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

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## ABOUT THE MRCSP

This report was produced by the Ohio Division of Geological Survey with funding supplied, in part, through the Midwest Regional Carbon Sequestration Partnership (MRCSP). The MRCSP is a public/private consortium that is assessing the technical potential, economic viability, and public acceptability of carbon sequestration within its region. The MRCSP region consists of eight contiguous states: Indiana, Kentucky, Maryland, Michigan, New York, Ohio, Pennsylvania, and West Virginia. A group of leading universities, state geological surveys, non-governmental organizations and private companies makes up the MRCSP, which is led by Battelle Memorial Institute. It is one of seven such partnerships across the United States that make up the U.S. Department of Energy's (DOE) Regional Carbon Sequestration Partnership Program. The U.S. DOE, through the National Energy Technology Laboratory (NETL), contributes the majority of funds for the MRCSP's research under agreement no. DE-FC26-05NT42589. The MRCSP also receives funding from all of the member organizations. For more information on the partnership please visit <http://www.mrcsp.org>.

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# CONTENTS



# FIGURES

## APPENDICES

### (SEE EXCEL DOCUMENTS ON CD)

# 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 carbon-capture-and-storage 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, led by Battelle Memorial Institute, includes research institutes and government agencies from the states of Indiana, Kentucky, Maryland, Michigan, New York, 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, three sites within the MRCSP region, including the Burger Power Plant site, are under investigation to be used as field tests to evaluate carbon-sequestration methodologies in geologic reservoirs.

The objective of this report is to summarize the geology and available geologic data of the Burger site and its immediate vicinity, and to provide a preliminary characterization of known geologic reservoirs and sealing units for use in further assessment work. Further assessment work would be used for developing the test well design and implementing various requirements for carbon capture and storage, as well as acquiring an underground-injection permit and developing a subsequent monitoring plan. This report was revised to include information collected during the drilling and geophysical well logging of the deep stratigraphic test well drilled at the Burger site, the FEGENCO #1 Well. Further well testing and injection of $CO_2$ are planned for this well. At the conclusion of such tests, a final report on this project will be published by the Ohio Department of Natural Resources, Division of Geological Survey (DGS).

The principal investigators for this feasibility study were Mark Baranoski, Ernie Slucher, and Larry Wickstrom of the DGS. This report was revised by Doug Mullett of the DGS. Additional contributions were made by Kristen Carter of the Pennsylvania Geological Survey and Lee Avary of the West Virginia Geological and Economic Survey.

## GEOGRAPHIC SITE 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, which is located on the Businessburg 7.5-minute U.S. Geological Survey (USGS) quadrangle (fig. 1). The Burger Power Plant 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 and the term "Burger Well" refers to the FEGENCO #1 Well (American Petroleum Institute number 3401320586). "AOR" as used in this report stands for area of review and includes well and other geologic data within approximately 20 miles of the site. The Burger Well was drilled 3,994 ft from the north line and 374 ft from the east line of Section 35, Mead Township, Belmont County.

## 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, and 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 geologic horizons in the eastern part of the AOR. Items 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. Department of Energy (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 SEQUESTRATION RESERVOIRS

The U.S. DOE 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: (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 ground water. 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/

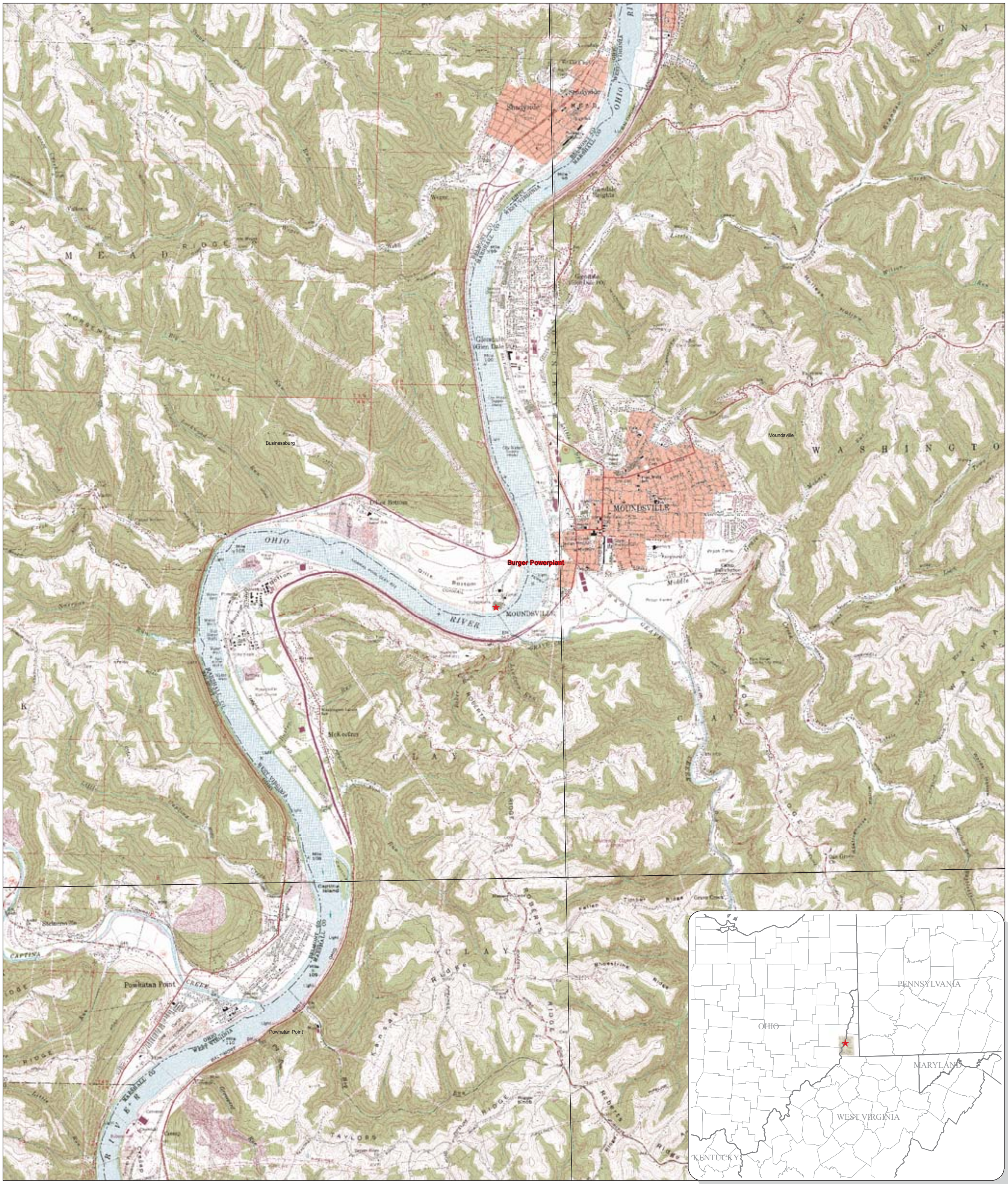


Figure 1.—Location of Burger Power Plant. Figure captured from four USGS digital raster graphic (DRG) files of the 7.5-minute quadrangles surrounding the site. A separate file containing this map, for detailed use and printing, is included on the CD submitted with this report.

disposal. In order to maintain injected $CO_2$ in its supercritical state (i.e., liquid), the injection horizon depth must be at or greater than 2,500 ft. Maintaining $CO_2$ in its liquid phase is desirable because, as a liquid, it takes up less volume than when it is in the gaseous phase. One ton of $CO_2$ at surface temperature and pressure (when it is in its gaseous phase) occupies approximately 18,000 cubic feet. The same amount of $CO_2$ will occupy only 50 cubic feet when injected into a formation at a depth of approximately 2,600 ft. Sequestration depths of at least 2,500 ft 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) that contain 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 (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 EOR operations are in the western United States, especially the Permian Basin of west Texas. These fields mainly use naturally occurring sources of $CO_2$, but recently, anthropogenic sources have been added to their extensive pipeline network. There are no known large natural-$CO_2$ sources in the eastern United States. 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 further economic incentive to develop a long-term sequestration operation at a site such as the Burger Power Plant.

### UNMINEABLE COAL BEDS

Unmineable coal beds offer a unique 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 it 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 potential 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 carbonaceous shale reservoirs could be used to enhance existing gas production. Additionally, it is believed that carbonaceous shales could adsorb $CO_2$ into the shale matrix, similar to coal adsorption, 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 developmental research stage.

## METHODS

A geologic characterization was conducted for the 20-mile radius AOR that includes 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 were used from as far as 30 miles from the site.

Data used for the 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 (API number). The API number 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 (in Ohio) the next 5 numbers representing the permit number within the county.

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.). A stratigraphic chart for strata underlying the Burger AOR, adapted from the MRCSP phase I report (Wickstrom and others, 2005), is shown in figure 3.

As of June 2006, 6,257 drill holes were on file at the WVGES, PGS, and DGS in the 20-mile radius AOR. The majority of these wells were drilled for oil and gas (including coalbed methane). The results of analyses using the well records were constrained because many of the records pre-dated modern regulations that require relatively more information than the records contain. For example, 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 on deeper geologic units within the AOR may exist in the records of current and historic operators of the Appalachian Basin. A listing of all wells within the AOR, as of June 2006, is attached (Appendix A). Other subsurface records of the AOR are from coal stratigraphic test holes and wells drilled for brine solution operations. Very little core or analyses of the AOR are available for rocks below the coal measures (Appendix B).

A dip cross-section was constructed across the AOR (fig. 4) to illustrate the regional stratigraphy, including the potential injection zones and confining units. For visual clarity, the cross section is split into a shallow section and a deep section (figs. 5, 6). Data used for the shallow and deep sections were derived from the top of the Onondaga Limestone and the Dayton Formation\"Packer Shell," respectively.

