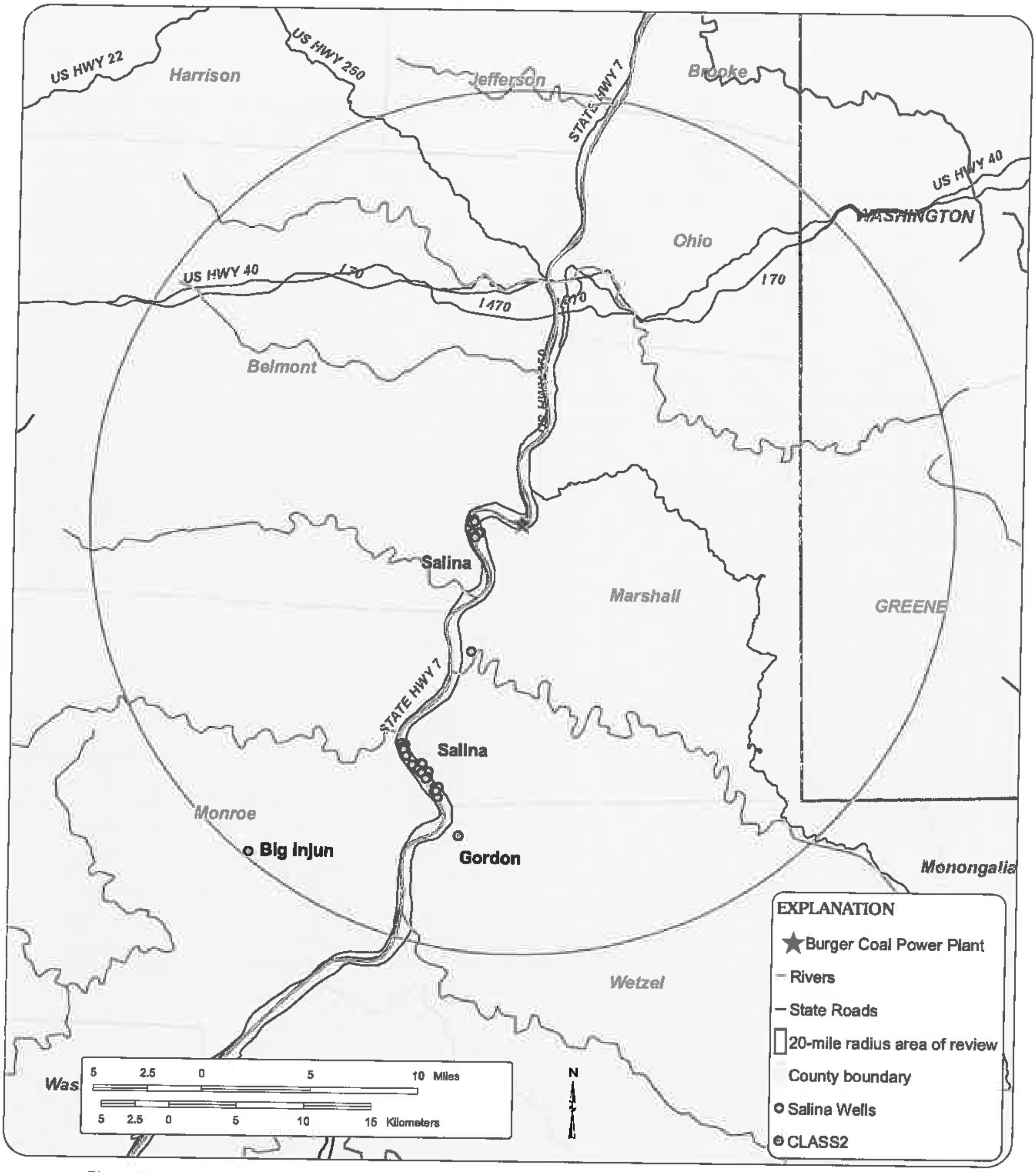

Figure 30.—Map showing the locations of class II (brine) AND class III (solution mining) injection wells within the Burger AOR.

is likely that seismic reflection data will not be able to adequately image the solution-created void because the halite beds are typically not thick enough to image individually. However, in absence of further data, the combined removal of thicker lower halite beds and accompanying collapse of roof material has the potential to be imaged on seismic reflection profiles. Other Salina solution mining operations are located along the Ohio River approximately 12 miles southwest of the Burger Power Plant in Natrium, Marshall County, West Virginia.

Solution mining operations create large cavernous voids, as well as rubble and breccia zones due to roof collapse. Such features would, of course, have extraordinary porosity and permeability making them possible CO_2 storage caverns. However, much more site data is necessary to judge the volumes or the safety of such a consideration at this site.

SEISMIC REFLECTION DATA

The nearest public domain seismic reflection data to the Tuscarawas County site is the Ohio COCORP profile, an east-west profile acquired in 1989. The COCORP acquisition parameters were designed to look at very deep geologic features within the earth's crust 10 to 30 miles deep. Thus, the upper few seconds of data, which contains the reflection records from the Paleozoic and shallow Precambrian, is rather coarse for normal structural and stratigraphic interpretations.

Currently, no industry-acquired seismic reflection data are available for acquisition or are known to exist in the vicinity of the Burger Power Plant (John Forman, personal comm. 3/21/06). The closest known available seismic information is the Consortium for Continental Reflection Profiling (COCORP) line, acquired in 1987, that crosses Belmont County approximately 15 miles north of the site. This seismic data was originally acquired as part of a larger study on the deep crust in the eastern midcontinent of North America (Pratt, and others, 1989). Later, the original dataset was reprocessed using standard industry techniques commonly applied to seismic data for hydrocarbon prospect evaluations. This reprocessing resulted in the enhancement of many of the shallow reflectors in the Paleozoic section when compared to the original seismic profile (which was performed using methods for analyses of deep crustal features) and therefore, may be useful in this analysis of the Burger site. However, the distance between the COCORP line and the site may limit the effectiveness of this data for use in modeling the subsurface geology in the AOR.

SEISMICITY

The DGS operates a statewide array of seismic monitors, with all data reported to, and collected at our central facility, the Horace R. Collins Laboratory near Delaware, Ohio. The DGS also cooperates closely with the U.S. Geological Survey's Earthquake center in Colorado, and operates one of the USGS strong-motion sensors at its Delaware facility. Lastly, in the event of a strong event within the state, the DGS cooperates with the USGS and the Lamont-Doherty Observatory to quickly place portable sensors around the area of the event to closely monitor any aftershocks. Close-spaced monitoring of aftershocks allows very precise placement of the epicenter and better solutions for the geometry of the fault plane involved. Figure 31 is a map showing all recorded earthquake locations and relative magnitudes in and surrounding Ohio (Hansen, 2002). Updates to this map and detailed information on most previous seismic events can be found on the OhioSeis website at: http://www.dnr.state.oh.us/OhioSeis

The Burger site lies within the eastern Ohio aseismic zone, an area that has not generated an earthquake within historic times. The nearest significant earthquakes were the January 31, 1986 Lake County (5.0 mbLg) at a distance of approximately 200 km and the September 25, 1998 Pymatuning earthquake (5.2 mbLg) at a distance of approximately 180 km. The NCEER catalog lists an earthquake in 1824 in West Virginia at a distance of approximately 34 km from the site. This earthquake was assigned a magnitude of 4.1 based upon the felt area, and a Modified Mercalli Intensity of IV. Such early earthquakes are notoriously inaccurate as to location and magnitude due to the sparse documentation in newspapers. This region of West Virginia has not experienced any seismic activity since the unique 1824 event.

The Burger site lies in the less than 6 percent g zone of the U.S. Geological Survey Peak Acceleration (%g) map with 2% Probability of Exceedance in 50 years (2002). The above data suggest that the site has a very low probability of significant seismic risk.

SUMMARY

Available literature, petroleum well and storage field data, well and core descriptions and analyses, and coal information were compiled and analyzed for an area within 20 miles of the Burger power plant in Belmont County, Ohio. A total of 6,257 records on producing oil and gas wells, dry holes, stratigraphic core tests, and brine-solution wells are contained in public archives in the AOR. Core tests and analyses of prospective injection reservoirs and cap rocks are non-existent or not known to be available for public use in the AOR. Other than shallow stratigraphic core hole tests, only one well is know to contain a deeper interval (Ohio Shale) that has been cored, and only one short description of the Oriskany Sandstone is known; both are from wells drilled in Belmont County, Ohio. Only 59 wells have been drilled into or deeper than the Devonian-age Onondaga Limestone in the AOR. Of these wells, only four wells were drilled deeper than the Silurian-age "*Clinton*-Medina" interval and just one well penetrated the Cambrian-age Knox Dolomite within the AOR. However, in a 30-mile radius around the study site, additional deep stratigraphic data exist that can be used to project data about these deeper units into the site area. The nearest well penetrating Precambrian rocks occurs 30 miles northwest of the Burger Power Plant. Many of the deeper wells have geophysical logs available in public records. Conventional industry acquired seismic data is not known within the AOR. Additional data is also lacking in the AOR on formation pressure, brine/formation fluid samples, and mineralogy.

Maps of oil and gas plays in the AOR are provided to assist in understanding their potential to impact CO_2 sequestration. Approximately 67 oil and gas pools/fields are within the AOR (fig. 22, Appendix C)). Many of these areas produce hydrocarbons from multiple horizons at depths that range from 800 to 7,300 feet below the surface. However, many of these field/pool data are not corrected/correlated for stratigraphic consistency. Developing geologic analogues using existing oil, gas and storage reservoir, and solution mining data within the AOR could be useful to evaluate prospective saline reservoirs at the Burger Power Plant site. Usefulness is dependent on available time to create stratigraphically consistent data sets. It is likely geologic conditions similar to the well-developed reservoirs in current and abandoned storage fields in West Virginia and Pennsylvania are not present at the Burger

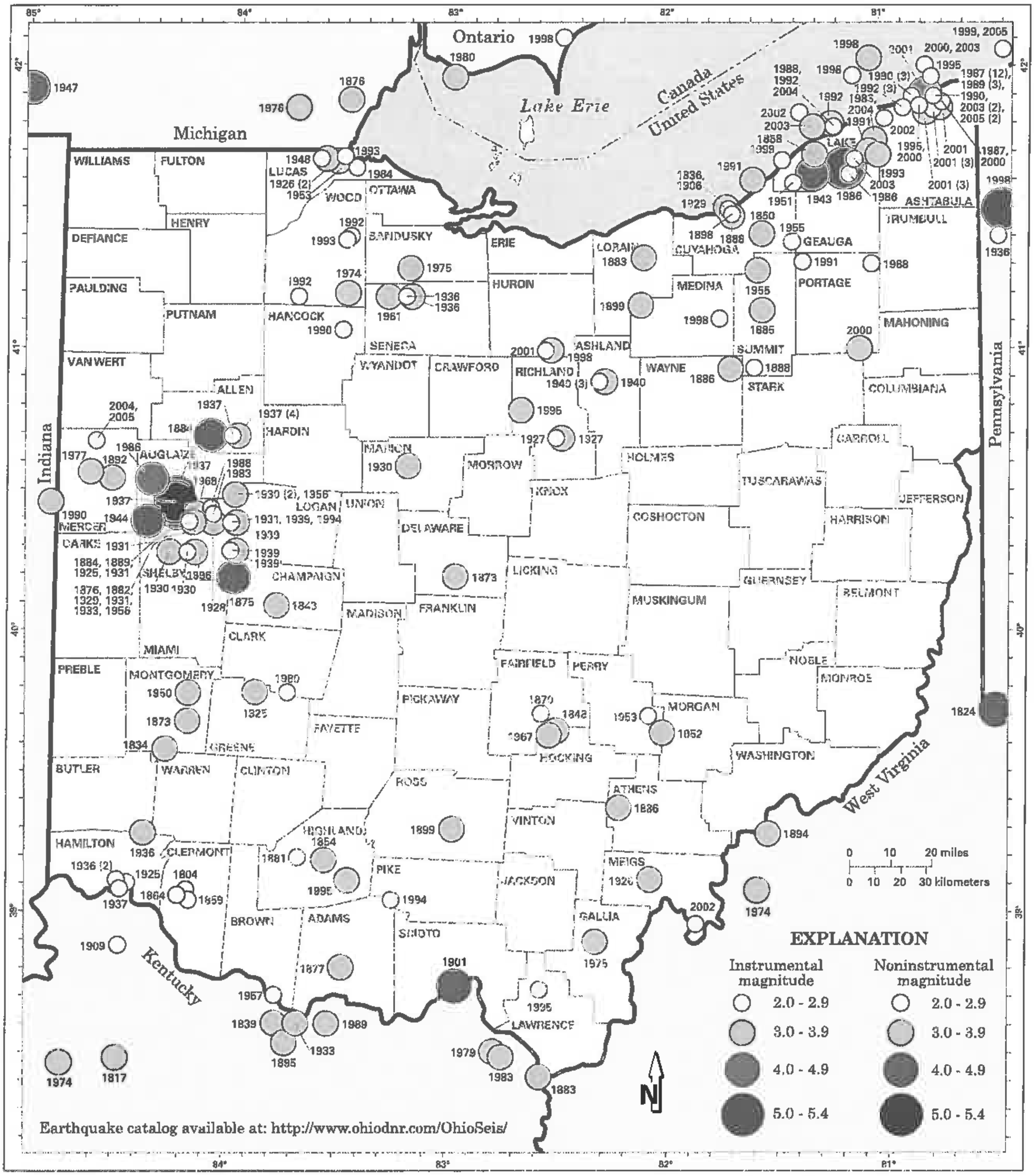

Figure 31.—Map of Ohio and surrounding areas showing known earthquake locations and relative magnitude (from Hansen, 2002). (http://www.dnr.state.oh.us/OhioSeis/images/epicentr.gif).

Power Plant site. The limited geophysical well log data for the few deep prospective saline reservoirs suggest thin and tight reservoirs beneath the Devonian black shales at the Burger Power Plant site. Analysis of these reservoirs indicates seismic transparency. No actual core data for these prospective reservoirs or cap rocks exists or is available within the AOR.

Nevertheless, formations with prospective hydrocarbon reservoirs may be targeted for non-commercial CO_2 injection. In the AOR, the following plays are discussed: the Lower Silurian "Clinton"/Tuscarora Sandstone and Lockport Dolomite, Upper Silurian Salina Group and Bass Islands Dolomite, Lower Devonian Oriskany Sandstone, Upper Devonian Black Shales, siltstones, and sandstones, Upper Devonian/Lower Mississippian Berea Sandstone, Upper and Lower Mississippian sandstones and carbonates, and the Lower and Middle Pennsylvanian sandstones (fig. 3 and 30). Oil and gas plays deeper than the Lower Silurian "Clinton"/Tuscarora Sandstone are not discussed, as these plays are considered "ultra-deep" therefore deemed economically impractical for the proposed test well. Production from these deep plays (Ordovician Trenton/Black River/St. Peter/Beekmantown, and Cambrian Rose Run/Conasauga) is located 50 to 100 miles or more from the Burger Power Plant site and the potential does exist for hydrocarbon discoveries in these zones within the AOR. Future economics may also warrant examination of these deep zones for potential CO_2 injection.

A minimum depth of approximately 2,500 feet is necessary for injected CO_2 to remain in a supercritical state. At the Burger Power Plant this will eliminate several Upper Devonian siltstone and sandstone beds, the Berea Sandstone and overlying porous Mississippian and Pennsylvanian limestone and sandstone reservoirs. However, injection into coal seams and, perhaps, organic shales, do not require this depth constraint. Therefore, these units should be thoroughly analyzed within the proposed test well.

Proximity to existing and abandoned Silurian Salina Group halite solution mining activities may also limit the injection options at the Burger site. Solution-mining activities in the Silurian Salina Group are located within 2-½ miles updip of the site. Presently, the extent and thickness of Salina halite removal, potential roof fall of overlying units, and cumulative production is unknown. Should the test well show that units close to the Salina are favorable for injection (such as the Bass Islands Dolomite or Oriskany Sandstone), extensive investigations and modeling will probably be required to insure integrity of the prospective operations prior to permitting.

Figure 32 shows the estimated depths of potential cap rocks and prospective and speculative injection reservoirs and cap rocks at the Burger Power Plant site. Overall, the Hamilton Group may prove to be the most favorable potential reservoir based on typical drilling characteristics for the region. The "*Clinton*" sandstone and Oriskany Sandstone are possible reservoirs based on limited well control within the AOR. The Lockport Dolomite, Salina Group, Bass Islands Dolomite, Onondaga Limestone, and Devonian shale and siltstones are considered speculative intervals. Deep unmineable coal beds beneath the site are also considered as possible injection zones. Potential buffer zones, which in part are represented by possible and speculative reservoirs that would not be used for injection, combine with cap rock units to reduce the potential migration of fluids vertically. Converse to reservoir rock, cap rock is generally considered very favorable throughout the region as it is relatively predictable from well log analyses tied to core and testing data from great distances. Although cap rock is considered favorable throughout the region, it does not preclude detailed analyses through coring and testing should the site be chosen for research.

RECOMMENDATIONS

Existing and abandoned solution mining operations of salts in the Silurian-age Salina Group occur about two miles west (and stratigraphically updip) of the Burger Power Plant site. We do not believe that these operations pose a threat for the proposed, very limited-scale, injection of the pilot well (unless the seismic analysis or test well results show otherwise). However, all data, from both publicly available regulatory agencies and private industrial operators, concerning these operations should be thoroughly analyzed and modeled before Burger were to proceed with any larger-scale injection program. Presently, data of the extent of cavernization and magnitude of any collapse features associated with these solution mining activities are undetermined nor are they known to exist at any West Virginia regulatory agency.

Seismic reflection data should also be acquired, processed, and analyzed prior to drilling the stratigraphic test. This data will be critical in determining structural framework of the strata that exist beneath the site. Seismic reflection data may be useful also in the additional characterization of any potential injection reservoirs and confining intervals as well as in determining whether solution-mining features exist in the immediate vicinity of the site. However, it should be noted, all of these features must be of an adequate thickness and extent to be imaged from properly acquired and processed seismic reflection data. Nonetheless, it is anticipated most prospective reservoirs beneath the site will likely be seismically transparent and not discernable on the seismic profile.

The lack of seismic data and the absence of significant modern drilling to depths below the Berea Sandstone along the Ohio River make our understanding of the attributes on the deep subsurface geology below the site speculative. The possibility of finding a poorly understood or even unknown hydrocarbon reservoir at depth, that may serve also as a potential EOR and miscible CO_2 injection target, exist at the Burger Power Plant site.

Any newly acquired seismic data should be used in combination with existing data sets and maps to make the best possible estimates on the depths to the top of key geologic formations when planning the Burger pilot well. Once the well is completed, prospective injection intervals should be sampled for both interstitial fluids and pressures during drilling operations. A vertical seismic profile (VSP) should be considered also as a means to directly correlate the well with the seismic reflection data.

It is suggested that the drilling program be designed to allow coring of the coal-bearing strata. Coal intervals should be properly captured in pressurized canisters and analyzed for gas desorption and CO_2 adsorption. The deep coals should also be a fully analyzed for standard coal quality characteristics (ash content, BTU content, maceral analysis, age-determination, etc.).

Sidewall cores should be taken of all prospective injection intervals and sealing units for analysis; these tests should include, among other things, the determination of the porosity, permeability (vertical and horizontal), capillary pressures, and mineralogy of each unit. Moreover, an extensive suite of geophysical logs should be performed using the best available modern logging tools. If possible, a good borehole imaging log, such as a FMI (Formation Mico imager) should be among the logs. Selected injection intervals should be tested for injectivity following thorough analyses and correlation with the seismic, well logs, and core data.

Lastly, this newly acquired data should be merged with existing data to create a new suite of maps and cross sections of pertinent geologic units and reevaluated for the AOR. This newly obtained

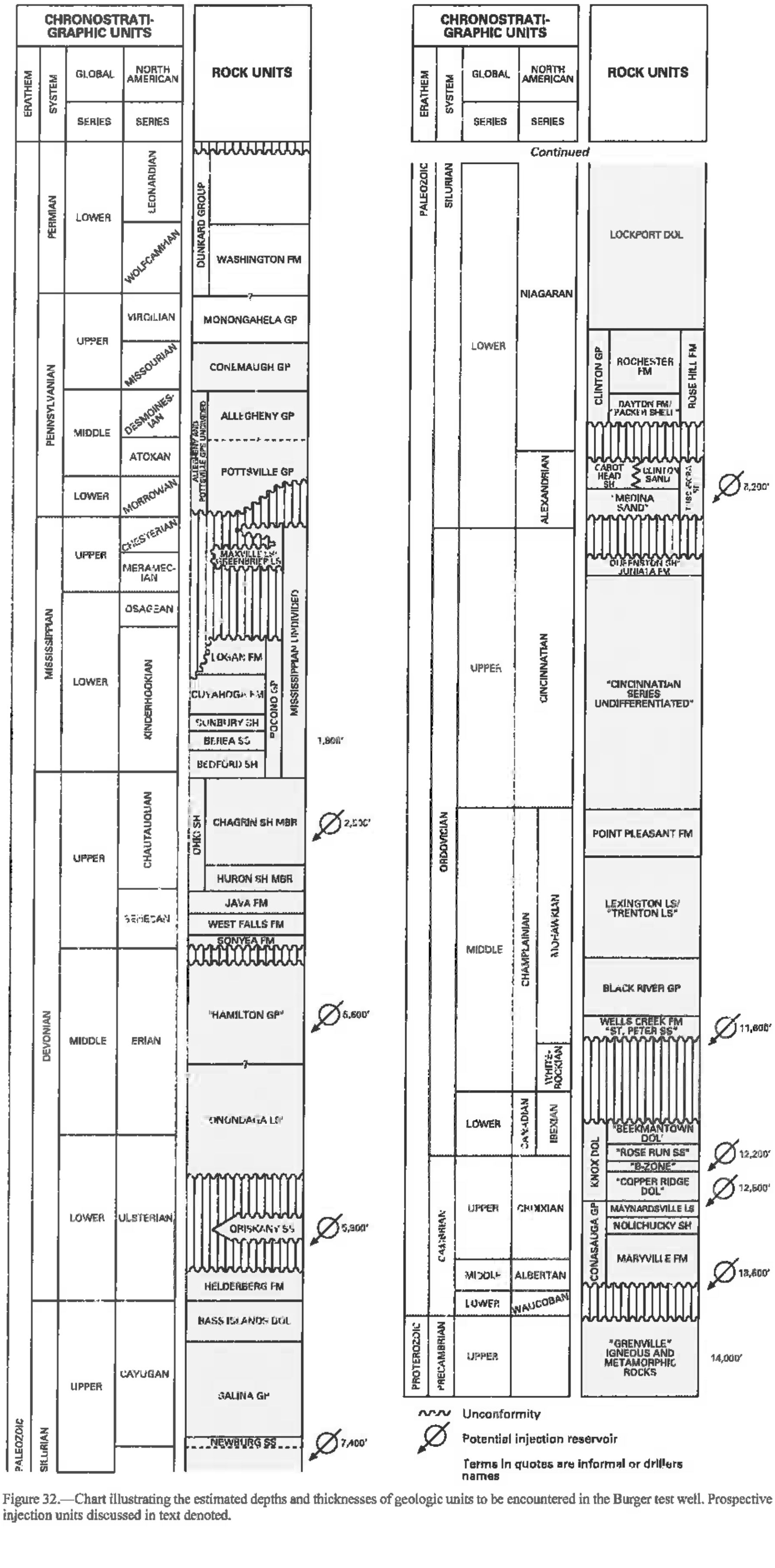

Figure 32.—Chart illustrating the estimated depths and thicknesses of geologic units to be encountered in the Burger test well. Prospective injection units discussed in text denoted.

data set generated by the Burger site investigation will allow an updated and more objective interpretation of the subsurface geology in an area of the Appalachian basin where little detailed data exist.

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APPENDIX B

2-D SEISMIC SURVEY MATERIALS

Summary of Seismic Acquisition Processing and Interpretation for the FirstEnergy Corp./Battelle R. E. Burger Power Plant Project Belmont County, Ohio and Marshall County, West Virginia

prepared for
Battelle Memorial Institute
December, 2006

Contents

Figures

Introduction

Twelve miles of 2-D seismic was run over and near the proposed Burger well site for the purpose of investigating reservoirs suitable for potential CO_2 sequestration. The site lies along the Ohio River in Belmont County, Ohio and across from Marshall County, West Virginia.

This seismic consisted of three lines, one designated as Burger-V1-06 which has a west-east orientation, a second denoted as Burger-V2-06 which has a south-north orientation and a third denoted as Burger-V3-06 which has a northwest-southeast orientation. Figure 1 and Figure 2 show the location of the seismic lines and the proposed test well site.

After acquisition, all three lines were processed by Elite Seismic Processing (ESP). A decision was made to have Exploration Development (EDI) reprocess Burger-V1-06 to focus more closely on the deeper strata. However, both ESP and EDI's processing method was developed to focus on structural and stratigraphic characteristics.

Acquisition

Appalachian Geophysical Services, LLC, Killbuck, Ohio, USA acquired three lines of seismic, Burger-V1-06, Burger-V2-06 and Burger-V3-06 in Belmont County, Ohio and Marshall County, West Virginia. The ARAM MK II distributive digital recording system was used for instrumentation. The following parameters were used for field acquisition:

<u>Recording:</u>	
Nominal fold	60
Channels	240
Sample rate	2 ms
Gain	30 dB
Field filters	3 Hz, low cut 123 Hz, high cut
Record length	4 seconds
<u>Receiver:</u>	
Geophone type	Sensor SM-4-High Sensitivity
Frequency	10 Hz
Station interval	110 feet (33.5 m)
Geophone array	12 phones over 110 feet (33.5 m)
Geophone spacing	9+ feet (3+ m)
<u>Source:</u>	
Source interval	220 feet (67 m)
Source type	Vibroseis
Source array – vibe	3 and 4 vibes over 110 feet (33.5 m), shot on ½ station
<u>Sweep:</u>	
Sweep length	8 sweeps x 12 seconds
Sweep type	Linear
Frequency range – vibe	15 – 120 Hz
Start taper	500 ms
End taper	300 ms
<u>Vibe information:</u>	
Electronics	Pelton Advance II, Model 5 w/ force control
Type	Mertz – Model 12 w/ 44,000# (16.5 Mg) pull down weight

Processing

Elite Seismic Processing, Inc. (ESP), Newark, Ohio, USA processed Burger-V1-06, Burger-V2-06 and Burger-V3-06 using their conventional Appalachian Basin processing sequence. The following parameters were used in the digital processing flow:

- Read and output SEGY Files
- Geometry and Trace Edits
- Exponential Gain Correction
- Relative Amplitude Scaling
- Elevation and Drift Correction
    - Datum: 700 feet (213 m)
    - Replacement Velocity: 12,000 ft/sec (3658 m/sec)
    - Refraction Statics: Hand and automatic
- Deconvolution (Surface Consistent)
    - Shot Domain:
        - Design Gate
        - Operator Length: 80 ms
        - Prewhitening: 0.1%
        - Bandpass: 10/20– 115/120 Hz
- Velocity Analysis
- Normal Move Out Analysis
- Mute
- Automatic Residual Statics
- Second Pass Velocity Analysis
- Second Pass NMO
- Second Pass Mute
- Trim Statics
- Zero Phase Spectral Whitening 15–115 Hz
- Stack
- Filter: Bandpass 10/20 – 115/125 Hz
- Relative Amplitude Scaling
- Post Stack Spectral Whitening
- Random Noise Attenuation w/ FX-Decon
- Migration for migrated sections only

Exploration Development, Inc. (EDI), Parker, Colorado, USA processed Burger-V1-06 using their conventional Appalachian Basin processing sequence. The following parameters were used in the digital processing flow:

- Load SEGY Data
- Geometry Update and Trace Edit
- Gain Recovery
- Surface Consistent Deconvolution
- CDP Sort
- Zero Phase Spectral Enhancement 15-120 Hz
- Refraction Statics
  Datum: 1500 feet (457 m)
  Velocity: 12,000 ft/sec (3658 m/sec)
- Velocity Analysis – 2 Passes
- Normal Move Out Corrections
- Mute
- Surface Consistent Statics – 2 Passes
- Trace Balance
- CDP Trim Statics
- DMO/Velocity Analysis/NMO
- 2 Band Split Trim Static
- Stack (CDP)
- Trace Balance
- Migration
- 33% Noise Estimation & Subtraction
- Time Variant Spectral Whitening
- FK Box Filter
- Trace Balance