Time budgeted for this assessment precluded using a large number of geophysical logs to interpret formation boundaries and properties and map unit depth and thickness. In addition, geophysical logs were not run or reported when many wells in the region were drilled. Therefore, drillers' reported formation depths (depth below

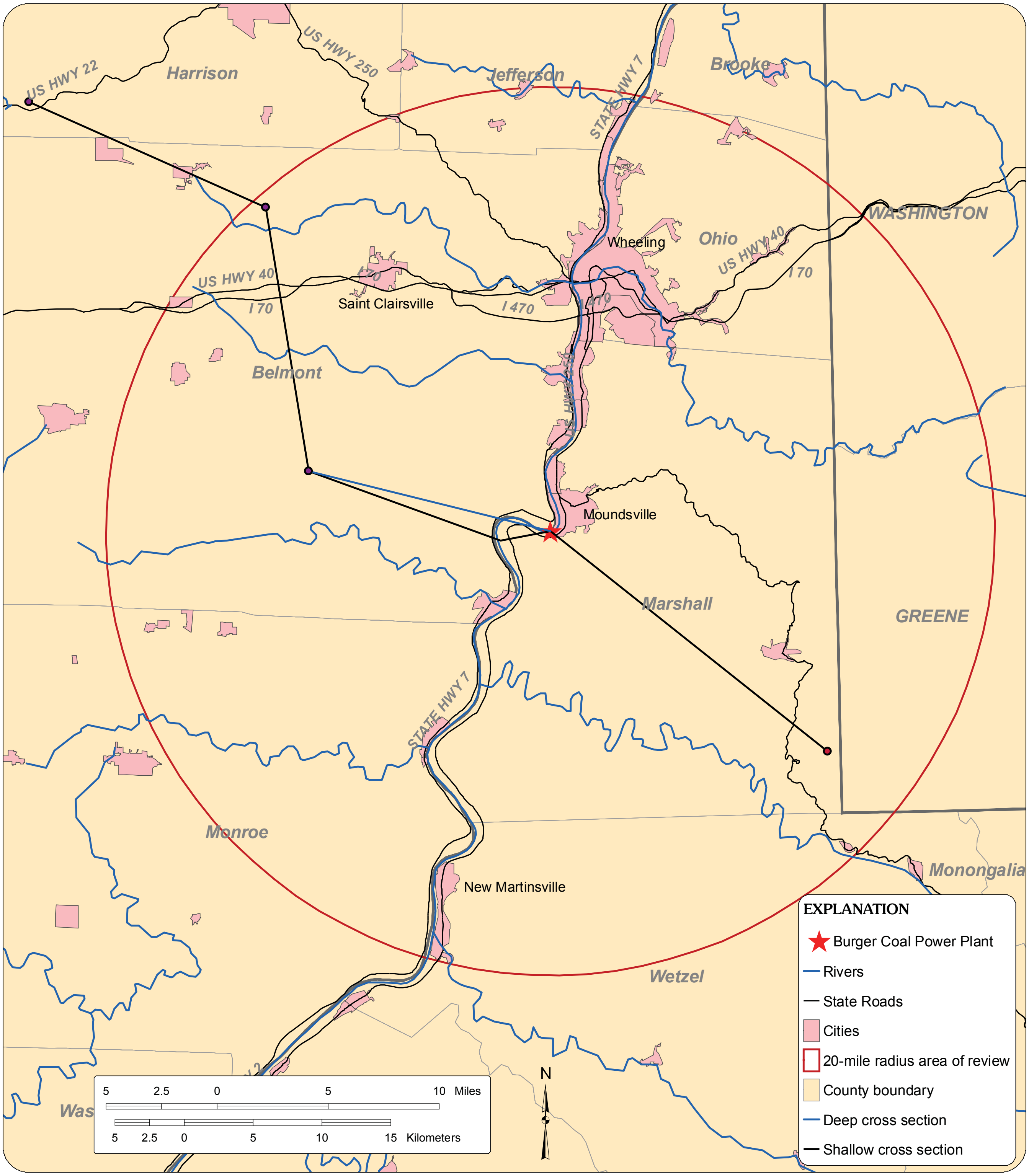


Figure 2.—Map of the Burger site with the 20-mile radius area of review (AOR) shown. Line of cross section (figs. 5, 6). The shallow portion of the cross section contains one control point not used on the deep section.

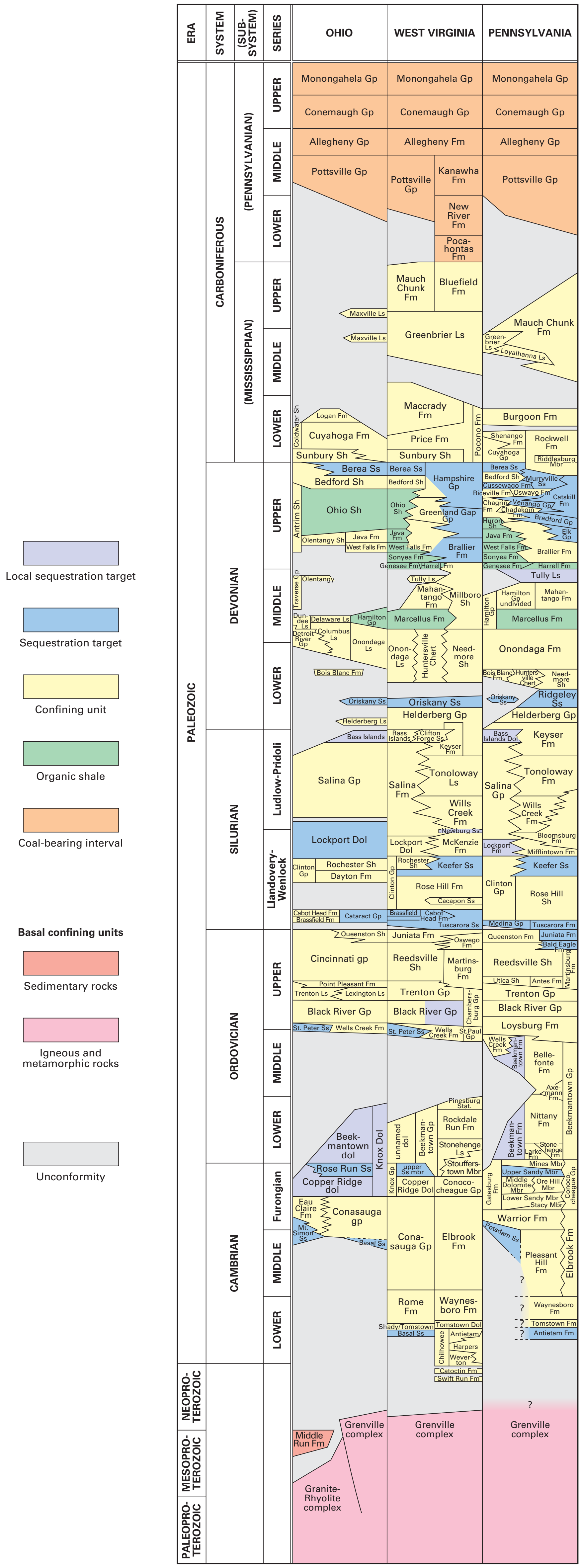


Figure 3.—Stratigraphic correlation and $CO_2$ sequestration characterization chart of geologic units in Ohio, Pennsylvania, and West Virginia (modified from Wickstrom and others, 2005).

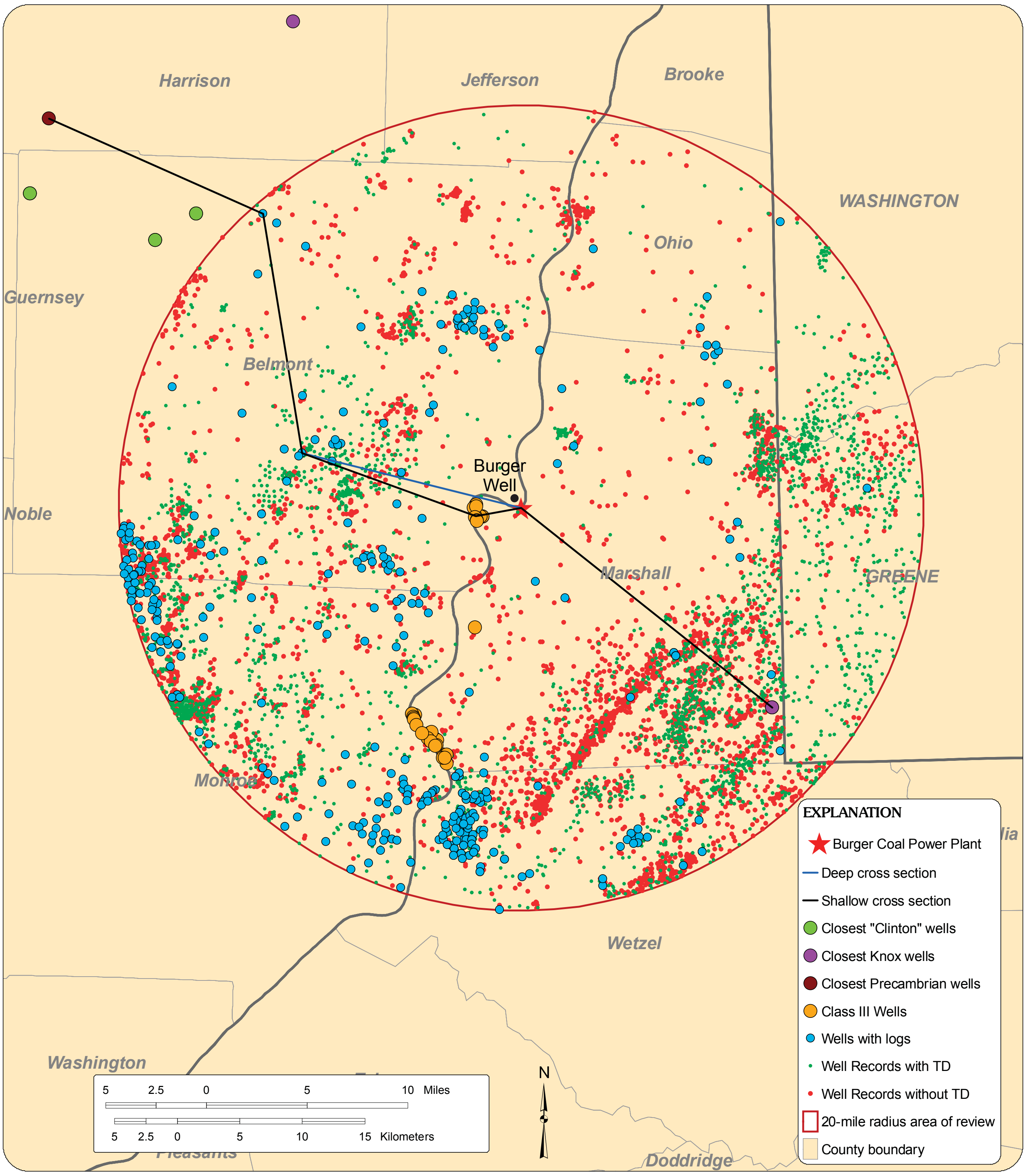


Figure 4.—Map of oil, gas, and solution mining wells located within the Burger AOR. Line of cross section (figs. 5, 6). The shallow portion of the cross section contains one control point not used on the deep section.