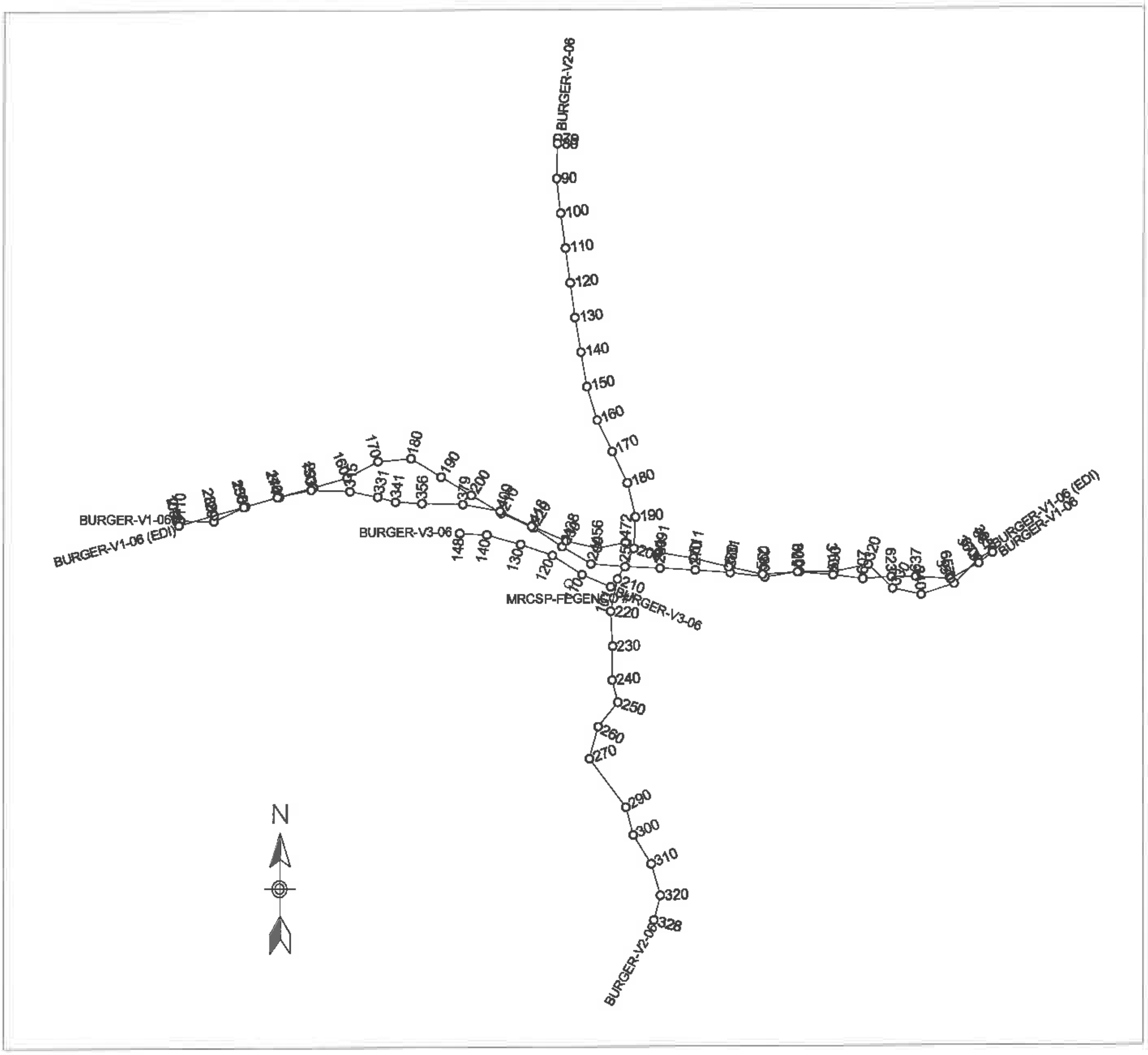


Figure 1 - Seismic CDP and well location map

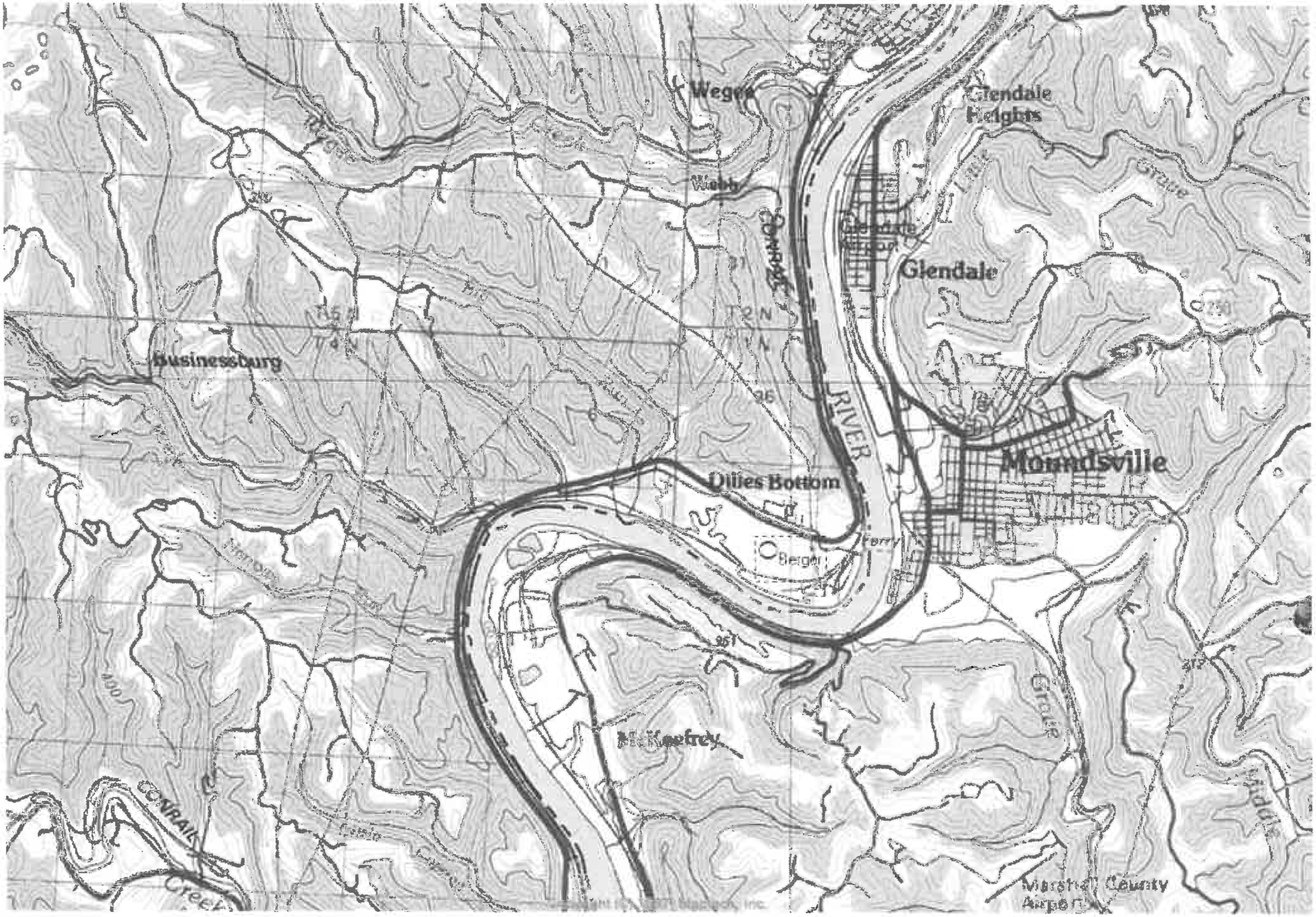


Figure 2 - R. E. Burger Power Plant Project site topography map

Interpretation

Correlation and Interpretation

John Forman and Amy Lang interpreted the seismic data processed by both ESP and EDI.

Figures 3 - 5 show the estimated Big Lime, Trenton and PreCambrian horizon picks. The horizon picks were estimated due to the lack of nearby data. However, the Burley #1 synthetic (Figure 7) was used in the interpretation because it is located in the southeast corner of Marshall County, West Virginia. It is recommended that sonic data be acquired when the Burger test well is drilled to aid in the correlation of the horizons.

Both ESP and EDI commented on the challenge in processing the data across the river valley. There is no way to determine whether the features beneath the Ohio River are real or are a result of static and velocity processing issues. The unconsolidated sediment (sand and gravel) in the valley cause the energy to be more absorbed than surrounding areas. Thus, the difficulty in interpreting whether or not there is structure present.

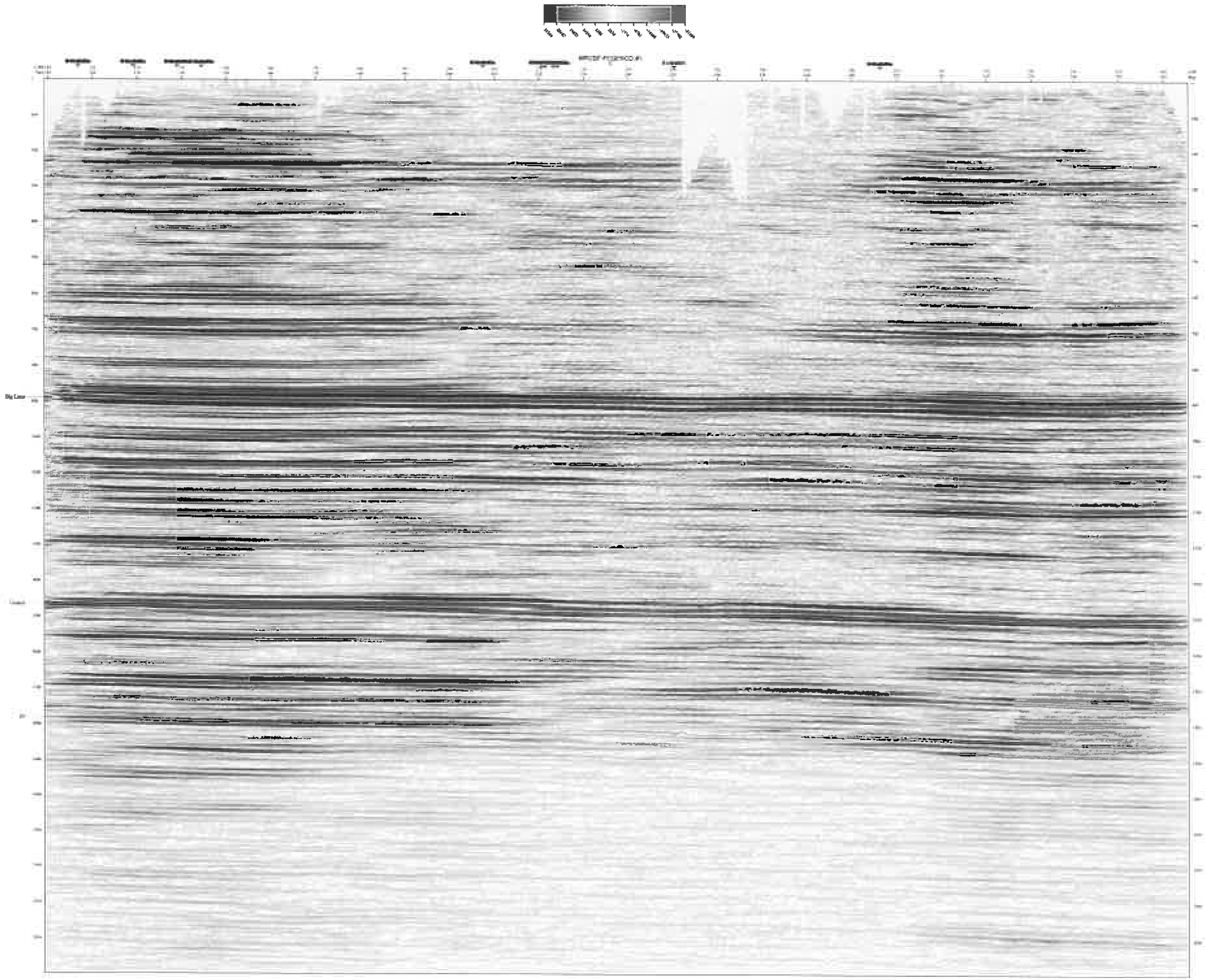


Figure 3 - Full section presentation of seismic line Bungan-V1-98 (SSP)

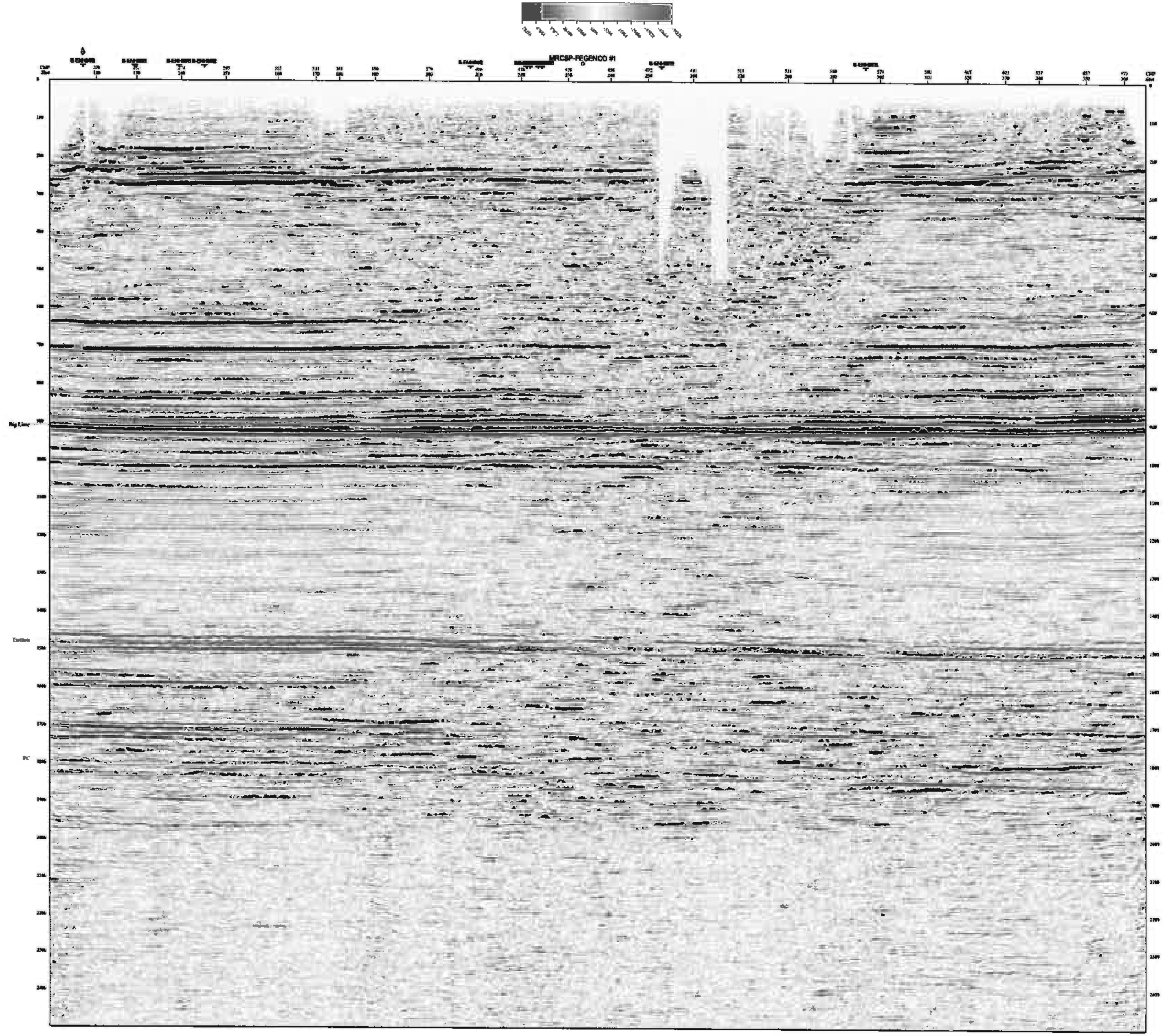


Figure 4- Full section presentation of seismic line Burger-V1-08 (EDI)

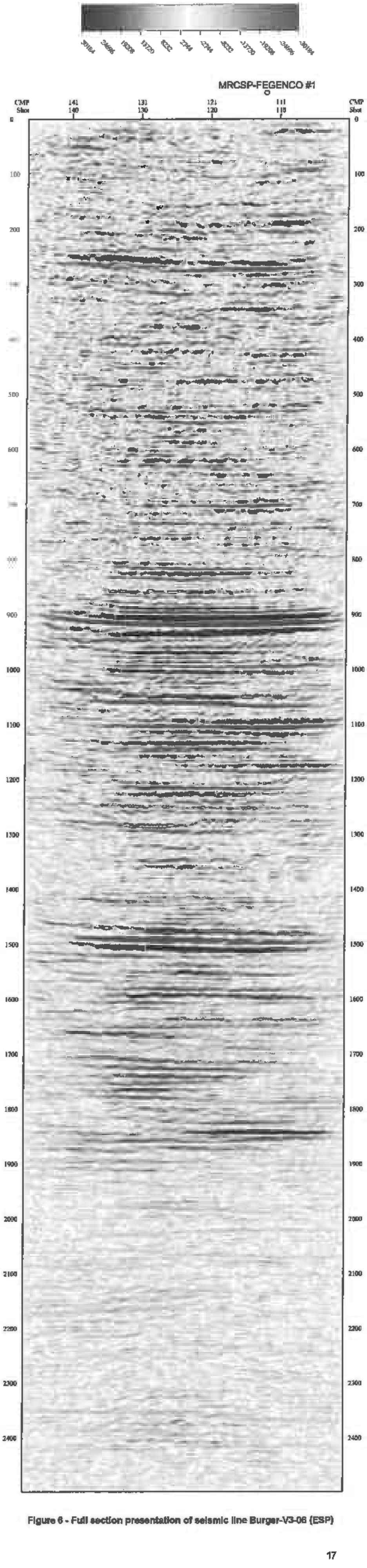


Figure 6 - Full section presentation of seismic line Burger-V3-06 (ESP)

Structural Setting

The R. E. Burger Power Plant Project site sits on the eastern edge of the Ohio Platform. There the typical structural setting is one of a flat to mildly undulating PreCambrian surface overlain by essentially flat strata, the whole having a slight southeast dip into the heart of the Appalachian Basin.

Three counties southeast of the Burger site is the western edge of the Rome Trough which is sharply delineated by the occurrence of strong basinward (down to the east) faults with throws of up to several thousand feet at the PreCambrian surface. Typically, these fault systems sustained several periods of reactivation, but each successive reactivation was weaker than that which preceded it. Though the initial faulting was normal, subsequent episodes were a mixture of normal and reverse movement. Rarely did faulting occur later than mid-Ordovician (Trenton) time.

The structural sequences observed in the Rome Trough are generally illustrative of those that occur elsewhere in the Appalachian Basin. Specifically, the most intense deformation occurred during the PreCambrian. Some additional deformation, either primary or reactivated, can be seen during the Cambrian and Early and Middle Ordovician periods. Deformation of any significance that occurred after the Middle Ordovician is uncommon.

Although the Ohio Platform is structurally separate from the Rome Trough, it is not entirely without structural features. Some basement-influenced arching of low relief is encountered. Small, isolated domes of low relief are to be found. They are generally the result of deep structure and may exert some stratigraphic influence in younger sediments. Draping over topographic highs on the PreCambrian surface is seen in many instances. Surface lineations may hint at deeper structure. Burger-V1-06 and Burger-V2-06 were acquired to see if there were any possible structural anomalies present.

Burley 1 (Kulander, 2005)

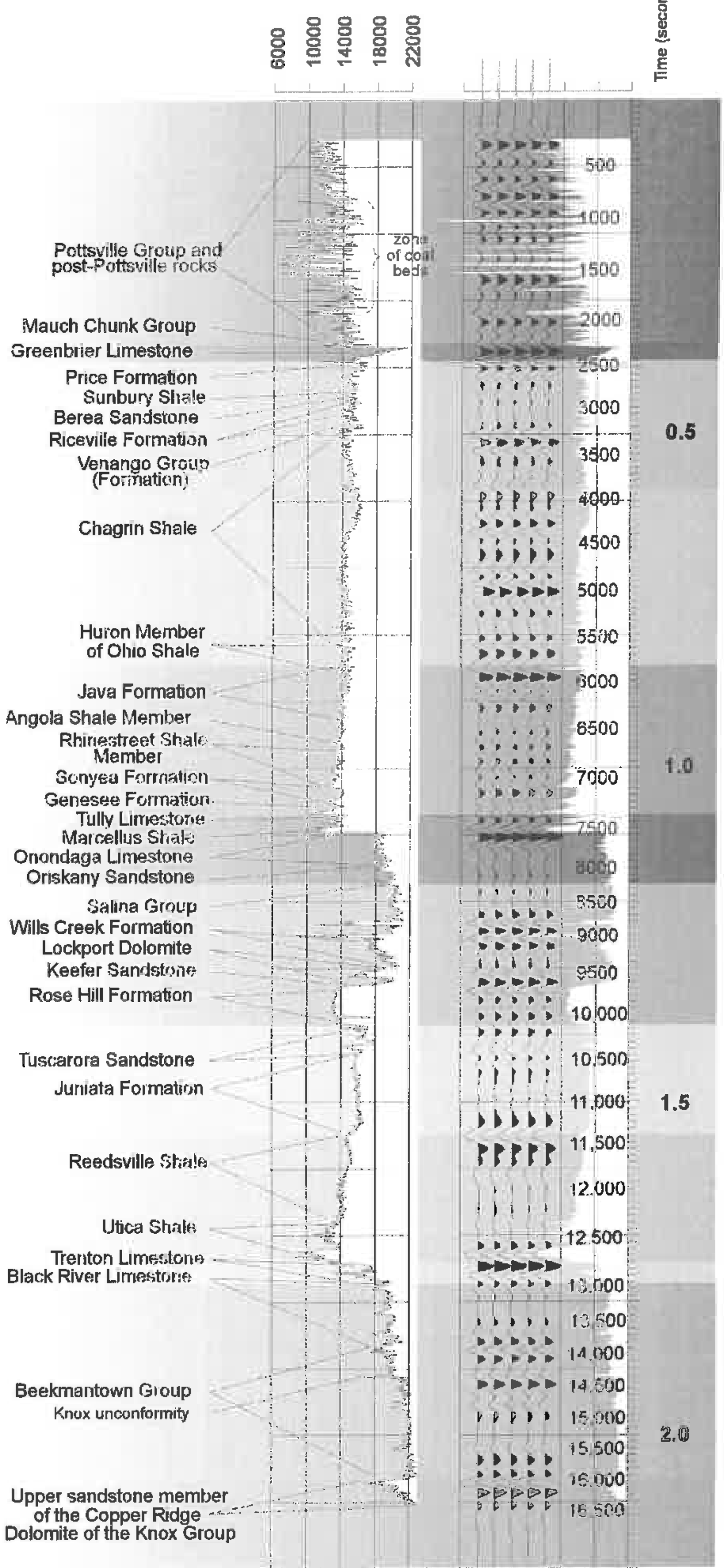


Figure 7 - Burley #1 synthetic, Marshall County, WV, Kulander, 2005

Post-Ordovician Structure

Seismic lines Burger-V1-06 (Figure 3-4) and Burger-V2-06 (Figure 5) do not depict any notable structure in the post-Ordovician sediments as indicated in the Devonian Big Lime marker horizon.

In Silurian and later time, structure on the Ohio platform was limited primarily to gentle subsidence to the east into the Appalachian Basin. Expectedly, the shallow formations mimic the shallow rolls of the deeper beds and adhere to the rate of dip and direction dictated by the Cambrian and Ordovician rocks. As was previously noted, differential compaction over early features may produce some discernable draping of younger strata, but none is evident on the seismic in this report.

Figure 8 is a time structure map of the interpreted Big Lime horizon. Figure 11 is an isochron map of the Big Lime to the Trenton. Figure 12 is an isochron map of the Big Lime to the PreCambrian.

Figure 8 - Big Lime horizon, time structure map

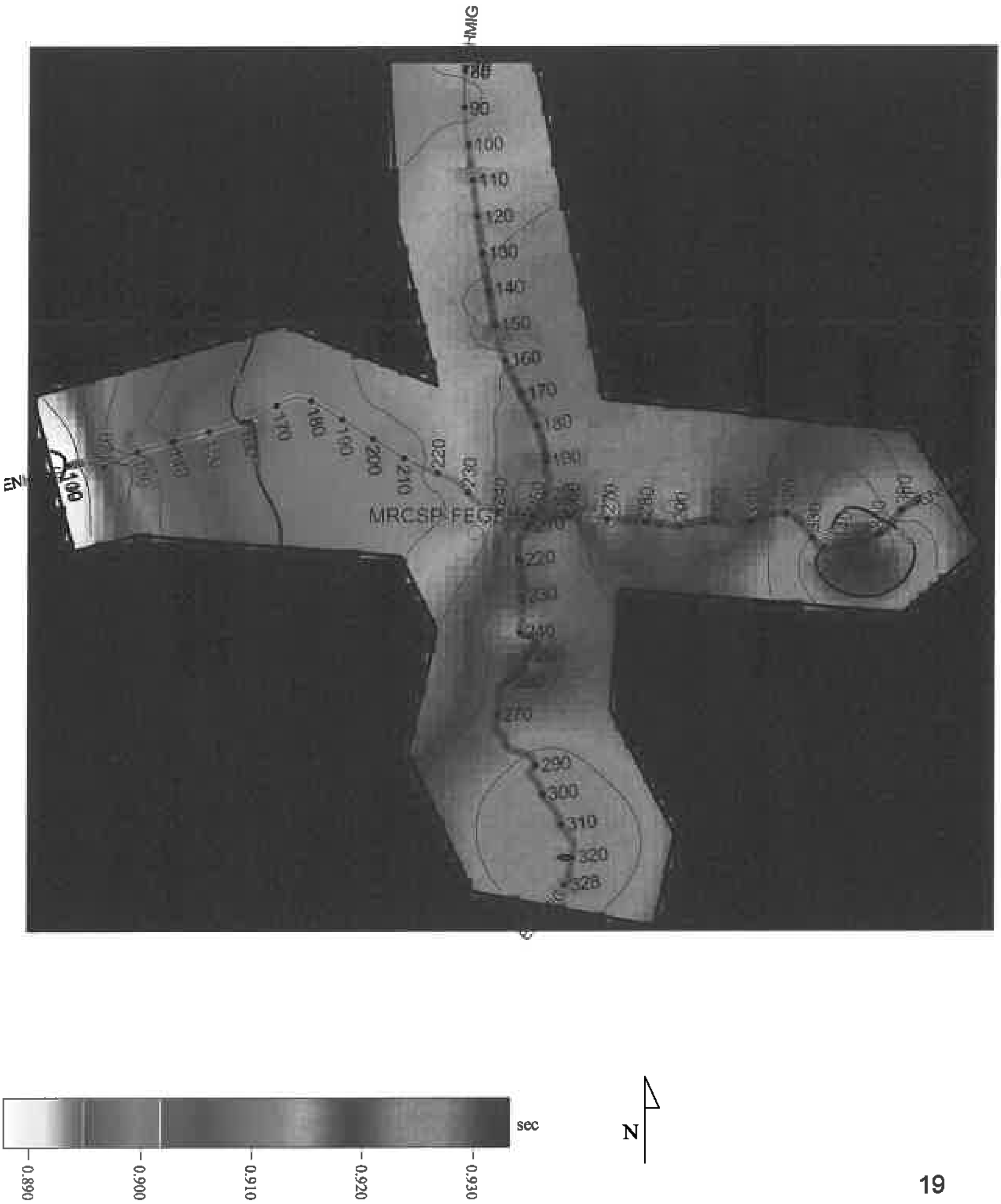


Figure 11 - Big Lime -- Trenton horizons, isochron map

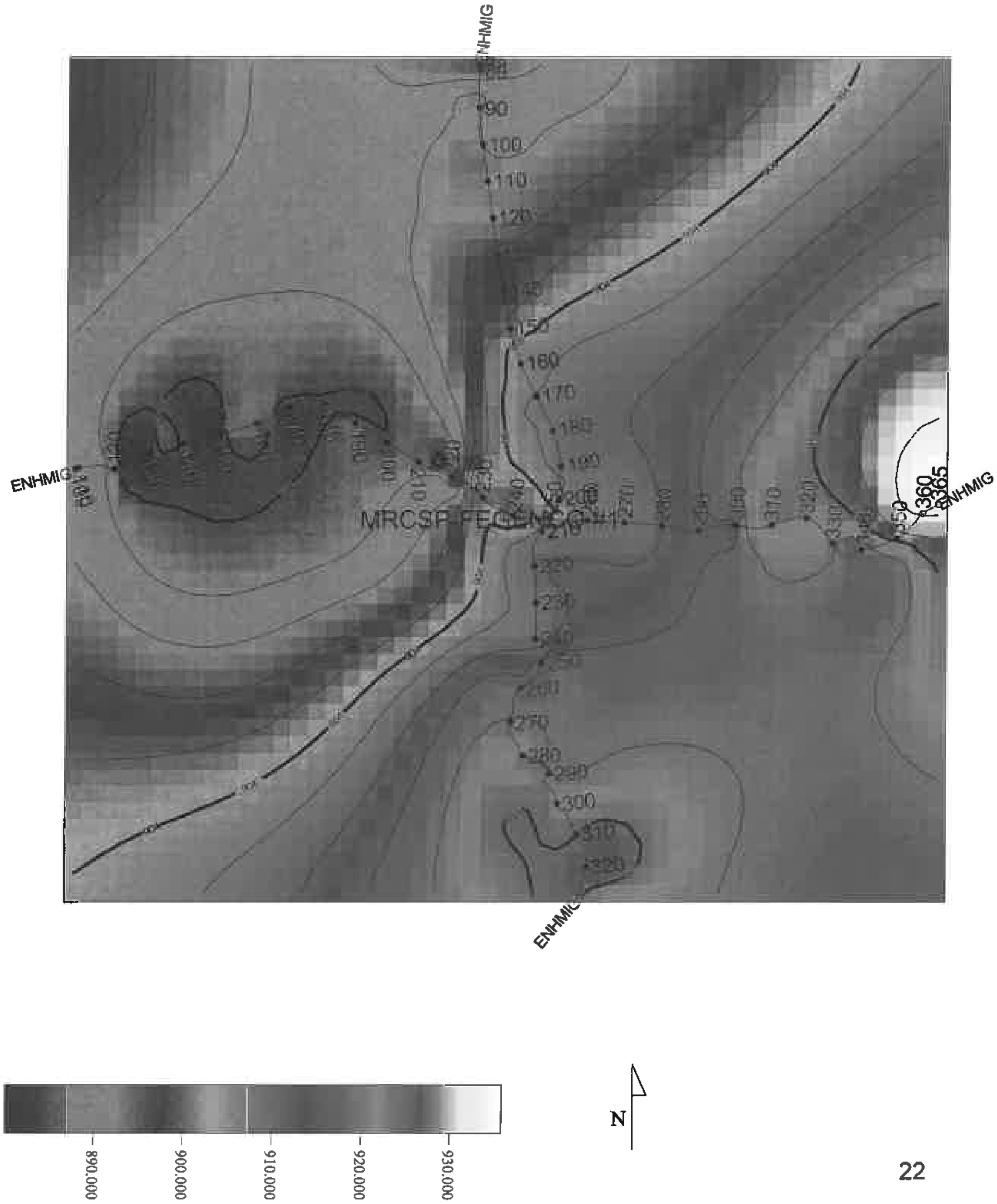
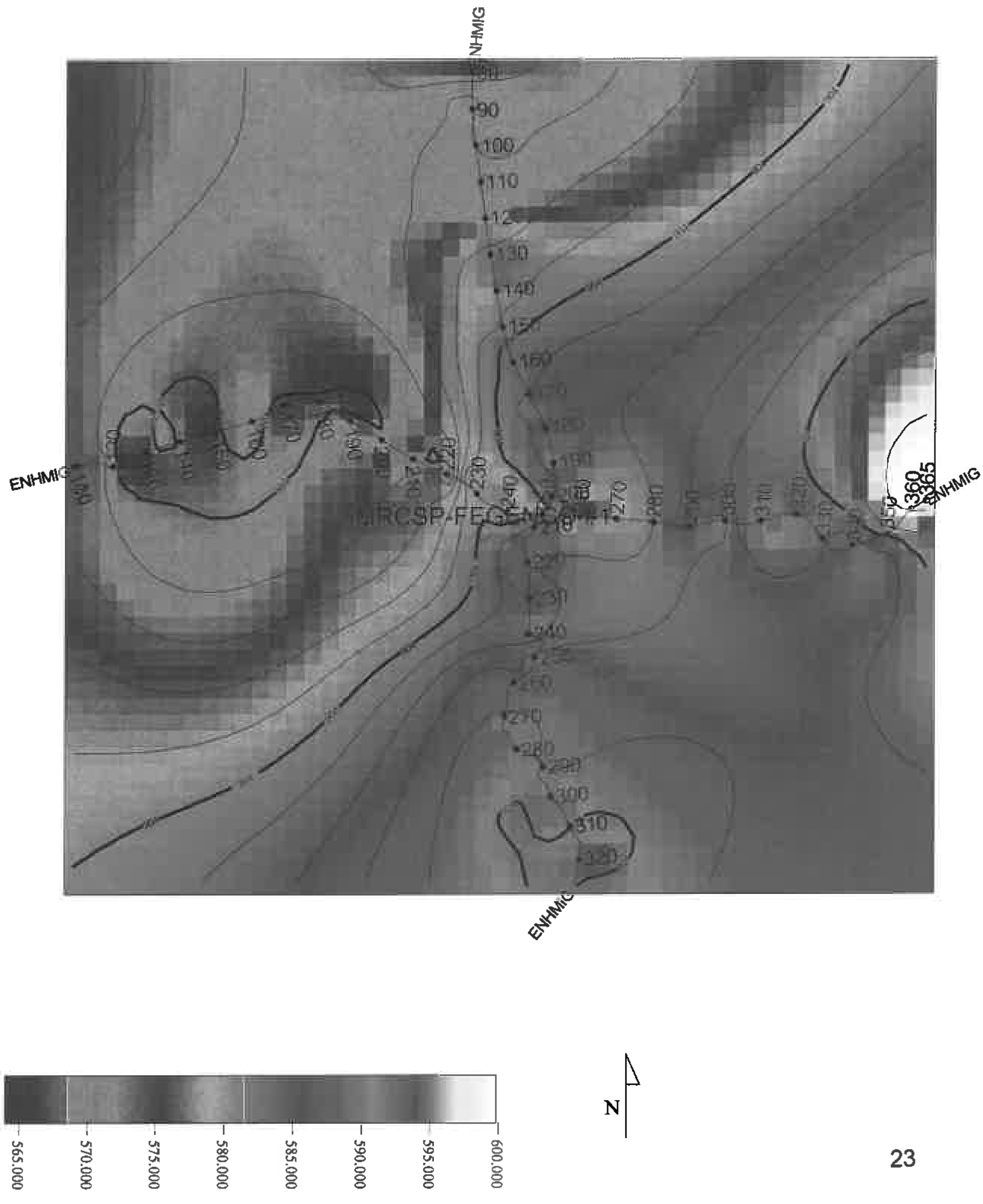


Figure 12 - Big Lime -- PreCambrian horizons, isochron map



Cambro-Ordovician Structure

The Ordovician Trenton marker horizon is the highest amplitude reflector and was used in the interpretation. While other horizon reflectors are present, they are not contiguous and have not been picked. What is seen on the Trenton is that the Paleozoic sediments were deposited as flat lying, parallel beds. There is no evidence of faulting or clustering of fractures. Figure 9 is a time structure map of the interpreted Trenton horizon.

A Trenton to the PreCambrian isochron map (Figure 13) was constructed as a crosscheck against the referenced time structure maps. The color variations that appear on the map occur principally in areas of interpolated data and away from the actual seismic lines.