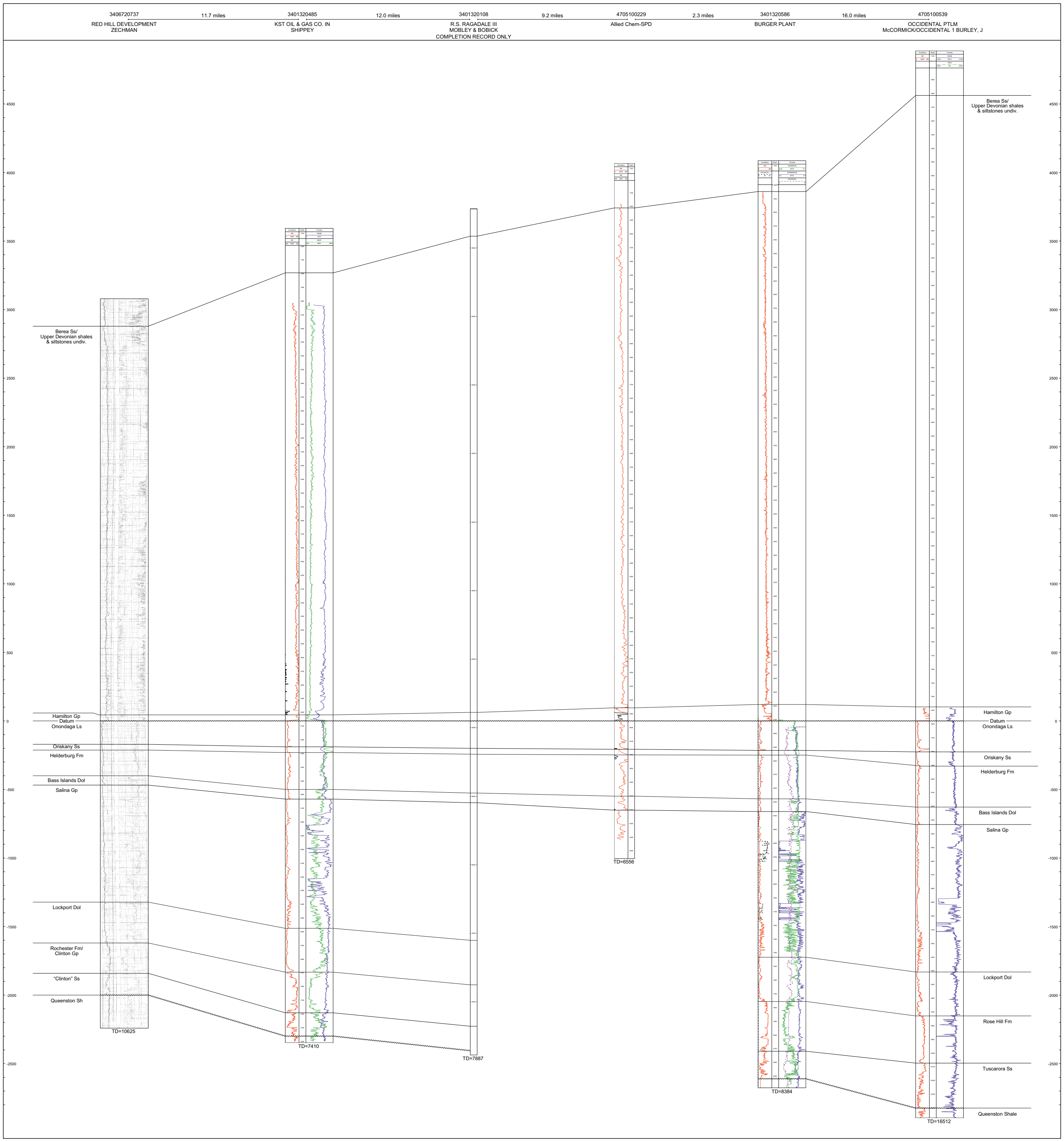


Figure 5.—Stratigraphic cross section oriented northwest-southeast across the AOR showing stratigraphic correlations and geophysical log signatures of shallow geologic units (Queenston Shale through the Berea Sandstone). Datum is the top of the Onondaga Limestone. See figure 2 for location of line. A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

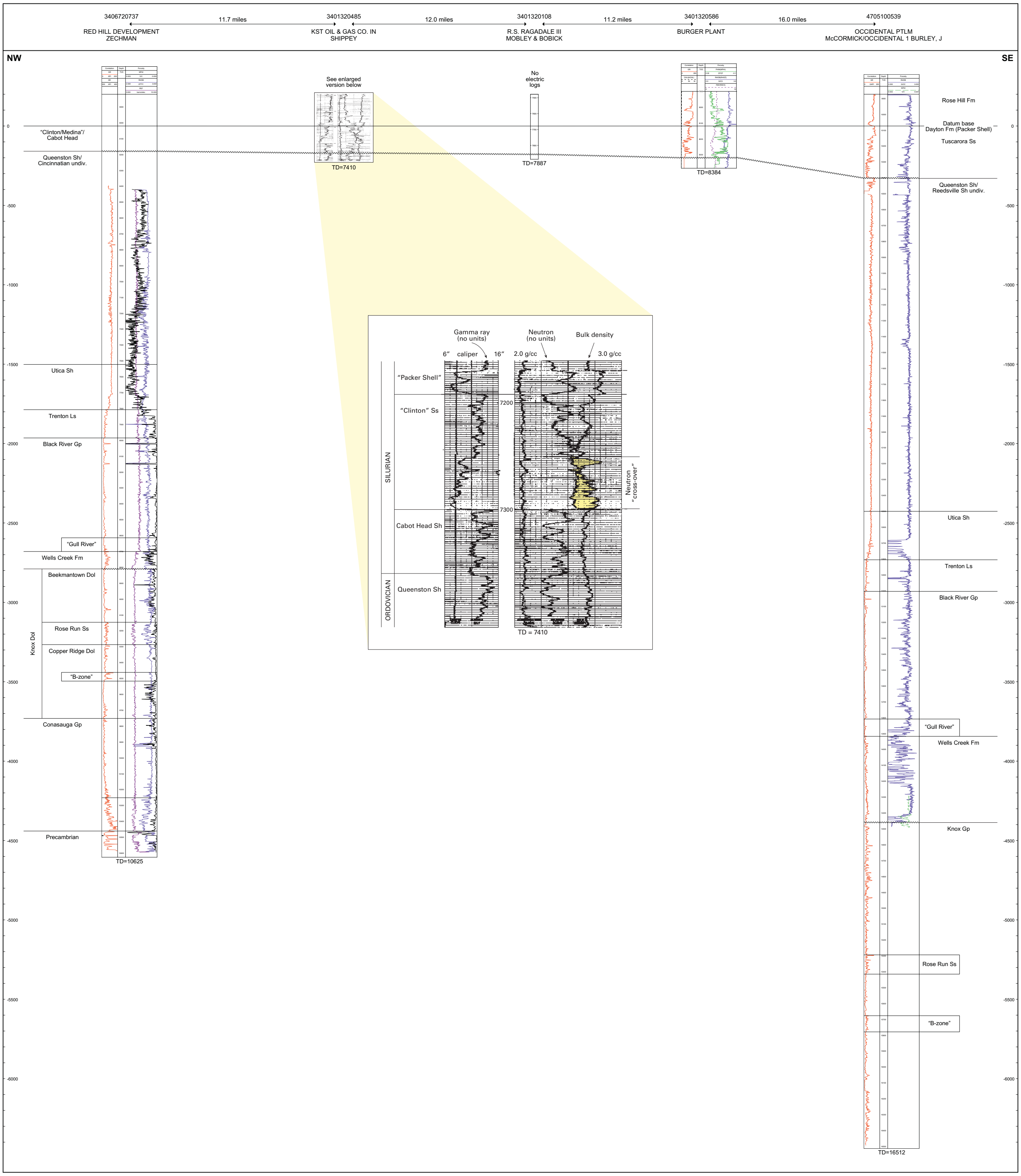


Figure 6.—Stratigraphic cross section oriented northwest-southeast across the AOR showing stratigraphic correlations and geophysical log signatures of deep geologic units (Precambrian through the Rose Hill Formation). Datum is the base of the Dayton Formation ("Packer Shell"). See figure 2 for location of line. Inset shows geophysical log from a Belmont County, Ohio well (API number 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 file containing this cross section, for detailed use and printing, is included on the CD submitted with this report.

sea level) were used to create two structure contour maps on the top of the Berea and Oriskany Sandstones (figs. 7, 8). It should be noted that maps created solely from reported tops (and not maps created from geophysical log data) are less accurate because methods used to ascertain the information reported varied within and among drilling operations.

As previously mentioned, few wells in the AOR penetrate deeper than the Onondaga Limestone. Therefore, maps for deeper horizons were cut from larger regional maps in the MRCSP phase I geologic report (Wickstrom and others, 2005). Depths or thicknesses on the computer-generated maps in this report most likely vary from actual depths and thicknesses, as the maps are best-fit approximations based on grids that are insufficient for site-specific accuracy. Thus, the contour maps presented in this report, especially the regional maps, are used only to show general depth and thickness trends.

## SURFACE AND NEAR-SURFACE SITE CHARACTERIZATION

The Burger 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 ft, especially along the Ohio River. The elevation at the Burger Well is 676 ft above sea level. Within a mile of the site to the northwest, the ridge top elevation is 1,240 ft; thus, relief adjacent to the site is approximately 600 ft. Also, the site occurs in the Ohio coalfield, an area of extensive coal and clay mining since the early 1800s (Slucher and others, 2006).

The site occurs relatively far south of the southern limit of the known glacial advance within Ohio (Pavey and others, 1999). Typically, at the base of local hill slopes, there are valleys and tributaries filled with many tens of feet of unconsolidated deposits. A water well at the site penetrated 85 ft 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 ft) 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 possibly one 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 targeted the Pittsburgh coal, which is 5 to 7 ft thick and approximately 200 ft 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 potential underground source of drinking water (USDW), as defined by the U.S. Environmental Protection Agency (<10,000 ppm TDS) near the Burger site in southeastern Belmont County is the Pennsylvanian-age Lower Freeport sandstone of the Allegheny Group (Vogel, 1982). Based upon Vogel's map, the elevation of the Upper and Lower Freeport sandstones range from 300 ft above sea level on the northern side of the AOR to an estimated 500 ft below sea level on the southern edge. The USDW is approximately 75 ft below sea level (approximately 750 ft deep) in the Burger Well. The surface casing in the Burger Well is set at a depth of 902 ft to protect freshwater aquifers. While limited domestic supplies of potable water are obtained from these thin Pennsylvanian sandstone beds, larger industrial and municipal water supplies are mainly taken from thick, permeable sand and gravel deposits in valley fill material that is hydraulically connected and adjacent to the Ohio River (Walker, 1991).

## GENERAL GEOLOGIC SITE CHARACTERIZATION

### 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 more than 542 million years old, 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 of the Precambrian complex is provided based on our interpretation of the limited data available on it.

The Precambrian basement complex of the 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). Uranium-lead age dates have not been determined for the Eastern Granite-Rhyolite Province or Grenville Province in Ohio. However, regional geochronological investigations in other states of the region indicate the Eastern Granite-Rhyolite Province is approximately 1.3 to 1.4 GA (Van Schmus and others, 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 terrain exposed in southern Canada; it 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 a Paleozoic sedimentary cover. The Grenville Province is known to contain numerous fault blocks where it has overridden the East Con-

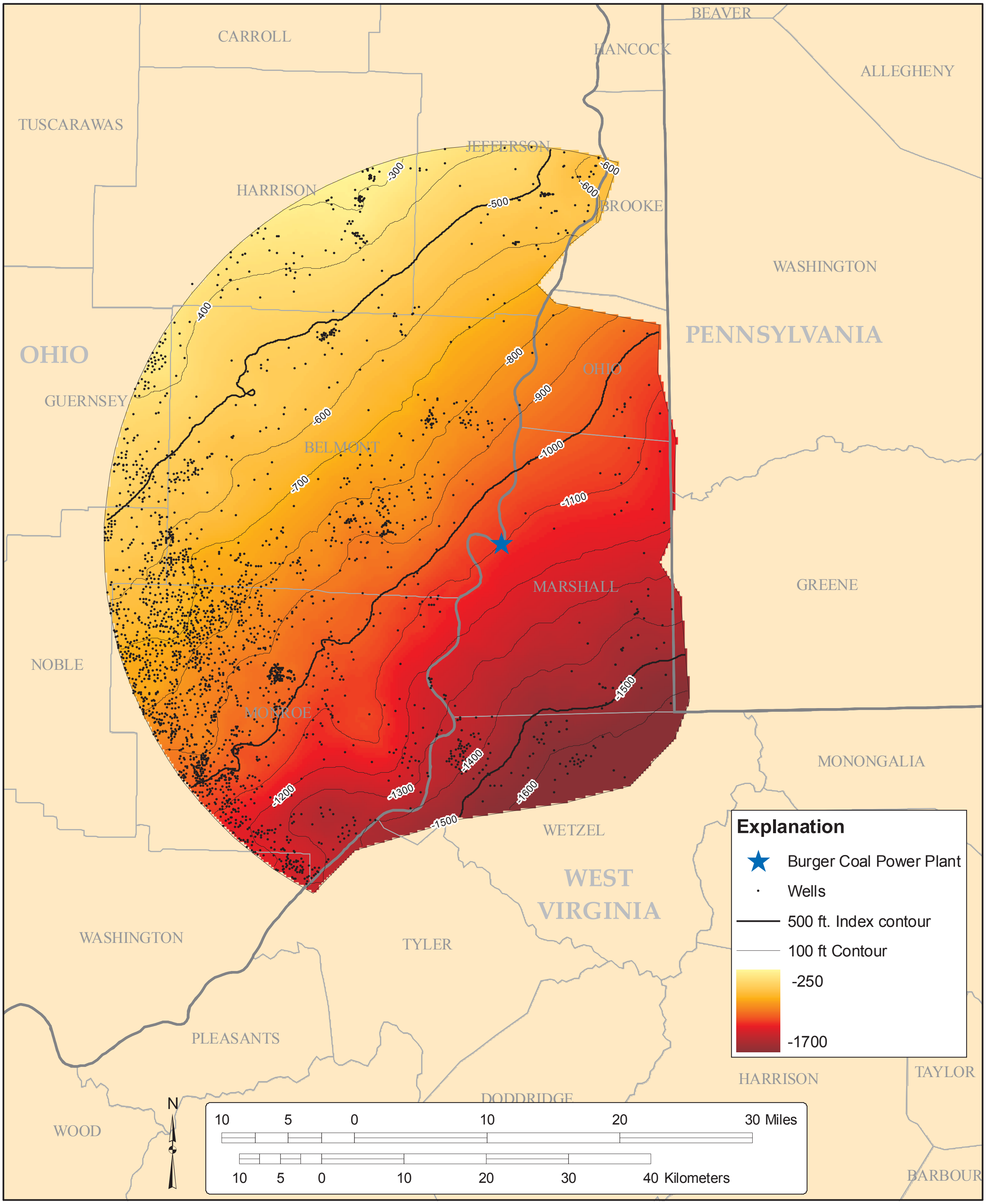


Figure 7.—Structure contour map on the top of the Berea Sandstone within the Burger AOR. Map computer contoured from formation tops taken from driller's records.

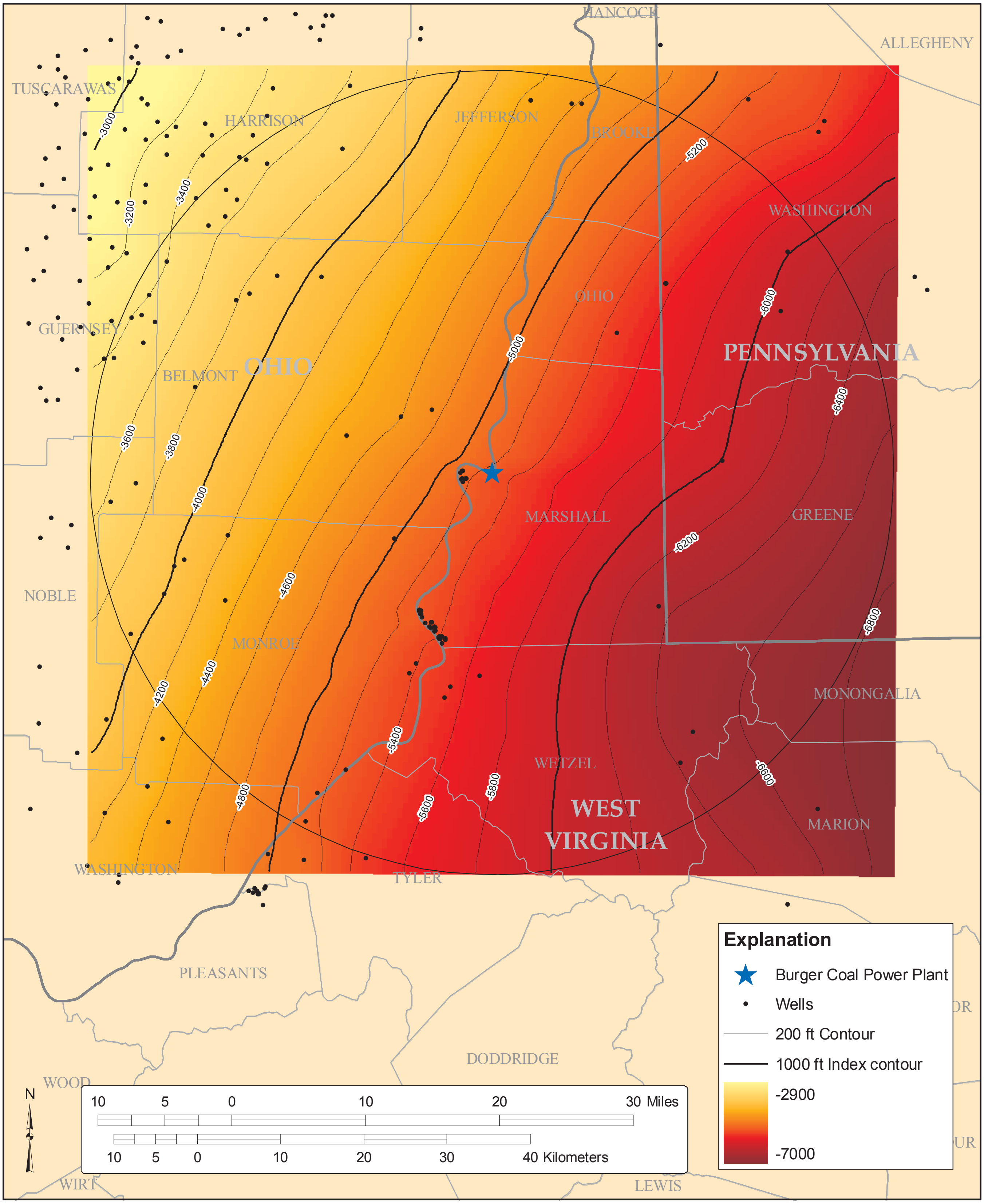


Figure 8.—Structure contour map on the top of the Oriskany Sandstone within the Burger AOR. Map computer contoured from formation tops taken from driller's records.

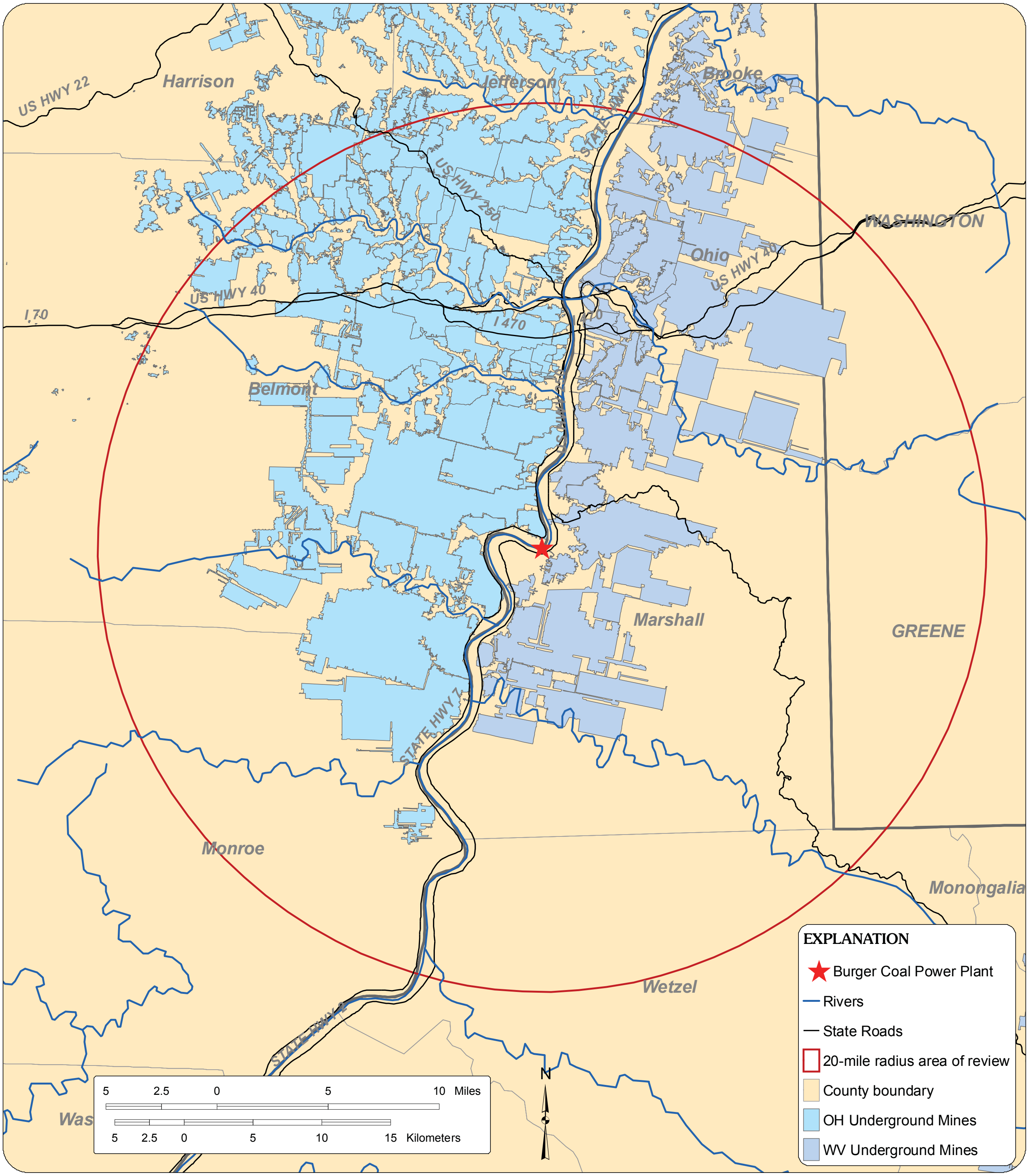


Figure 9.—Map showing the locations of abandoned underground mines within the Burger AOR.