Figure 9 - Trenton horizon, time structure map

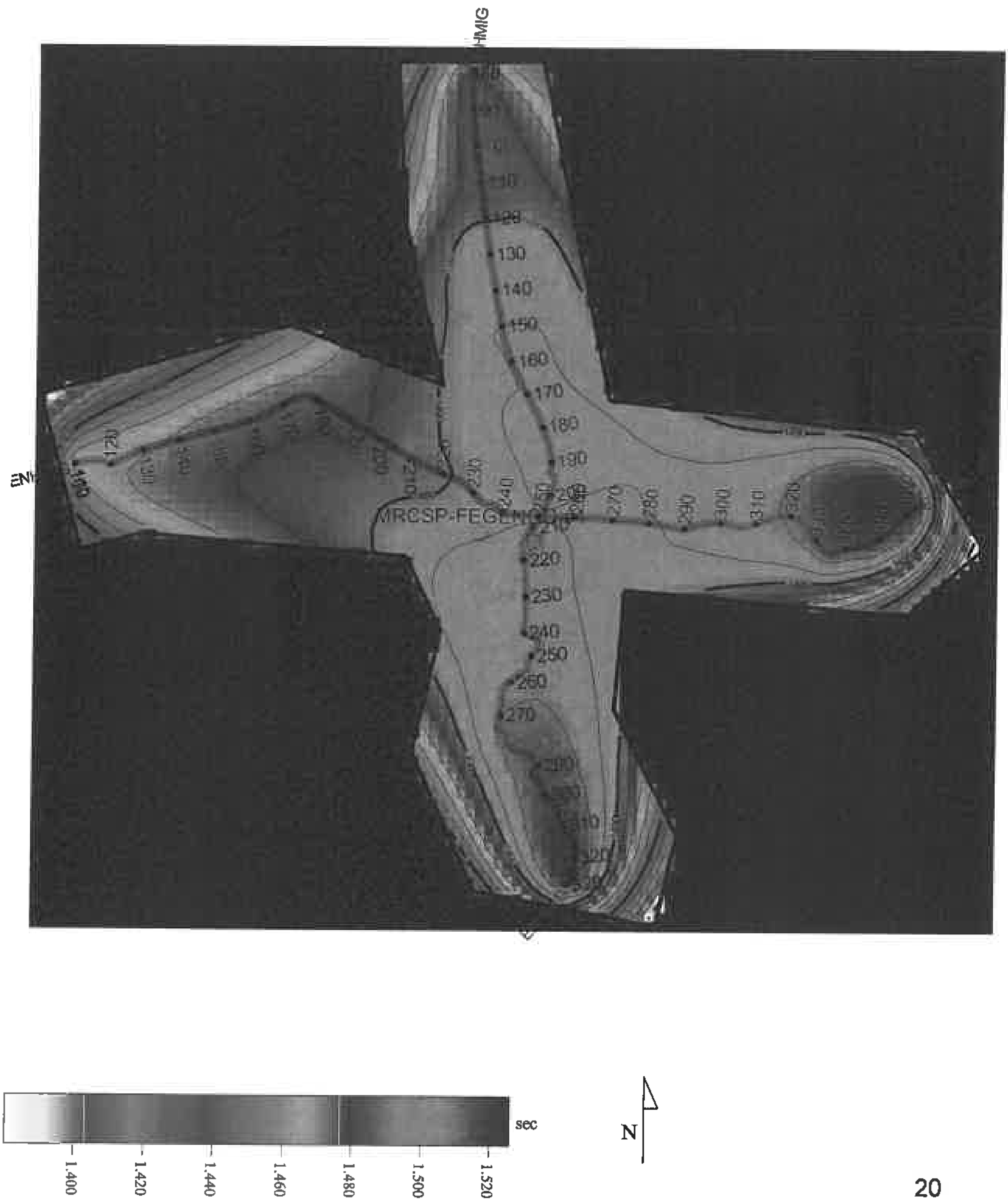
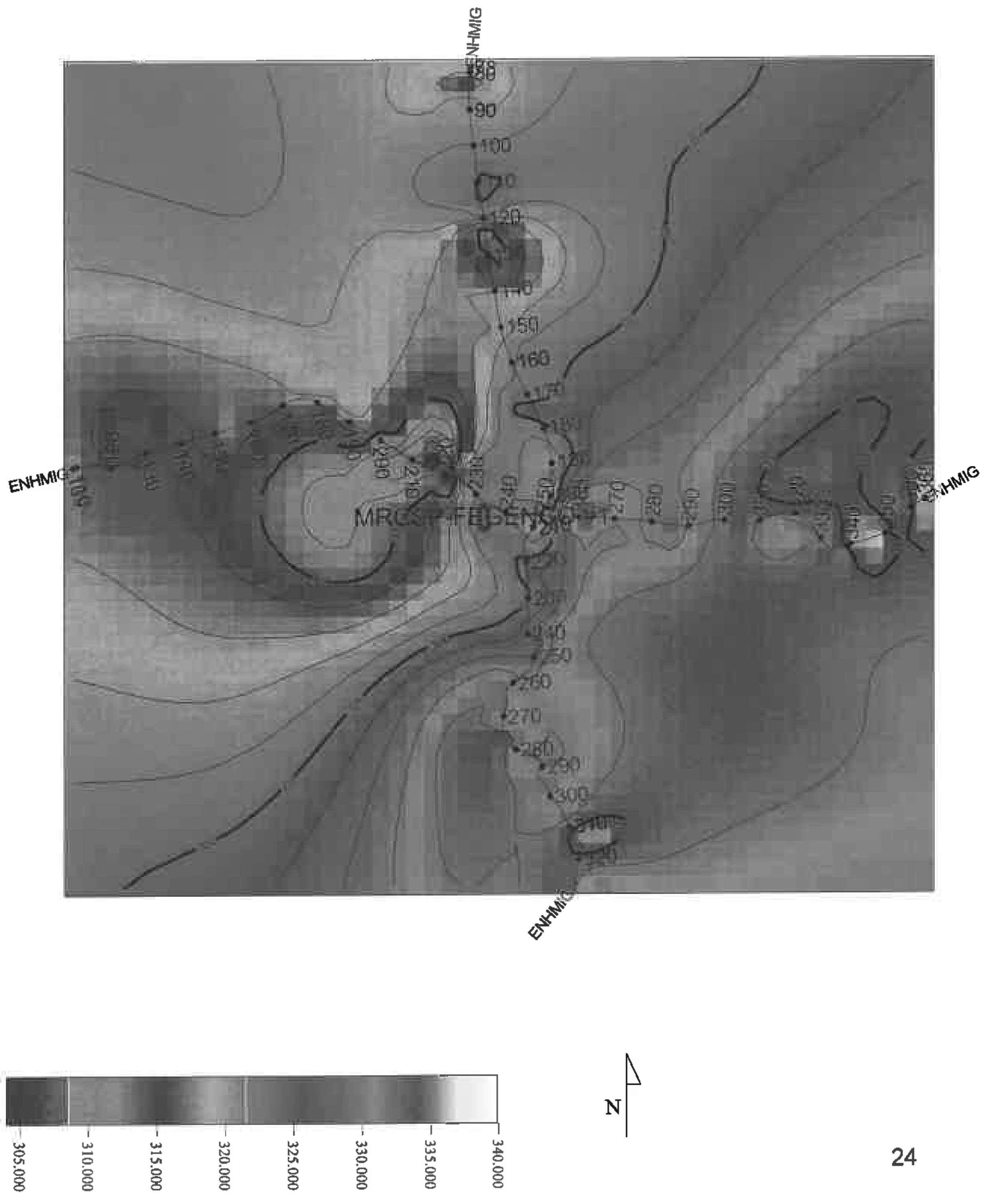


Figure 13 - Trenton -- PreCambrian horizons, isochron map



PreCambrian Structure

The PreCambrian surface on the Ohio Platform is an erosional surface. The area of the R. E. Burger Power Plant Project is granitic in nature and may be bare granite or a wash composed of either in-situ weathered granite or transported clastics derived from the PreCambrian elsewhere. Based on limited penetrations to the PreCambrian, the washes are typically thin and suggest a long period of exposure that produced an essentially flat featureless surface.

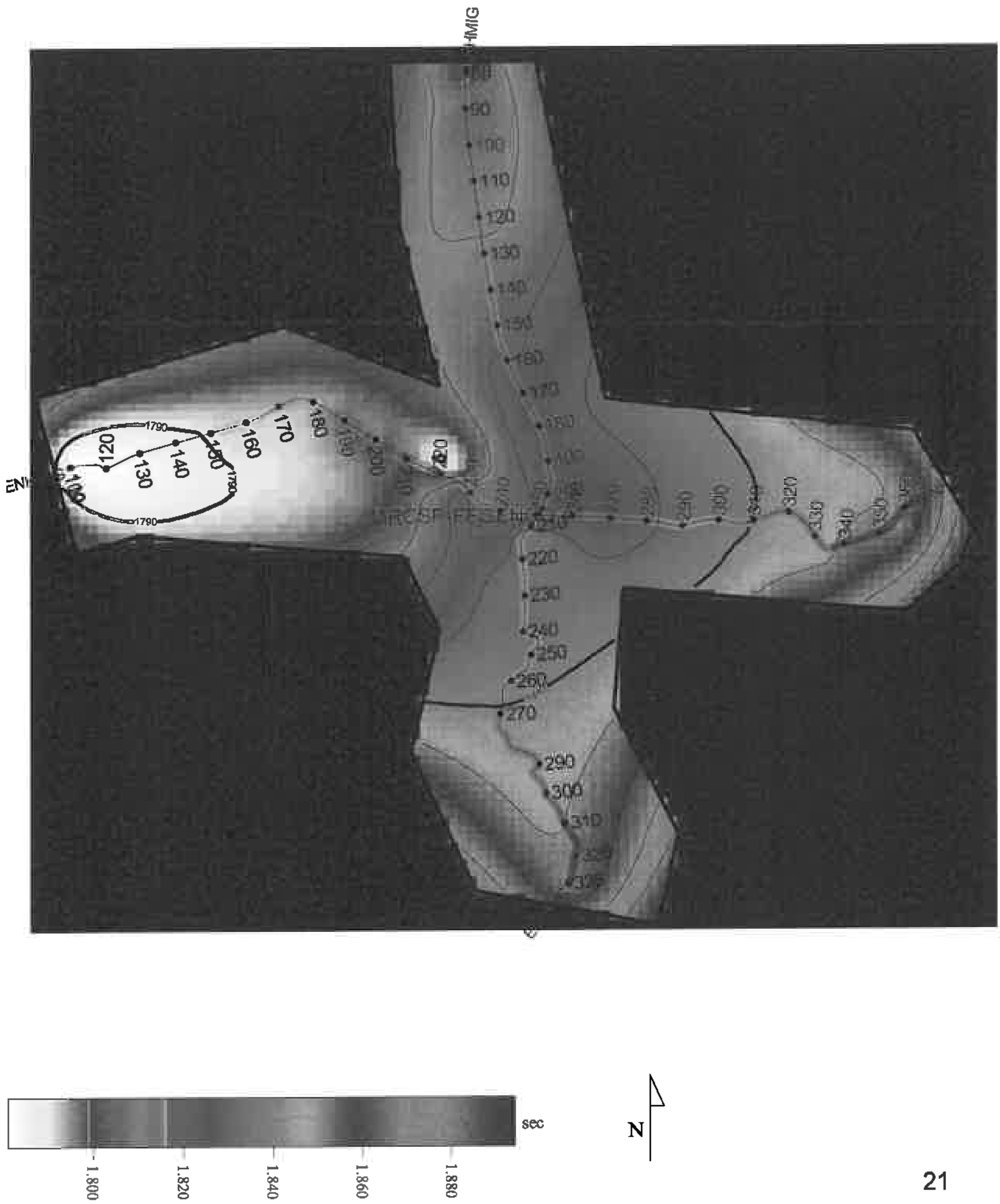
The PreCambrian surface on the Burger seismic lines does not generate a coherent seismic reflector. The nature of that surface is in part inferred from nearby reflectors in the basal Paleozoic section and from reflectors contained within the PreCambrian mass.

The ESP and EDI seismic versions are inconclusive as to structure within the PreCambrian. A rate of dip is approximately 70 feet per mile (13.3 m/km) in an east direction (Figure 3-4). The reflectors below the top of the PreCambrian are weak or inconsistent. However, there appears to be no discernable faulting in the basement complex. Figure 10 is a time structure map of the interpreted PreCambrian horizon.

Respectfully submitted,

John L. Forman
Amy L. Lang

Figure 10 - PreCambrian horizon, time structure map



APPENDIX C

WELL DRILLING PERMIT

STATE OF OHIO DEPARTMENT OF NATURAL RESOURCES FORM 51 REVISED 3/01	DIVISION OF MINERAL RESOURCES MANAGEMENT WELL PERMIT	API WELL NUMBER 34-013-2-0586-00-00

OWNER NAME, ADDRESS	DATE ISSUED	PERMIT EXPIRES
FIRST ENERGY GENERATION CORP (Owner # 8122) 76 S MAIN STREET AKRON OH 44308	11/22/2006	11/22/2007
	TELEPHONE NUMBER (740) 671-2918	

IS HEREBY GRANTED PERMISSION TO: Drill New Well AND ABANDON NEW WELL IF UNPRODUCTIVE

PURPOSE OF WELL: Stratigraphic

SUBSTANCE TO BE STORED OR COMPLETION DATE IF PERMIT TO PLUG: Cmpltd Dt:

DESIGNATION AND LOCATION:

LEASE NAME	MRCSP-FEGENCO	SECTION	35
WELL NUMBER	1	LOT	
COUNTY	BELMONT	FRACTION	
CIVIL TOWNSHIP	MEAD	QUARTER TOWNSHIP	
TRACT OR ALLOTMENT		X:	2455359
FOOTAGE LOCATION	3594' NL & 374' EL OF SECTION 35	Y:	701380

TYPE OF TOOLS: Cable/Air Rotary/Fluid Rotary

PROPOSED TOTAL DEPTH 8250 FEET

GROUND LEVEL ELEVATION 676 FEET

GEOLOGICAL FORMATION(S): ORISKANY/CLINTON

SPECIAL PERMIT CONDITIONS: Permit is subject to the attached terms and/or conditions
Samples Requested, see attached letter

CONDITIONALLY APPROVED CASING PROGRAM (SUBJECT TO APPROVAL OF THE OIL AND GAS WELL INSPECTOR):

20" CONDUCTOR APPROX. 100'
13-3/8 " APPROX. 500 ' WITH CEMENT CIRCULATED TO SURFACE
9-5/8 " APPROX. 1900 ' WITH CEMENT CIRCULATED TO SURFACE
7 " APPROX. 5750 ' WITH CEMENT CIRCULATED TO SURFACE

This permit is NOT TRANSFERABLE and expires 365 days after issuance unless drilling has commenced prior thereto. This permit, or an exact copy thereof, must be displayed in a conspicuous and easily accessible place at the well site before permitted activity commences and remain until the well is completed. Ample notification to inspector is necessary. All mudding, cementing, placing and removing casing, and plugging operations must be done under the supervision of

OIL AND GAS WELL INSPECTOR:
KAVAGE MIKE
16900 LEATHERWOOD RD.
LORE CITY, OH 43822
Inspector's #: (614) 264-7585
District #: (740) 439-9079

JOE HOERST - Supervisor
(614) 264-6912

FIRE AND EMERGENCY NUMBERS

FIRE (740) 671-2947
MEDICAL SERVICE (740) 671-2947

DEPUTY MINE INSPECTOR: MUST BE NOTIFIED IF WELL IN A COAL-BEARING TOWNSHIP IS TO BE PLUGGED AND ABANDONED.

Michael L. Sponsler
CHIEF, DIVISION OF MINERAL RESOURCES MANAGEMENT

DNR 5606 (Rev. 3/01)

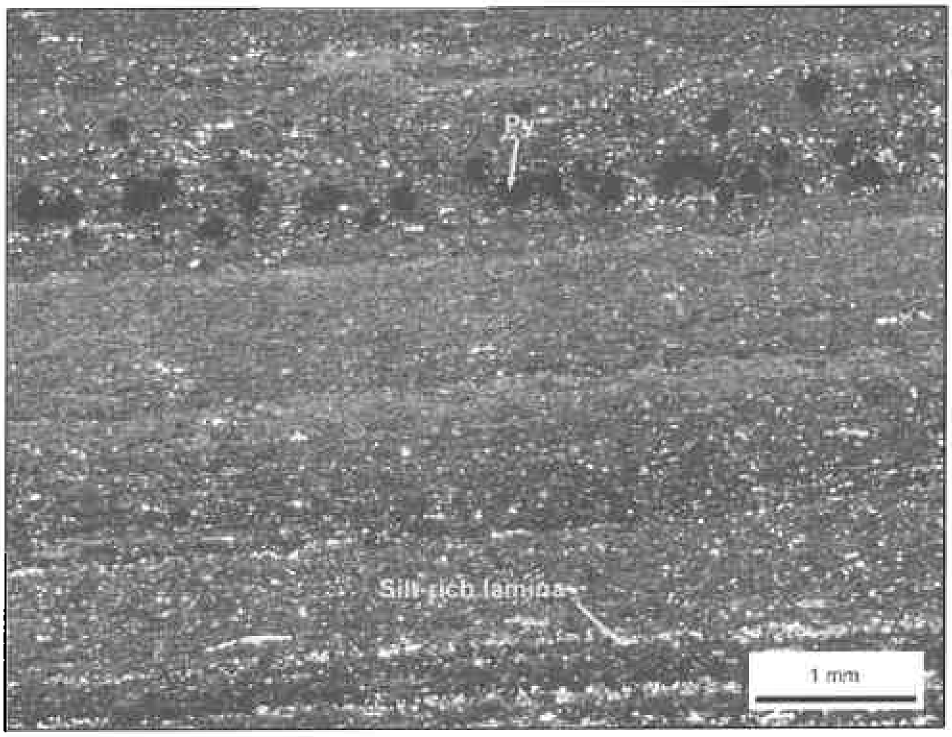
APPENDIX D

CORE ANALYSES

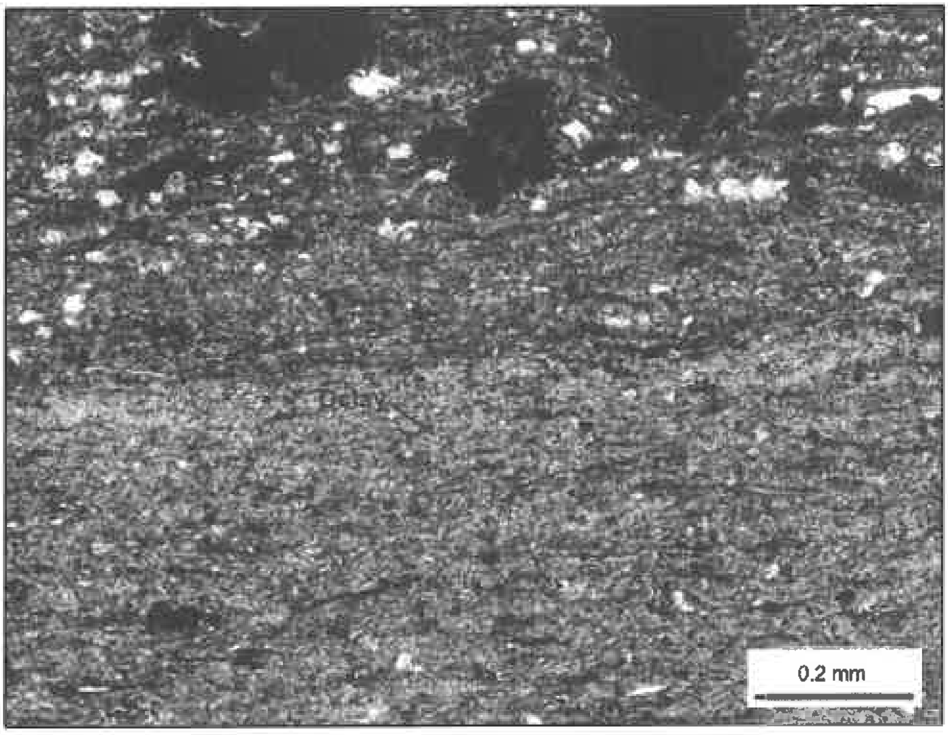
APPENDIX D

CORE ANALYSES

Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio
Depth (feet): 5500.0



4A



4B

MINERALOGY REPORT

PETROGRAPHIC EVALUATION OF SIDEWALL CORE SAMPLES FROM THE BURGER SITE WELL BELMONT COUNTY, OHIO

Job Number: 071029G

Prepared for:

Battelle Memorial Institute

Prepared by:

CORE LABORATORIES

December 2007

PETROGRAPHIC ANALYSIS

This report presents the results of thin section analysis performed on eight (8) sidewall core samples from the Burger Site Well, located in Belmont County, Ohio. The objectives of this study are to determine texture, mineralogy, pore-filling constituents, pore types, and diagenetic features. A list of samples analyzed is presented in Table 1. Thin section photomicrographs are attached as Plates 1 to 8. The eight (8) analyzed samples consist of four (4) silty claystones, one (1) sandstone, two (2) limestones, and one (1) dolostone (Table 1).

Silty claystone: Thin section analysis reveals that silty claystones are laminated and locally burrowed. Detrital clay matrix is the predominant constituent and consists mostly of illitic clays; minor amounts of authigenic pyrite are dispersed throughout. Quartz, mica and feldspars are the most common grains. These silty claystones contain silt-rich laminae/burrows; one sample (5500.0 feet) is relatively organic-rich. Visible pores are absent; micropores are the major pore type and associated with the detrital clay matrix.

Sandstone: One sample (5945.0 feet) is fine-grained, well sorted sandstone. Framework grains are dominantly quartz; feldspars are much less common. Fossil fragments are also present in minor to moderate quantities. Quartz overgrowths are abundant and occlude most intergranular areas; Fe-calcite is locally present in trace quantities. Stylolites are common, crosscutting quartz overgrowths and Fe-calcite cements. The paragenetic sequence is that quartz overgrowths formed relatively early, followed by Fe-calcite and stylolites. Macropores are very rare; micropores are estimated to be trace to minor in abundance.

Limestone: Two samples (5710.0, 6200.0 feet) are limestones, which are further classified as packstone (5710.0 feet) and grainstone (6200.0 feet). Stylolites are present in both packstone and grainstone.

In the packstone; fossil fragments are the most common allochem grains and consist mostly of mollusks and echinoderms. Interparticle areas are filled with micrite matrix, which is locally replaced by dolomite. Intraskeletal pores are occluded by Fe-calcite cement. Authigenic pyrite is a trace component and scattered. No pores are visible; micropores associated with the micrite matrix are the principal pore type.

In the grainstone; fossil fragments are also the principal allochem grains and consist mostly of mollusks and echinoderms. Minor amounts of detrital quartz grains are scattered. Interparticle areas are occluded with calcite cement. No pores are visible; micropores are estimated to be minor in abundance.

Dolostone: One sample (6500.0 feet) is a finely crystalline dolostone. Dolomite crystals exhibit an interlocking crystalline texture. Authigenic pyrite is locally present in trace to minor quantities. Dolomitization has generally destroyed the primary texture of original rock (lime mudstone?). Visible pores are intercrystalline and estimated to be minor to moderate in abundance.

Thank you for choosing Core Laboratories to perform this study. Please feel free to contact us if you have any questions or comments concerning this report or if we can be of further service.

Yong Q. Wu
Senior Geologist
Core Laboratories
Ph. 713-328-2554
Email: yongqiang.wu@corelab.com

TABLE 1
ANALYTICAL PROGRAM AND PETROGRAPHIC SUMMARY
Battelle Memorial Institute, Burger Site Well

Sample ID	Depth (feet)	Thin Section	Formation	Lithology	Plate No.
Burger_14_2000	2000.0	X	Chagrin U & M Huron shale	Silty Claystone	1
Burger_12_3000	3000.0	X	L. Huron shale	Silty Claystone	2
Burger_5_5440	5440.0	X	U. Olentangy shale	Silty Claystone	3
Burger_4_5500	5500.0	X	Hamilton shale	Silty Claystone	4
Burger_2_5710	5710.0	X	Onondaga limestone	Limestone (packstone)	5
Burger_8_5945	5945.0	X	Oriskany sandstone	Sandstone	6
Burger_5_6200	6200.0	X	Helderberg limestone	Limestone (grainstone)	7
Burger_2_6500	6500.0	X	Salina anhydrite/salt/dolomite	Dolostone	8

Battelle Memorial Institute, Burger Site Well

THIN SECTION PHOTOMICROGRAPHS
WITH DESCRIPTIONS

PLATE 1 A-B

THIN SECTION PHOTOMICROGRAPHS

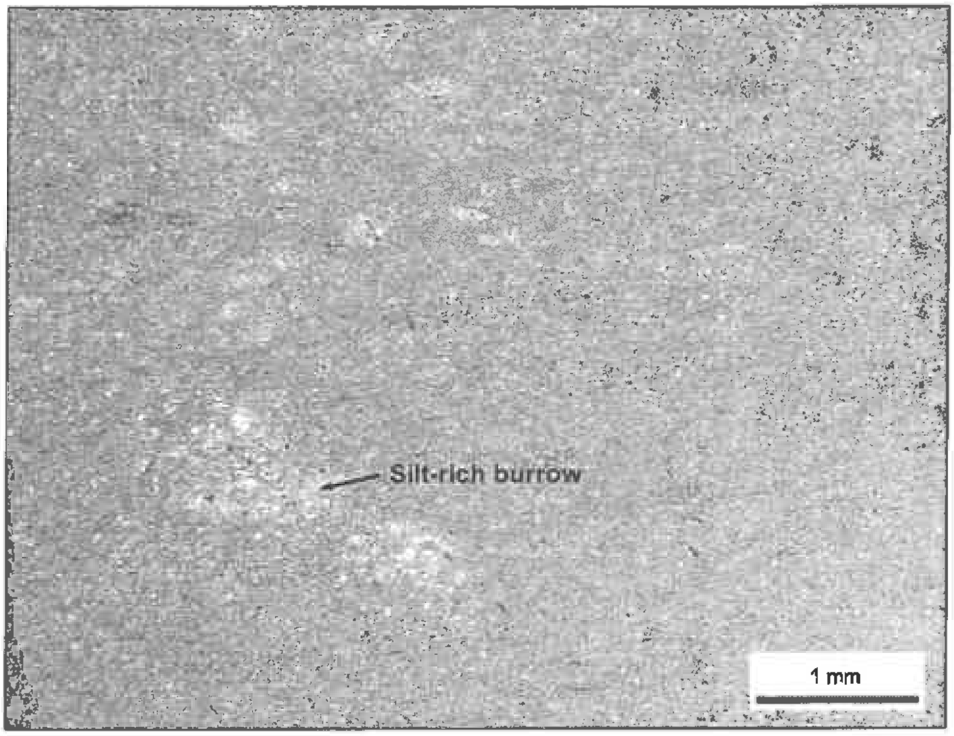
Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio

Depth (feet): 2000.0

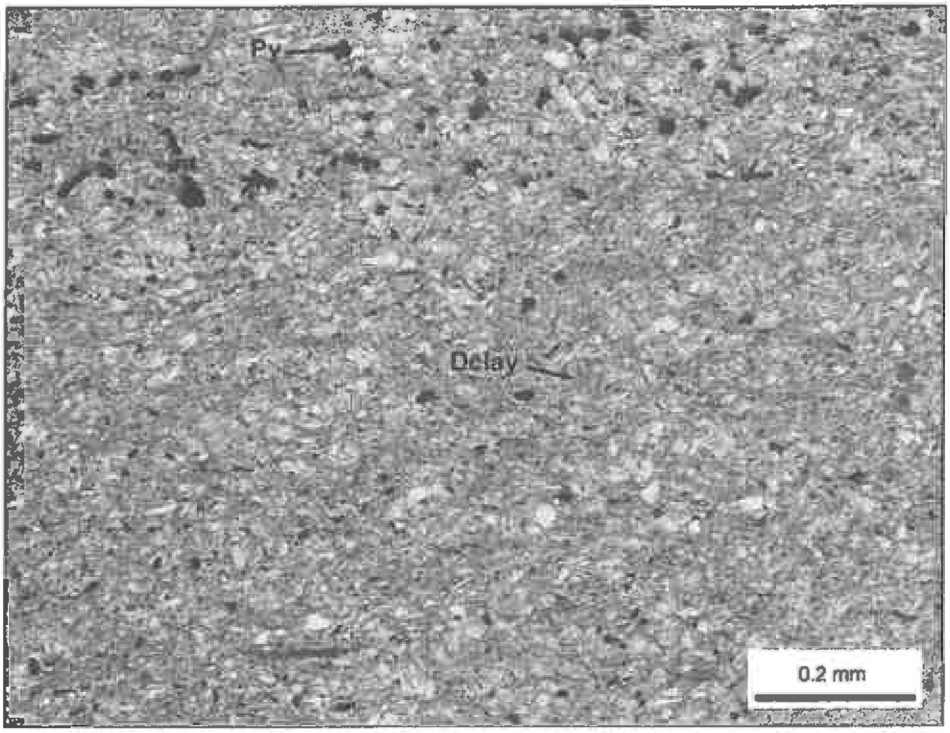
Lithology: Silty Claystone
Foramtion: Chagrin U & M Huron shale
Sample ID: Burger_14_2000

This sample is a silty claystone. Silt-rich burrows are locally present. Detrital clay matrix (Dclay; mainly illitic clay) is the predominant constituent. Silt-sized grains are mostly quartz and feldspars; mica grains are minor to moderate in abundance. Minor amounts of authigenic pyrite (Py) are scattered throughout. Macropores are absent; micropores associated with the clay matrix are the principal pore type.

Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio
Depth (feet): 2000.0



1A



1B

PLATE 2 A-B

THIN SECTION PHOTOMICROGRAPHS

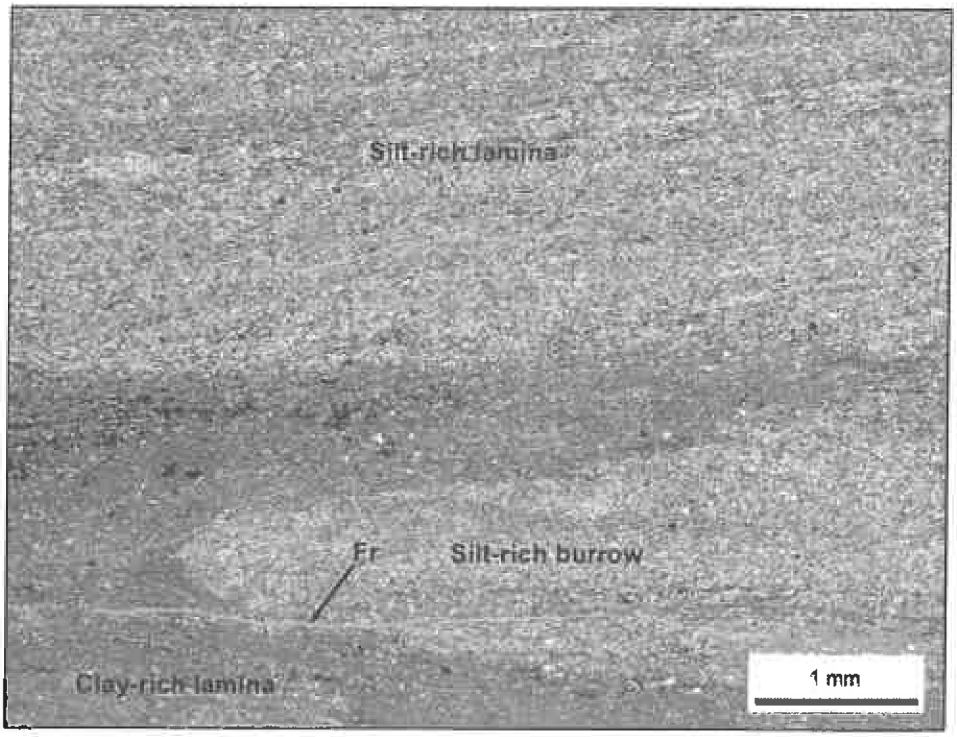
Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio

Depth (feet): 3000.0

Lithology: Silty Claystone
Foramtion: L. Huron shale
Sample ID: Burger_12_3000

This silty claystone consists of alternating silt-rich laminae/burrows and clay-rich laminae/burrows. The silt-rich portions are highlighted in the Plate 2B; quartz, mica and feldspars are the most common grains; detrital clay matrix (Dclay) fills intergranular areas; minor amounts of authigenic pyrite (Py) are dispersed throughout. Visible pores are absent; micropores are the major pore type and associated with the detrital clay matrix. Open fractures (Fr) are probably artificially induced.

Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio
Depth (feet): 3000.0



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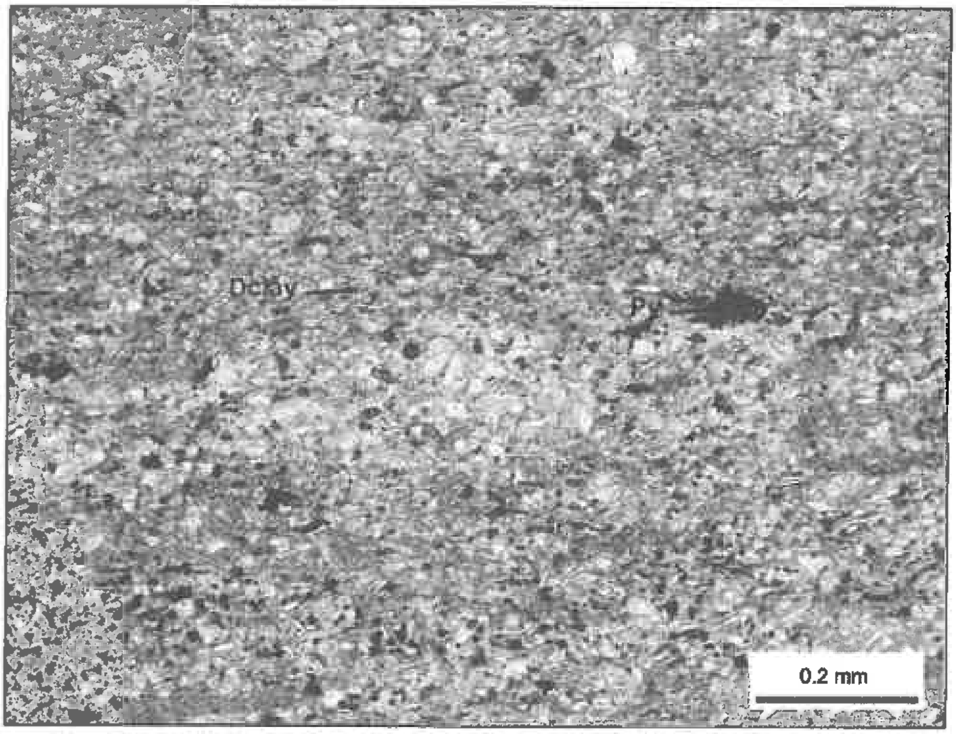


2B

PLATE 3 A-B

THIN SECTION PHOTOMICROGRAPHS

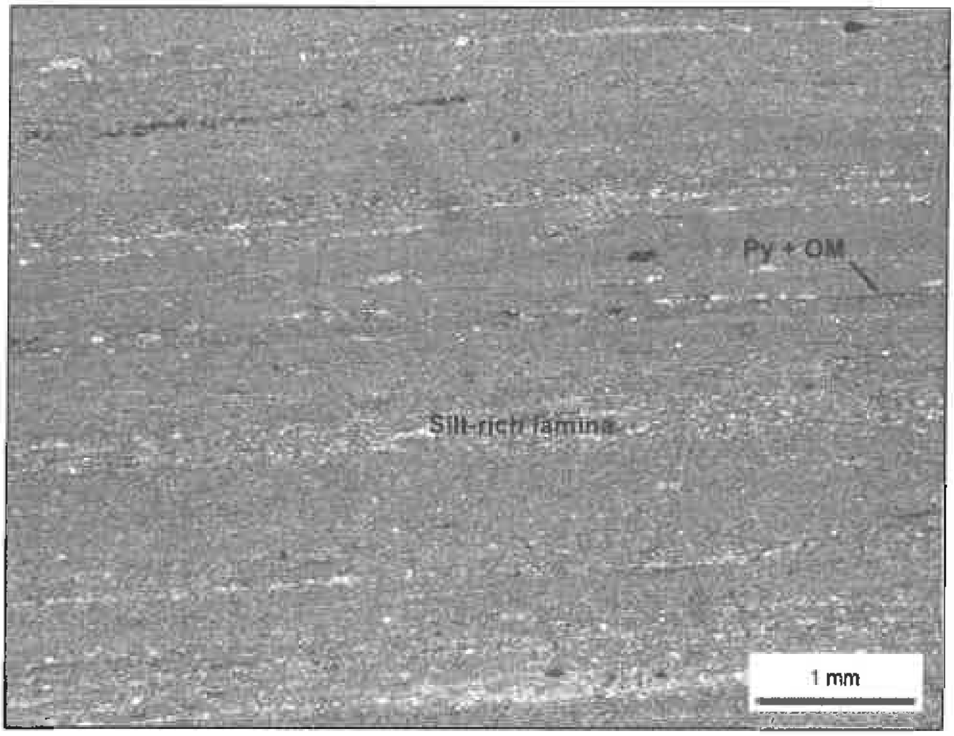
Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio

Depth (feet): 5440.0

Lithology: Silty Claystone
Foramtion: U. Olentangy shale
Sample ID: Burger_5_5440

This silty claystone contains minor amounts of silt-rich laminae. Note that organic stringers (OM; plant fragments) are locally present and partly replaced by pyrite (Py). Detrital clay matrix is the predominant constituent, followed by quartz, feldspars and mica grains. Fe-dolomite (Fdol; stained blue) is relatively common in the silt-rich laminae. Macropores are absent; micropores are associated with the clay matrix.

Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio
Depth (feet): 5440.0



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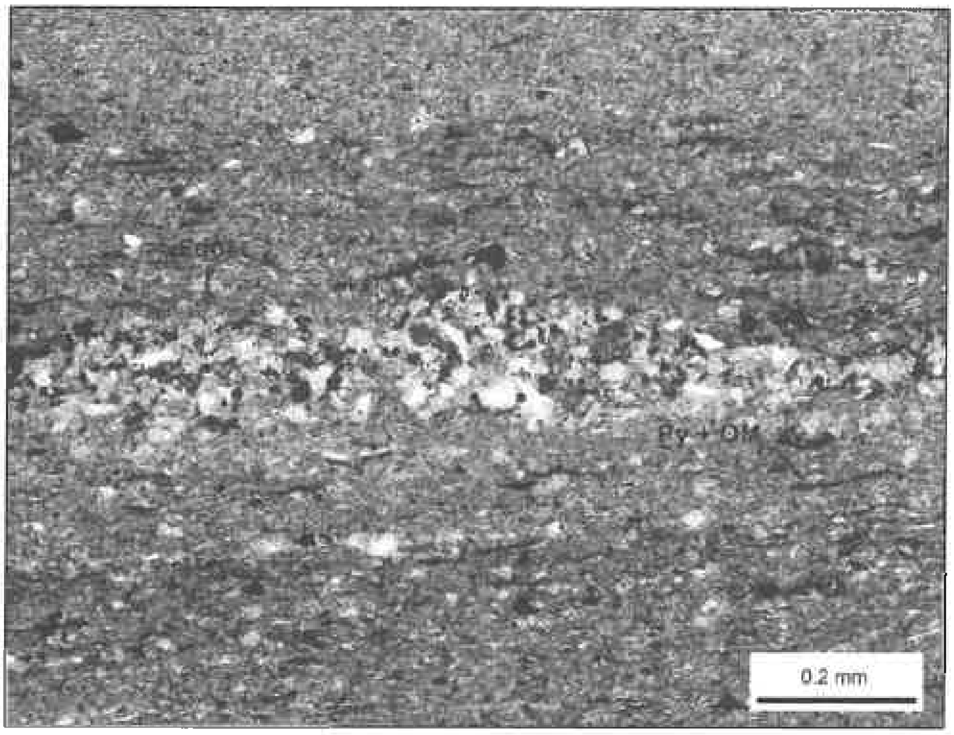


3B

PLATE 4 A-B

THIN SECTION PHOTOMICROGRAPHS

Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio

Depth (feet): 5500.0

Lithology: Silty Claystone
Foramtion: Hamilton shale
Sample ID: Burger_4_5500

This silty claystone is organic-rich, as indicated by the relatively dark color of some clay-rich laminae. Minor amounts of silt-rich laminae are also present in this sample. Authigenic pyrite (Py) is locally common and probably replaces organic matter (plant fragments). Detrital clay matrix (Dclay) consists mostly of illitic clays; silt-sized detrital grains are largely quartz and feldspars. Visible pores are absent; micropores are the major pore type and associated with the detrital clay matrix.

PLATE 5 A-B

THIN SECTION PHOTOMICROGRAPHS

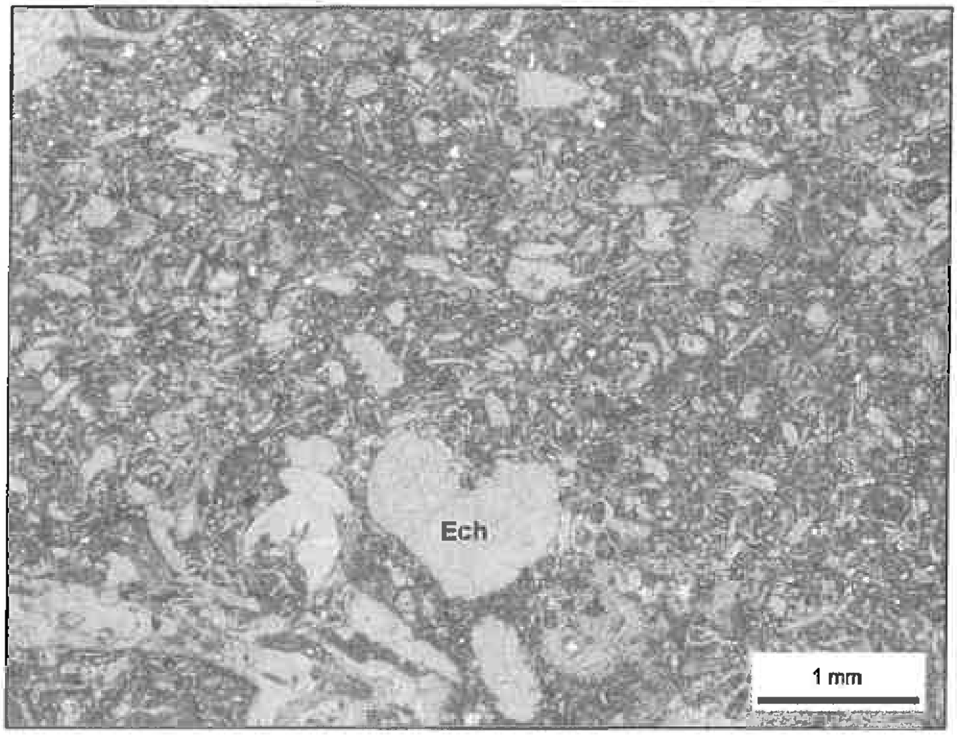
Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio

Depth (feet): 5710.0

Lithology: Limestone (packstone)
Foramtion: Onondaga limestone
Sample ID: Burger_2_5710

This limestone sample is a packstone; fossil fragments are the most common allochem grains and consist mostly of mollusks (Mol) and echinoderms (Ech). Interparticle areas are filled with micrite matrix (M), which is locally replaced by dolomite crystals (Dol). Intraskeletal pores have been occluded by Fe-calcite cement (Fcal). Authigenic pyrite (Py) is a trace component. No pores are visible; micropores associated with the micrite matrix are the principal pore type. Stylolites are also observed in this packstone.

Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio
Depth (feet): 5710.0



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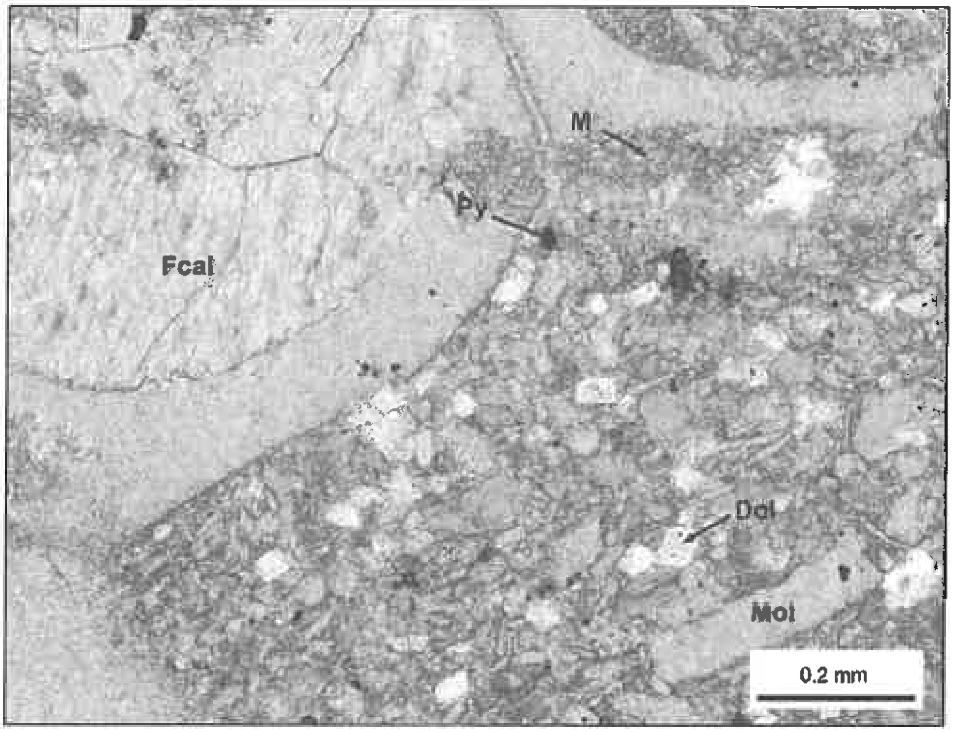


5B

PLATE 6 A-B

THIN SECTION PHOTOMICROGRAPHS

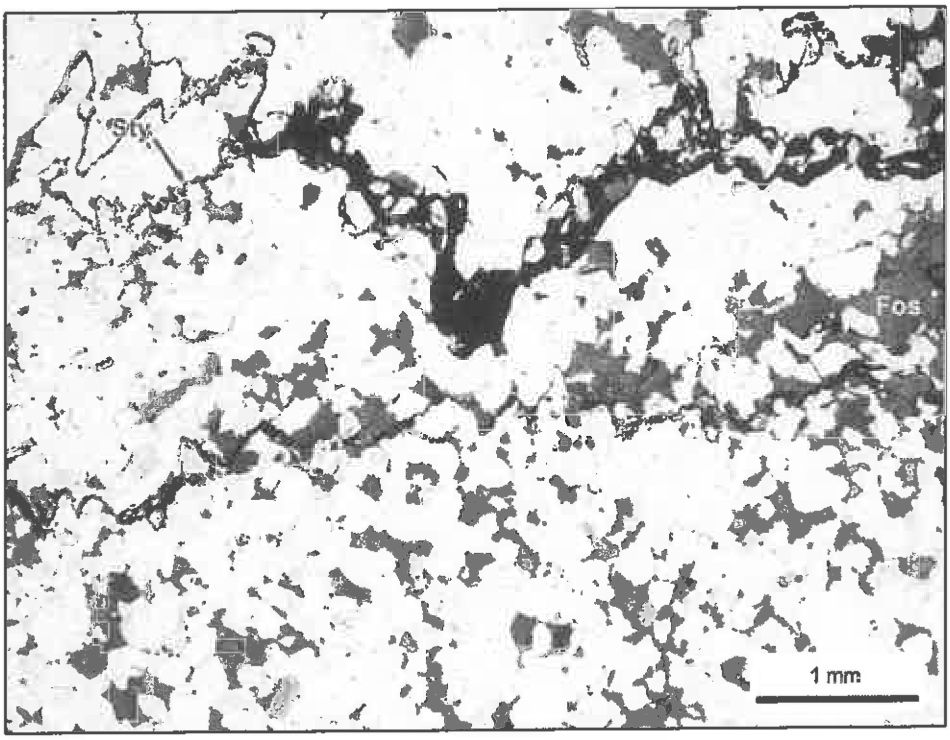
Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio

Depth (feet): 5945.0

Lithology: Sandstone
Foramtion: Oriskany sandstone
Sample ID: Burger_8_5945

White grains are mostly quartz (Q) and feldspars; fossil fragments (Fos) are minor to moderate and stained red. Framework grains are subrounded to rounded and well sorted. Intergranular areas are occluded by quartz overgrowths (QO) and minor amounts of Fe-calcite (Fcal; stained bluish purple). Open intergranular pores are very rare; micropores are trace to minor in this fine-grained sandstone. Stylolites (Sty) are common, crosscutting quartz overgrowths and Fe-calcite cements.

Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio
Depth (feet): 5945.0



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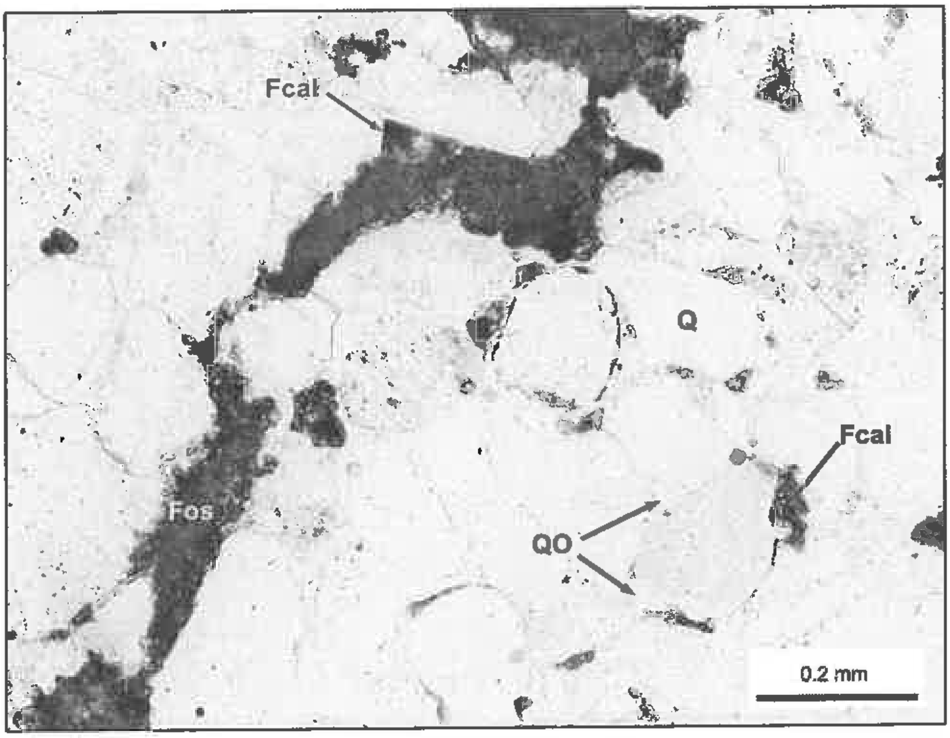


6B

PLATE 7 A-B

THIN SECTION PHOTOMICROGRAPHS

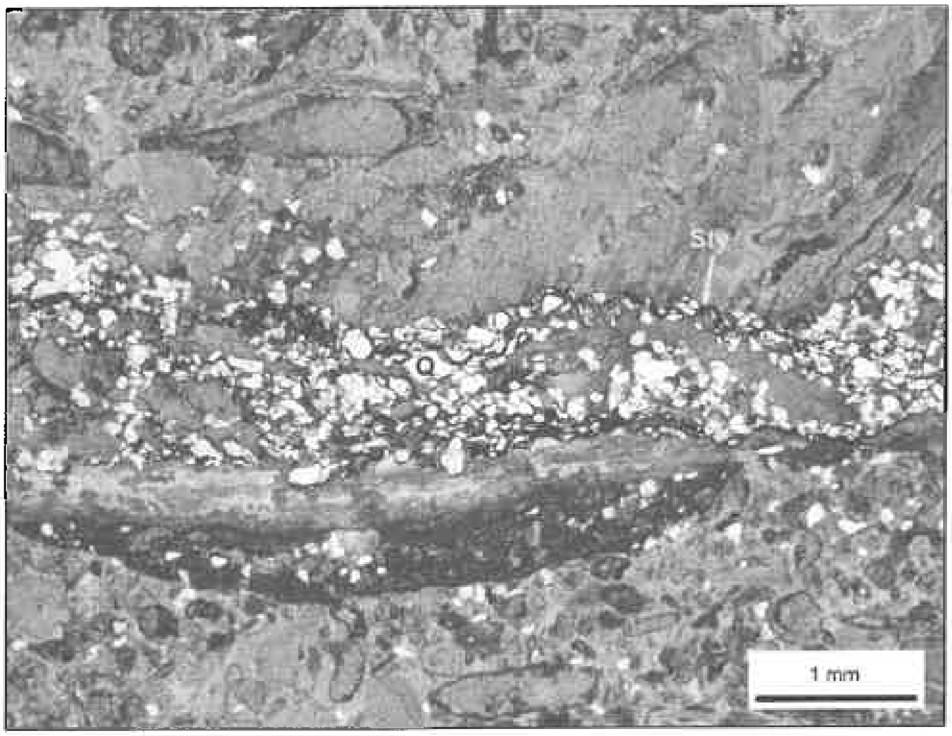
Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio

Depth (feet): 6200.0

Lithology: Limestone (grainstone)
Foramtion: Helderberg limestone
Sample ID: Burger_5_6200

This limestone sample is a grainstone; fossil fragments are the principal allochem grains and consist mostly of mollusks and echinoderms. Minor amounts of detrital quartz grains (Q) are scattered. Interparticle areas are occluded with calcite cement (Cal). No pores are visible; micropores are estimated to be minor in abundance. Stylolites (Sty) are present in this grainstone; quartz grains and other insolubles are relatively common along the stylolites.

Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio
Depth (feet): 6200.0



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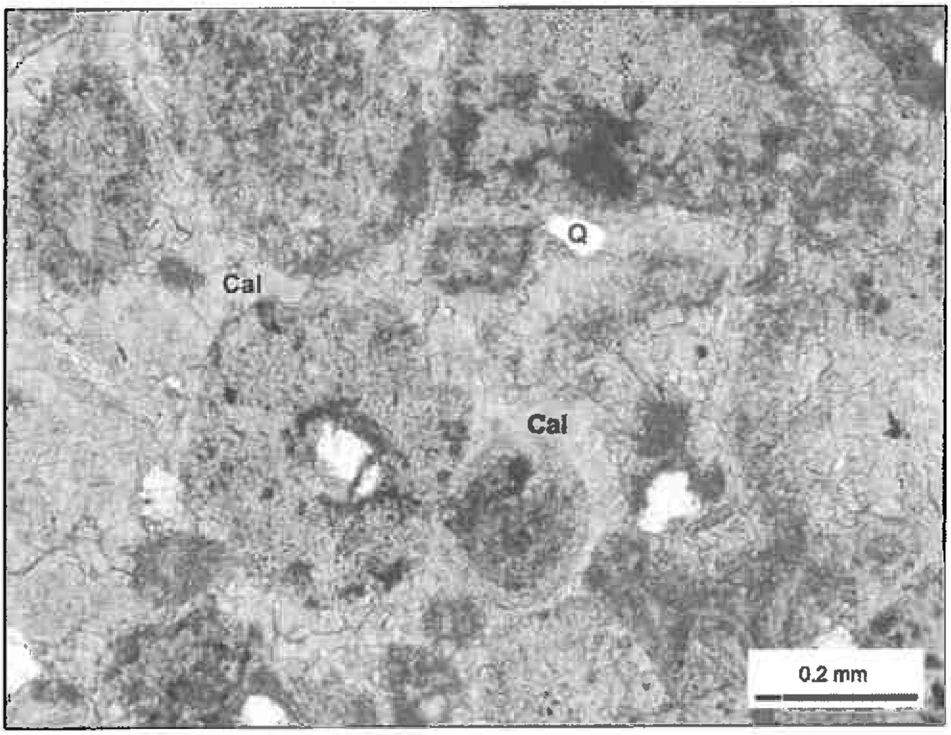


7B

PLATE 8 A-B

THIN SECTION PHOTOMICROGRAPHS

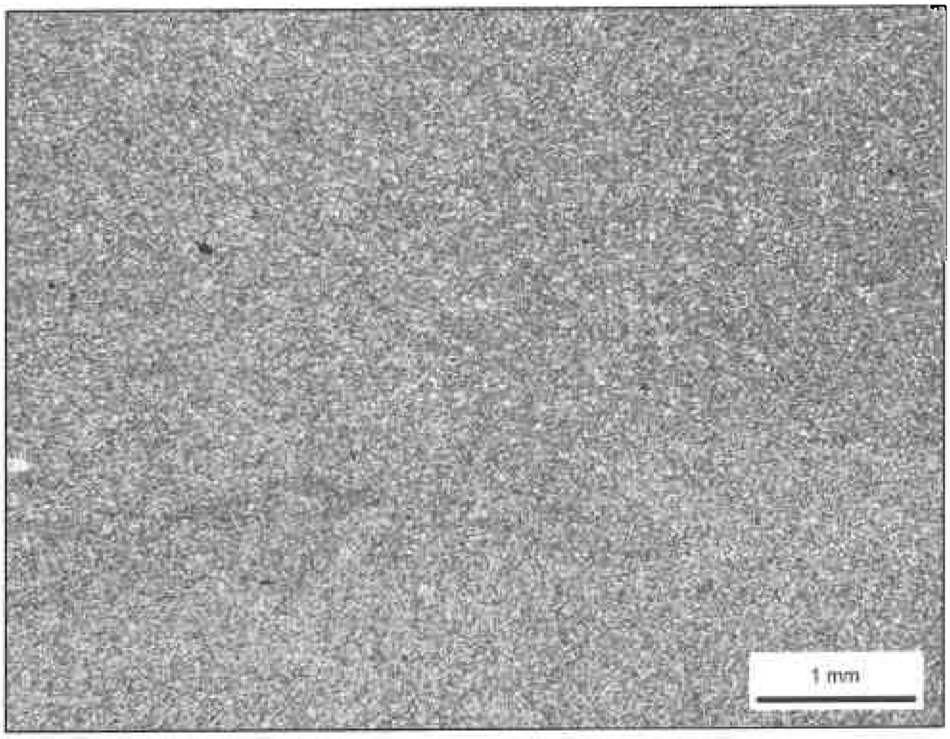
Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio

Depth (feet): 6500.0

Lithology: Dolostone
Foramtion: Salina anhydrite/salt/dolomite
Sample ID: Burger_2_6500

This dolostone contains minor to moderate amounts of intercrystalline pores (P), which make up the principal pore system. Dolomite is the predominant mineral in this sample and shows a finely crystalline texture. Authigenic pyrite (Py) is a trace component. Dolomitization is overall fabric-destructive; the original rock type (lime mudstone?) is difficult to determine.

Battelle Memorial Institute
Burger Site Well
Belmont County, Ohio
Depth (feet): 6500.0



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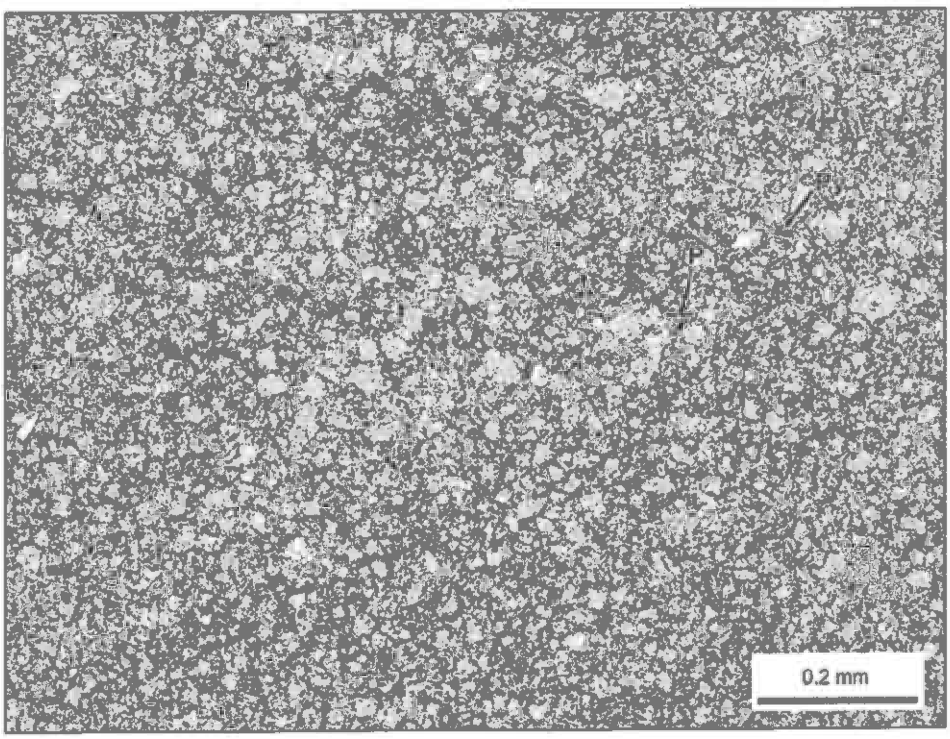

8B

PETROGRAPHIC EVALUATION OF SIX SIDEWALL CORE SAMPLES FROM THE BURGER SITE WELL BELMONT COUNTY, OHIO

Job Number: 071029GA

Prepared for:

Battelle Memorial Institute

Prepared by:

CORE LABORATORIES

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PETROGRAPHIC ANALYSIS

This report presents the results of thin section analysis performed on six (6) sidewall core samples from the Burger Site Well, located in Belmont County, Ohio. The objectives of this study are to determine texture, mineralogy, pore-filling constituents, pore types, and diagenetic features. A list of samples analyzed is presented in Table 1. Thin section photomicrographs are attached as Plates 1 to 6. The six (6) analyzed samples consist of four (4) dolostones, one (1) argillaceous siltstone, and one (1) sandstone (Table 1).

Dolostone: Four samples (6782.0, 6865.0, 6905.0, 7476.0 feet) are dolostones. Two dolostones (6782.0, 6865.0 feet) are probably derived from silty claystone and claystone. Dolomite is the dominant mineral; minor amounts of detrital quartz grains are still present. Trace amounts of barite (?) are present and have locally replaced dolomite. Micropores are the principal pore type in these two dolostones; visible pores are rare and mainly associated with the dolomitized silt-rich laminae.

Two dolostones (6905.0, 7476.0 feet) are probably derived from limestones (grainstone and wackestone). Visible pores are moderate to common and consist of interparticle and intercrystalline pores. Peloids are the most common allochem grains in the dolograinstone. Fractures are locally observed (Plate 3) and have been filled with clear dolomite crystals. Dolomite is locally replaced by barite.

Argillaceous siltstone: One sample (8133.0 feet) is an argillaceous siltstone, which is locally burrowed. The most common framework grains are quartz, K-feldspar and plagioclase; these grains are silt-sized, subangular in shape and moderately sorted. Intergranular areas are occluded by detrital clay matrix; hematite is highly dispersed in the matrix and shows a reddish color under reflected light. Visible pores are absent; micropores are the major pore type and associated with the detrital clay matrix.

Sandstone: One sample (8235.0 feet) is fine-grained, well sorted sandstone. Framework grains are dominantly quartz; feldspars and lithic fragments are much less common. Framework grains are subrounded to rounded and well sorted. Intergranular areas are largely occluded by abundant quartz overgrowths and trace amounts of Fe-calcite. Intergranular and moldic pores are minor in abundance; micropores are estimated to be minor and associated with lithic fragments. Moldic pores are the result of dissolution of chemically unstable feldspar grains and lithic fragments.

Thank you for choosing Core Laboratories to perform this study. Please feel free to contact us if you have any questions or comments concerning this report or if we can be of further service.

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TABLE 1

ANALYTICAL PROGRAM AND PETROGRAPHIC SUMMARY

Battelle Memorial Institute, Burger Site Well

Sample ID	Depth (feet)	Thin Section	Formation	Lithology	Plate No.
Burger_23_6782	6782.0	X	Salina anhydrite/salt/dolomite	Dolostone (dolomitized silty claystone)	1
Burger_20_6865	6865.0	X	Salina anhydrite/salt/dolomite	Dolostone (dolomitized claystone)	2
Burger_19_6905	6905.0	X	Salina anhydrite/salt/dolomite	Dolostone (dolomitized grainstone)	3
Burger_13_7476	7476.0	X	Lockport dolomite/limestone	Dolostone (dolomitized wackestone)	4
Burger_9_8133	8133.0	X	Red Clinton siltstone	Argillaceous siltstone	5
Burger_6_8235	8235.0	X	White Clinton sandstone	Sandstone	6