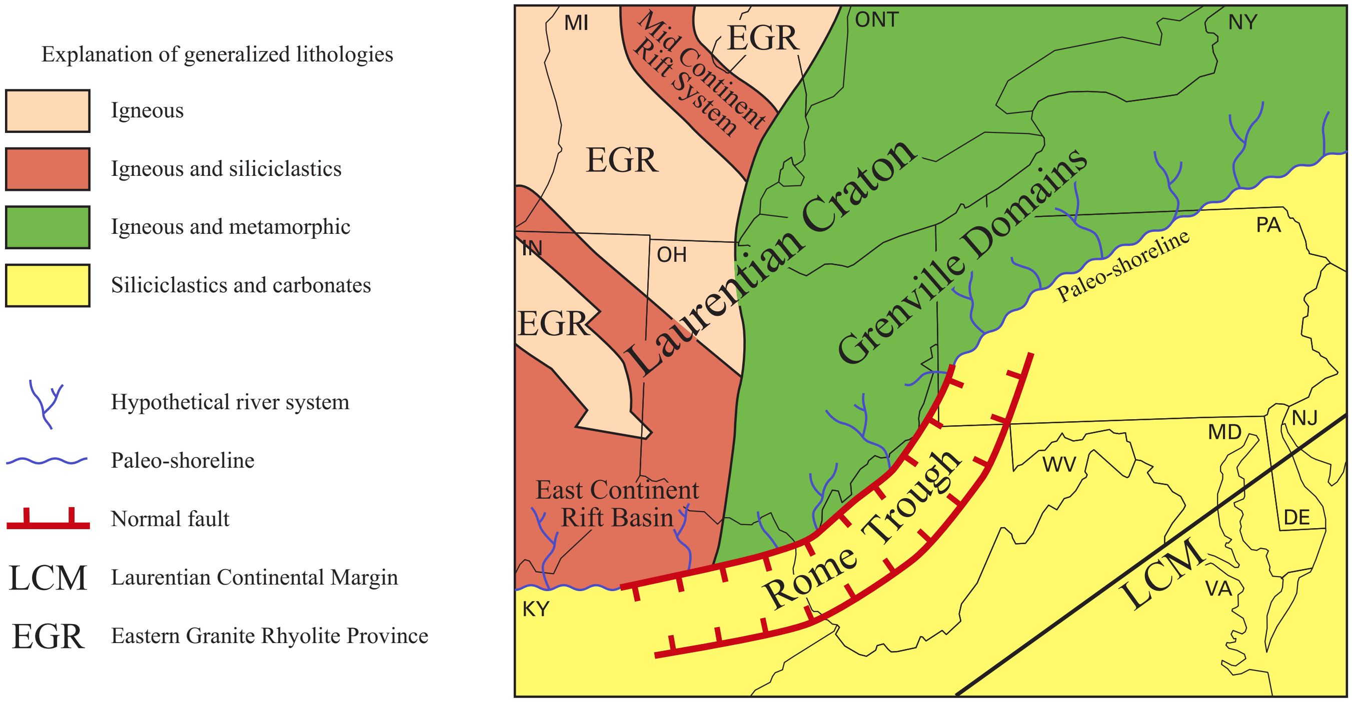


Figure 10.—Map showing the locations of major geologic elements (paleogeography) during early Cambrian time (from Baranoski, in prep.).

tinent 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, 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; it 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 northwest 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 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 important when developing deep injection operations. Thickness of Paleozoic Appalachian Basin rock units ranges from approximately 3,000 ft in central Ohio to approximately 14,000 ft in southeastern Ohio, and may reach as much as 45,000 ft in parts of central Pennsylvania. The Paleozoic stratigraphic column of rocks present within the AOR range in age from Middle Cambrian to Late Pennsylvanian (fig. 3) and represent a variety of sedimentary lithologies (carbonates, evaporites, shale, sandstone, siltstone, k-bentonite, chert, coal, etc).

Analyzing the stratigraphy of the Lower and Middle Cambrian in the tri-state area (Ohio, Pennsylvania, and West Virginia) is particularly problematic because of sparse deep-well data and a lack of continuous cores from the region. Another difficulty in analyzing the stratigraphy has been a lack of Cambrian paleontological studies to adequately assign age placements of lithostratigraphic correlations (Babcock, 1994). However, 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 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

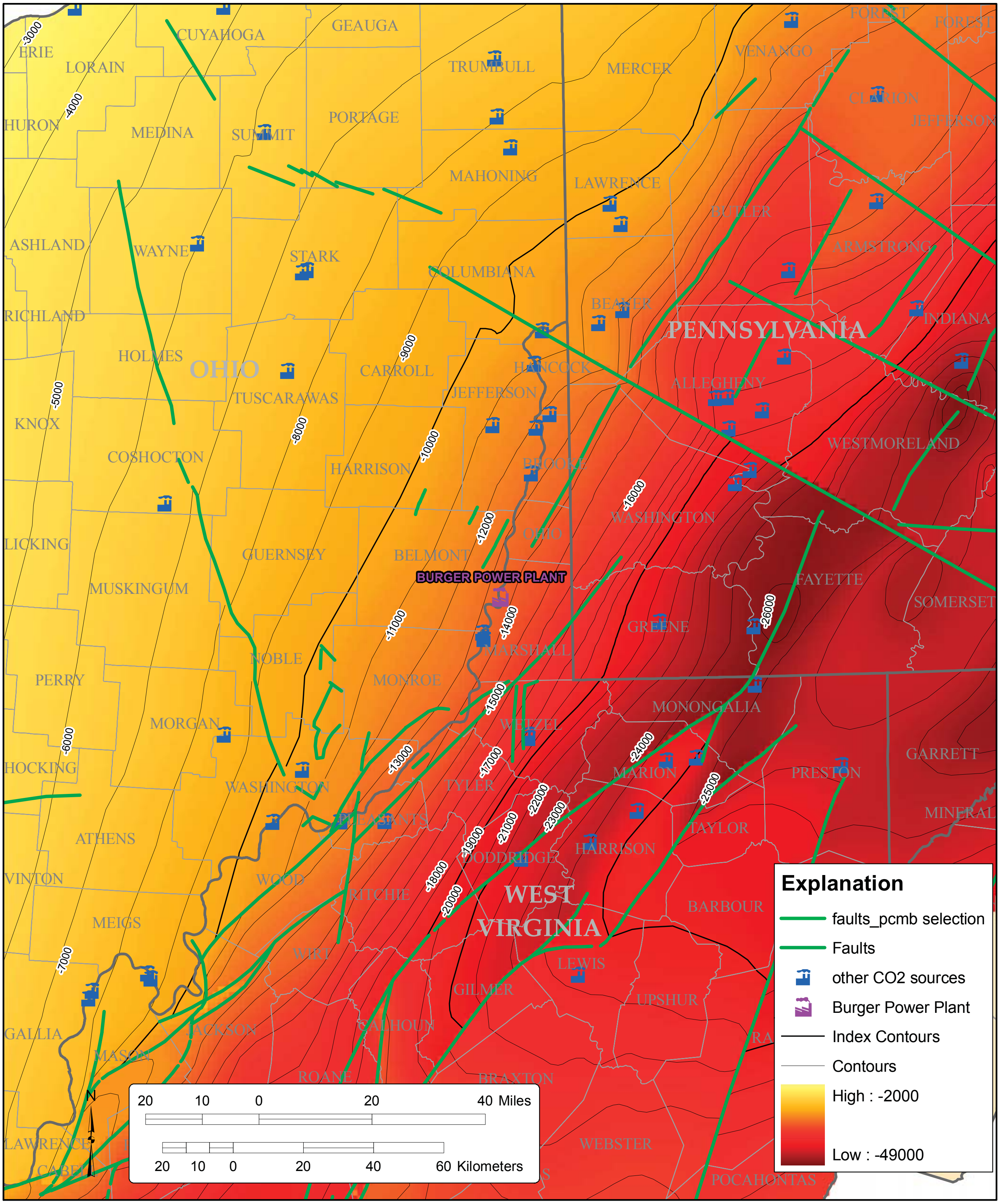


Figure 11.—Structure contour map on the top of the Precambrian unconformity within the Ohio, Pennsylvania, and West Virginia region. Also shown is the location of major (>100,000 tons per year) point sources of $CO_2$. (Map elements taken from Wickstrom and others, 2005.)

Conasauga Group (Ryder, 1992; Ryder and others, 1996). The Conasauga Group includes the Maryville Formation (including the "lower unit"), Nolichucky Shale, and 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 Late 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 ft of pre-Knox sediments accumulated in the Rome Trough (Ryder, 1992; Ryder and others, 1996).

From the 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 ft 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, mainly comprised of dolomite, in the eastern portion of Ohio. It is unknown if there is significant sandstone within this lower interval in the tri-state area. 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, 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 approximately 150 ft 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 surface. 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; its 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 in 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 to marginal marine deposition above 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 West Falls and Java 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 ft at the Burger site indicates up to ten 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, Copper Ridge Dolomite (both vugular porosity zones and the "B" zone sand within this unit), Rose Run sandstone, Beekmantown dolomite, "Clinton" sandstone, Lockport Dolomite, porous carbonate zones within the Salina Group, Bass Islands Dolomite, Oriskany Sandstone, and black shales of the Hamilton Group and West Falls Formation.

Unfortunately, although many oil and gas wells have been drilled in the AOR, very few wells have been drilled deeper than the Onondaga Limestone (shallower than the Oriskany). Thus, little to no near-field data are available for most of the potential saline aquifers at the site. Further, aside from standard geophysical logs, relatively

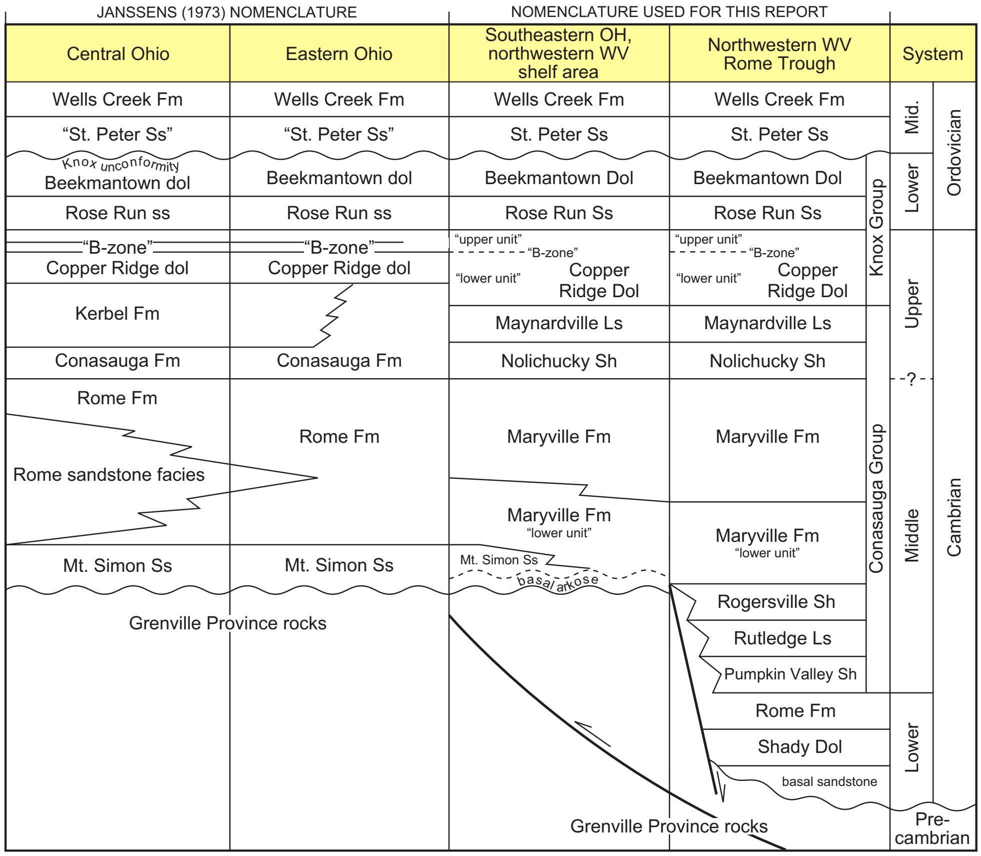


Figure 12.—Stratigraphic correlation chart for the AOR showing details of the Cambrian and lower part of the Ordovician (modified from Janssens, 1973; Ryder, 1992; and Harris and Baranoski, 1996).

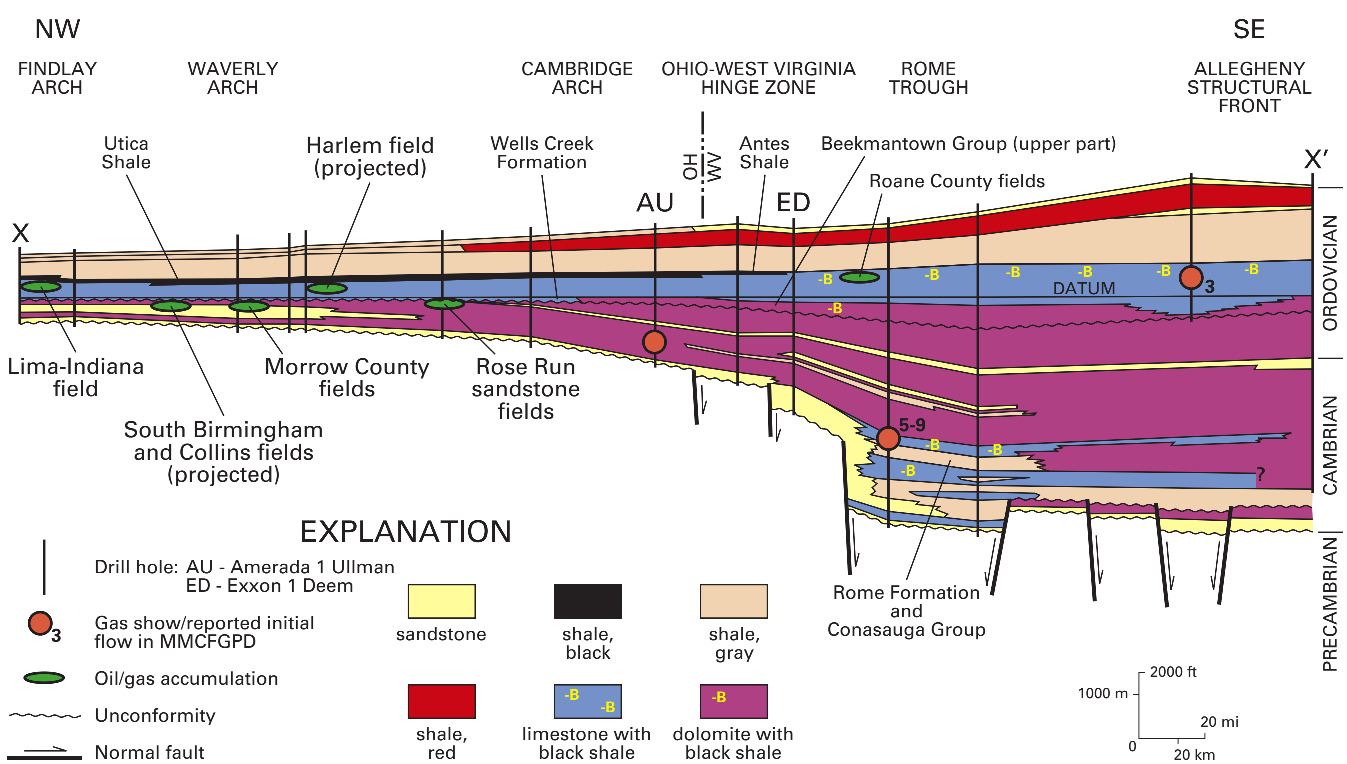


Figure 13.—Stratigraphic cross section from Sandusky County, Ohio to Pendleton County, West Virginia showing Cambrian and Ordovician sequences (modified from Ryder and others, 1998).

little quantitative data are 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. This lack of data firmly underscores the need to acquire seismic information and to drill a test well at this location. Information from the Burger Well has been incorporated into this report to better evaluate potential injection horizons and confining units that were penetrated at the site.

## 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 by dolomite in southeastern 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 through this interval is the Zechman-Thomas Unit well in Harrison County, Ohio (API number 3406720737), approximately 30 miles distant. According to the geophysical logs for this well, approximately 36 ft of sand was encountered 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 ft at the Burger site. At such a depth it is possible that any porosity that may have been present has been occluded due to pressure solution effects.

The Maryville Formation mainly consists 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. Locally common are glauconite, anhydrite-filled vugs, rip-up clasts, stylolites, shaley discontinuity surfaces, scour surfaces, and bioturbation. 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. Locally common are trough cross-bedding, fining upwards sequences, anhydrite replacement clasts, shaley discontinuity surfaces, scour surfaces, bioturbation, vertical burrows, trace fossils, and intraformational breccia. 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, 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 unconformity surface (fig. 14). Within the vicinity of the Burger site, the Beekmantown dolomite is found at the unconformity surface at a depth of approximately 11,600 ft. 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 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 throughout an interval of at least 400 ft 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 the American Electric Power 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 encountered uniformly throughout the Copper Ridge. 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 ft above the base of the Knox and informally referred to as the “B” zone. This interval can be as thick as 50 ft 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 that this unit is sandy and porous in the AOR. Drilling through the potential reservoir and seal units within the Copper Ridge (and preferably coring them) would be required to further evaluate their sequestration potential at this location. Depth to the top of the Copper Ridge at the Burger site is approximately 12,300 ft.

## 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. 15).

From a regional study of cores and outcrops in Ohio and 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

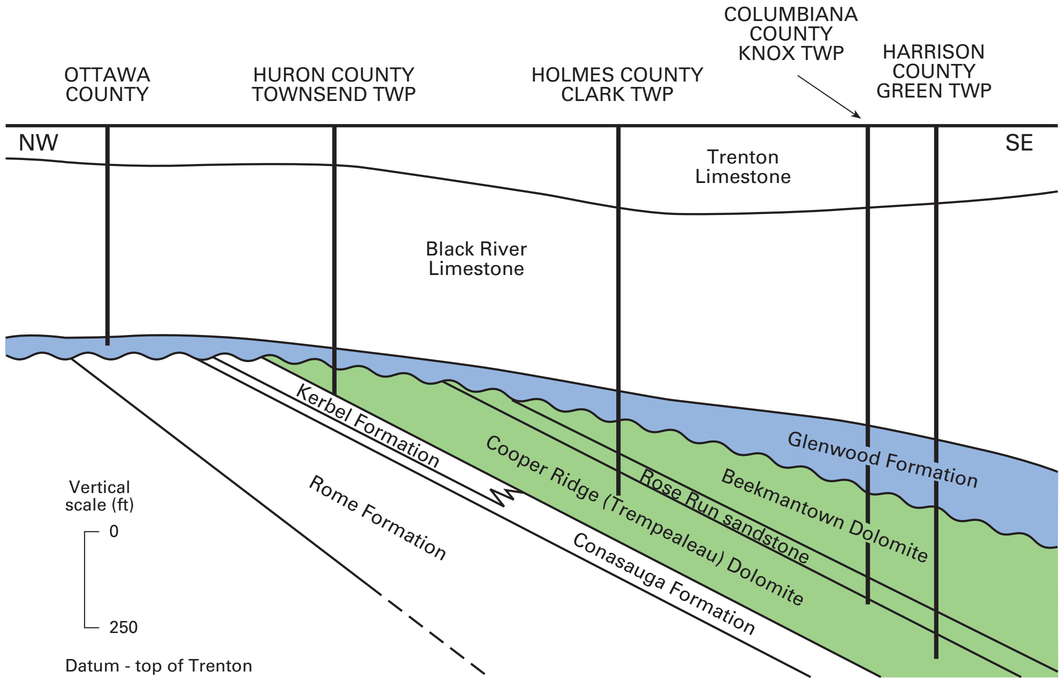


Figure 14.—Diagram illustrating the various units found at the Knox unconformity subcrop traversing from north-central to southeast Ohio.

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 a dip to the east and southeast with strike trending northeast-southwest (fig. 15). Due to a lack of wells drilled through this unit in the Burger vicinity, we cannot be certain of this unit being sandy and porous in the AOR. 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 ft.

## 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 estimated to be at a depth of approximately 11,600 ft.

## 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 drillers’ 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

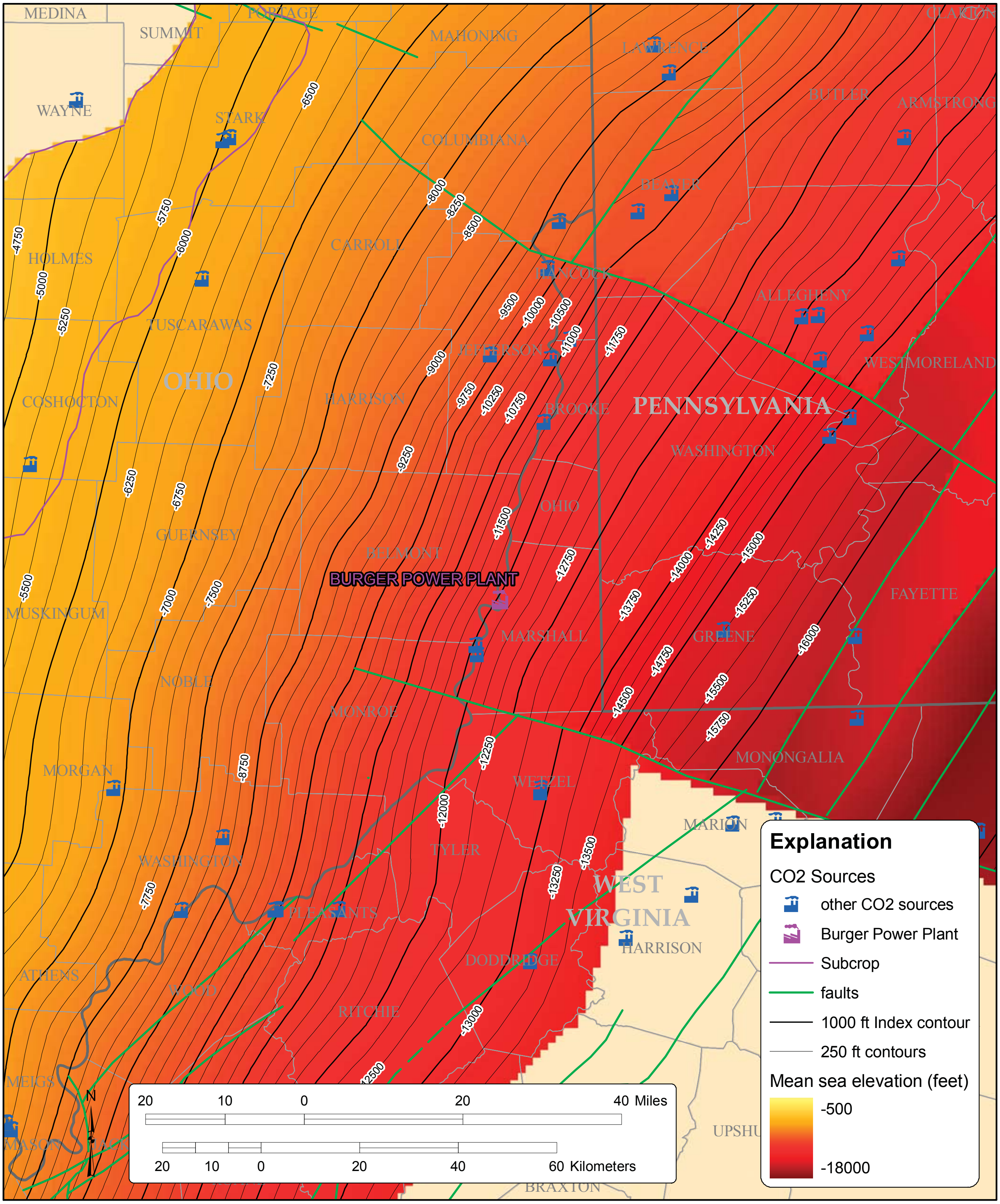


Figure 15.—Structure contour map on the top of the Rose Run Sandstone, with area of subcrop delineated. (Map elements taken from Wickstrom and others, 2005.)

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, which marks the top of the Cataract Group and is roughly equivalent to the Tuscarora Sandstone to the east, is often used as a surface to map for structure when examining the Clinton (fig. 16). The top of the Packer Shell is located 8,086 ft deep (7,396 ft below sea level) at the Burger Well.

Some deep drilling (greater than 7,000 ft) 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 the interval a reservoir, others have found the interval to be very tight at this depth.

In some areas of eastern Ohio, the total Clinton interval may reach 200 ft thick with the thickness of the Clinton and equivalents increasing eastward (fig. 17), but the effective porosity within the interval will vary widely from a few feet to more than 100 feet. The measured log porosities in the net sand intervals may range from 5 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 number 3412121890) indicate a porosity range of 2.5 to 4.7 percent and a permeability range of less than 0.1 millidarcy (md) to 423 md over a 65-ft interval. Calculated geophysical log porosity from a Belmont County well (API number 3401320485) was reported as 6.7 percent over a 48-ft 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), there are recorded average permeabilities of over 100 md, and isolated permeabilities 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.

The Burger Well geophysical log response of the Clinton is shown in figure 18. The total thickness of the Clinton interval is 200 ft. A massive siltstone and sandstone section is present in the Burger Well. This well-developed section is characterized by 45 net-ft of sandstone or siltstone with porosities greater than 5 percent, as measured by the density-porosity curve, over a 84-ft gross interval. The maximum porosity is 7.5 percent and roughly 10 net-ft of sandstone with porosities greater than 6 percent are scattered throughout the sandstone interval. Small gas shows, up to 155 units, were detected across the Clinton sandstone interval.

## 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 patch reefs, 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 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, as 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.

The depth to the Lockport at the Burger Well is 7,450 ft with a total interval thickness of 286 ft. Scattered, thin porous zones are present based on the geophysical well logs and several minor gas shows (fig. 19). According to the well site geologist, a 350-unit gas show at a depth of 7,476 ft corresponds to a 2-ft thick silty zone that crossplots at 8 percent porosity. A 190-unit gas show was detected at a depth of 7,565 ft; however, the geophysical well log response is not characteristic of a porous reservoir.

## SILURIAN SALINA GROUP

The Salina Group consists of interbedded dolomite, anhydrite, shale, and salt. These layers are laterally extensive and are subdivided into seven stratigraphic intervals (units A–G). This strata is best known for thick salt beds, which are mined mechanically underground and by solution wells in many locations within the Michigan and Appalachian Basins. In Ohio, the thickest accumulations of salt occur in units B, D, E, and F. Although present-day salt formation is limited to shallow, restricted marine environments, most investigators agree that Salina salt beds formed in relatively deep, restricted marine basins with density-layering conditions caused by salinity variations (Clifford, 1973).

The Burger Well penetrated the Salina Group from a depth of 6,369 to 7,450 ft. A total of 185 ft of salt was encountered in units D, E, and F. The thickest salt accumulation is correlated to the $F_4$ bed and is represented on the geophysical well log as a 91-ft washout zone. A sidewall core of dolomite was collected at a depth of 6,500 ft and a sidewall core of anhydrite was collected at a depth of 6,450 ft. Gas shows of 440 and 445 units were detected in the lower section of unit F at depths of 6,805 and 6,905 ft, respectively (fig. 20). These gas shows are associated with thinly bedded dolomites, which are very finely crystalline and occasionally vuggy. Based on geophysical well log responses and mudlog information, the most promising injection target within the Salina is the 6,900 to 6,936-ft interval.

## 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.

The depth to the Bass Islands in the Burger Well is 6,295 ft with an interval thickness of 73 ft. Based on sidewall cores, borehole cuttings, and geophysical well logs, the dominant lithology of this interval is limestone. A sidewall core was collected at a depth of

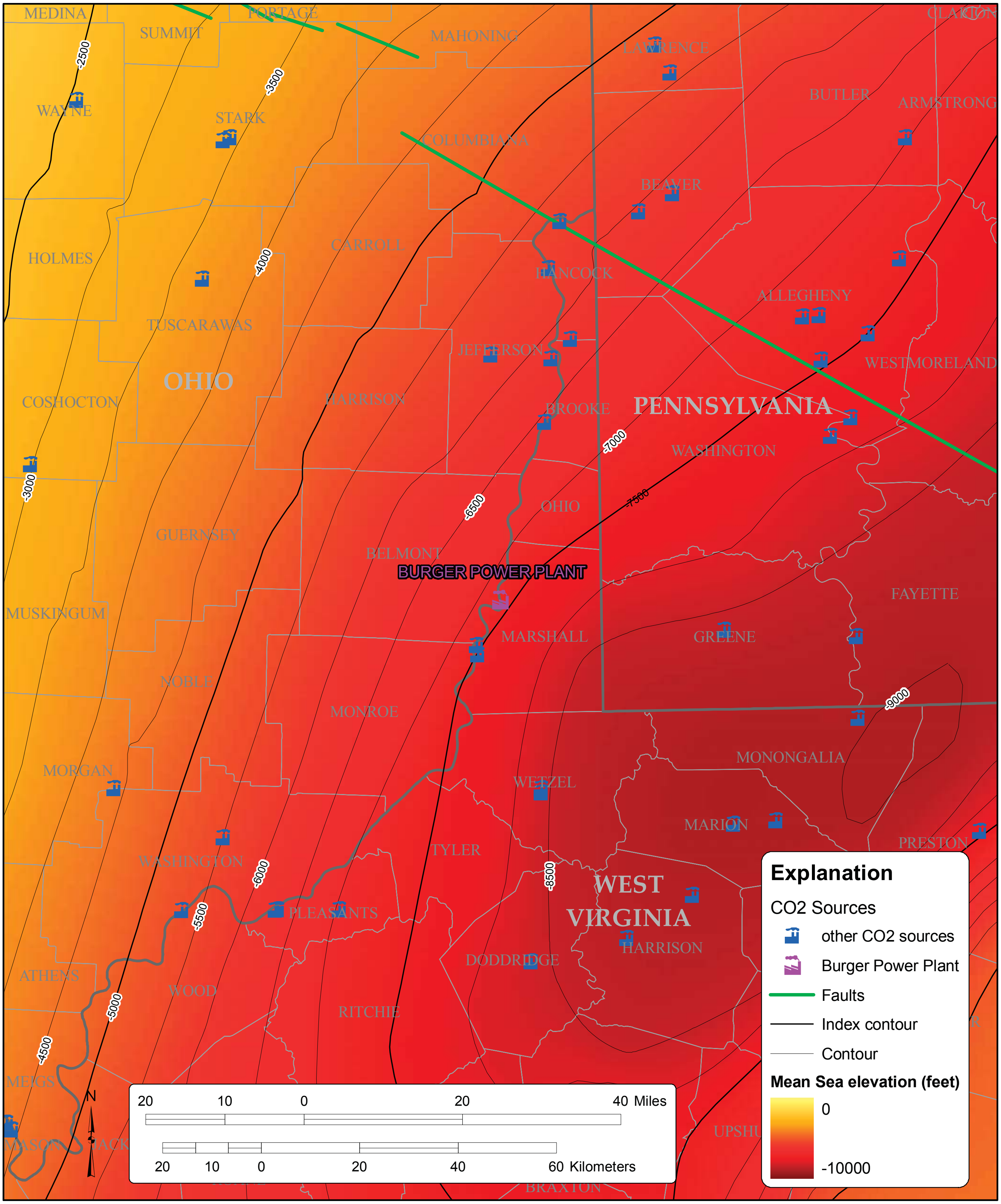


Figure 16.—Structure contour map on the top of the Tuscarora Sandstone and equivalents within the Ohio, Pennsylvania, and West Virginia region. Also shown is the location of major (>100,000 tons per year) point sources of $CO_2$. (Map elements taken from Wickstrom and others, 2005.)

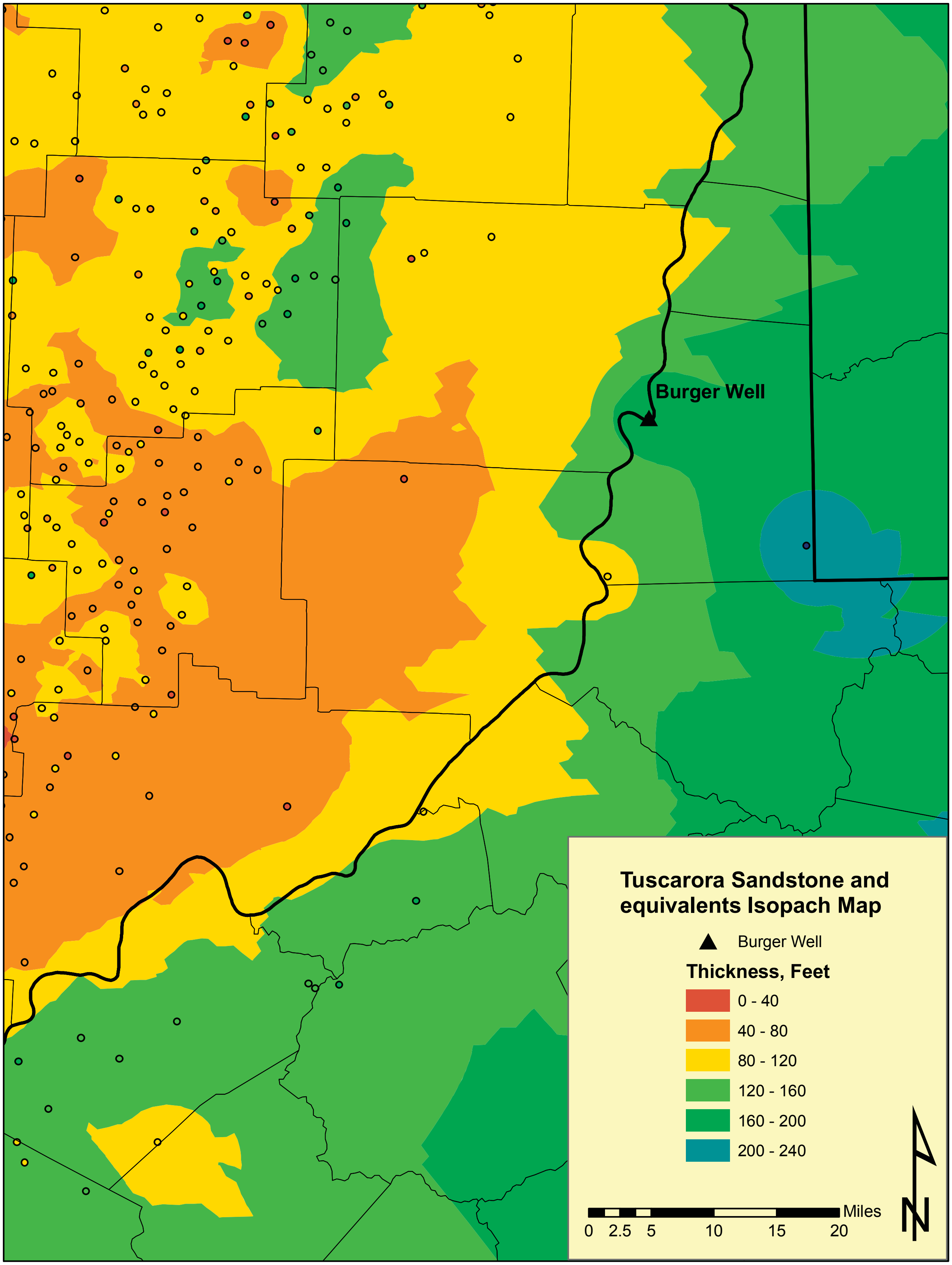


Figure 17.—Isopach (thickness) map of the Tuscarora Sandstone and equivalents within the Ohio, Pennsylvania, and West Virginia region. Also shown is the location of major (>100,000 tons per year) point sources of $CO_2$.

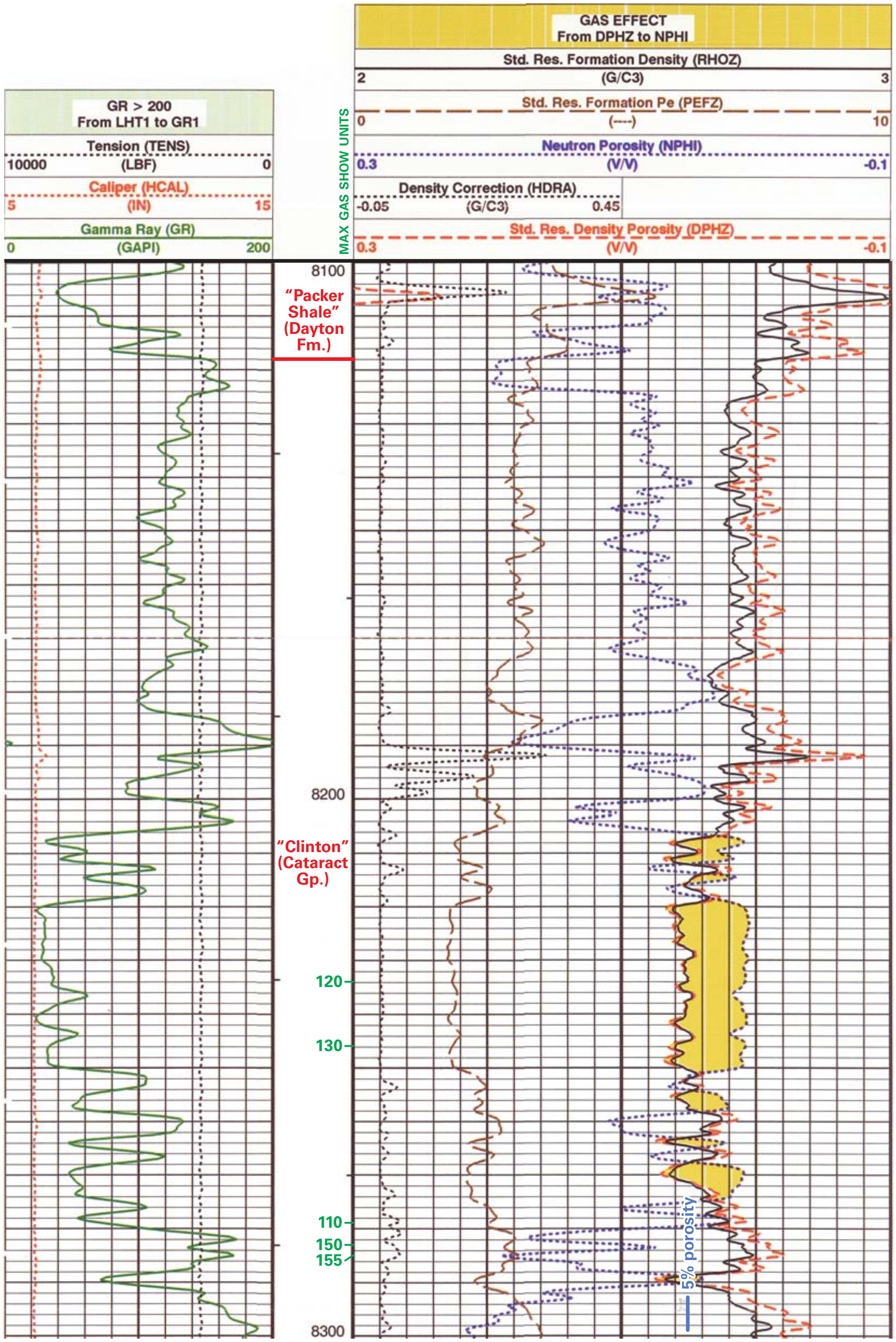


Figure 18.—Geophysical log response of the "Clinton" sandstones and gas shows from the Burger Well (API number 3401320586).

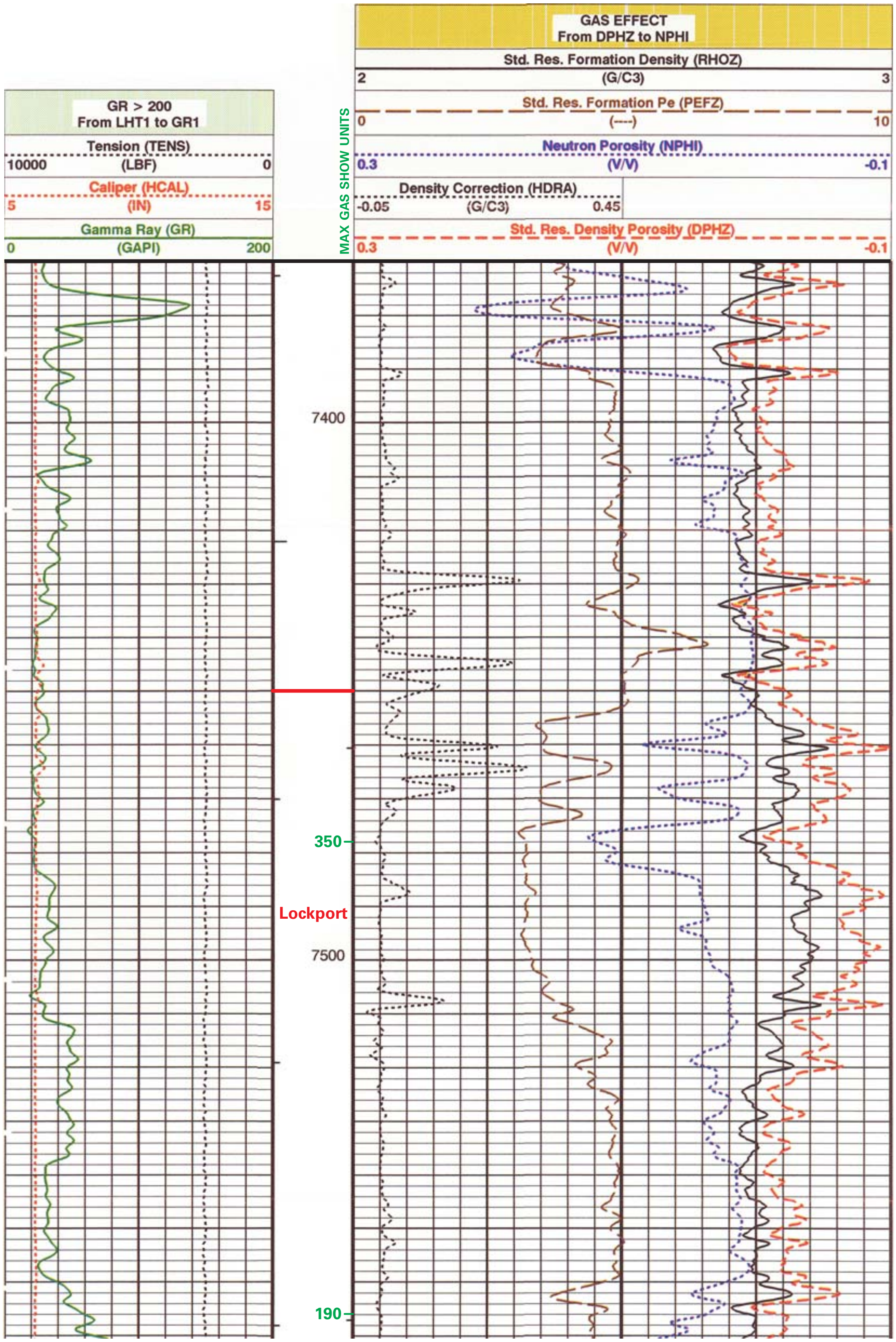


Figure 19.—Geophysical log response of the Lockport interval exhibiting gas shows from the Burger Well (API number 3401320586).

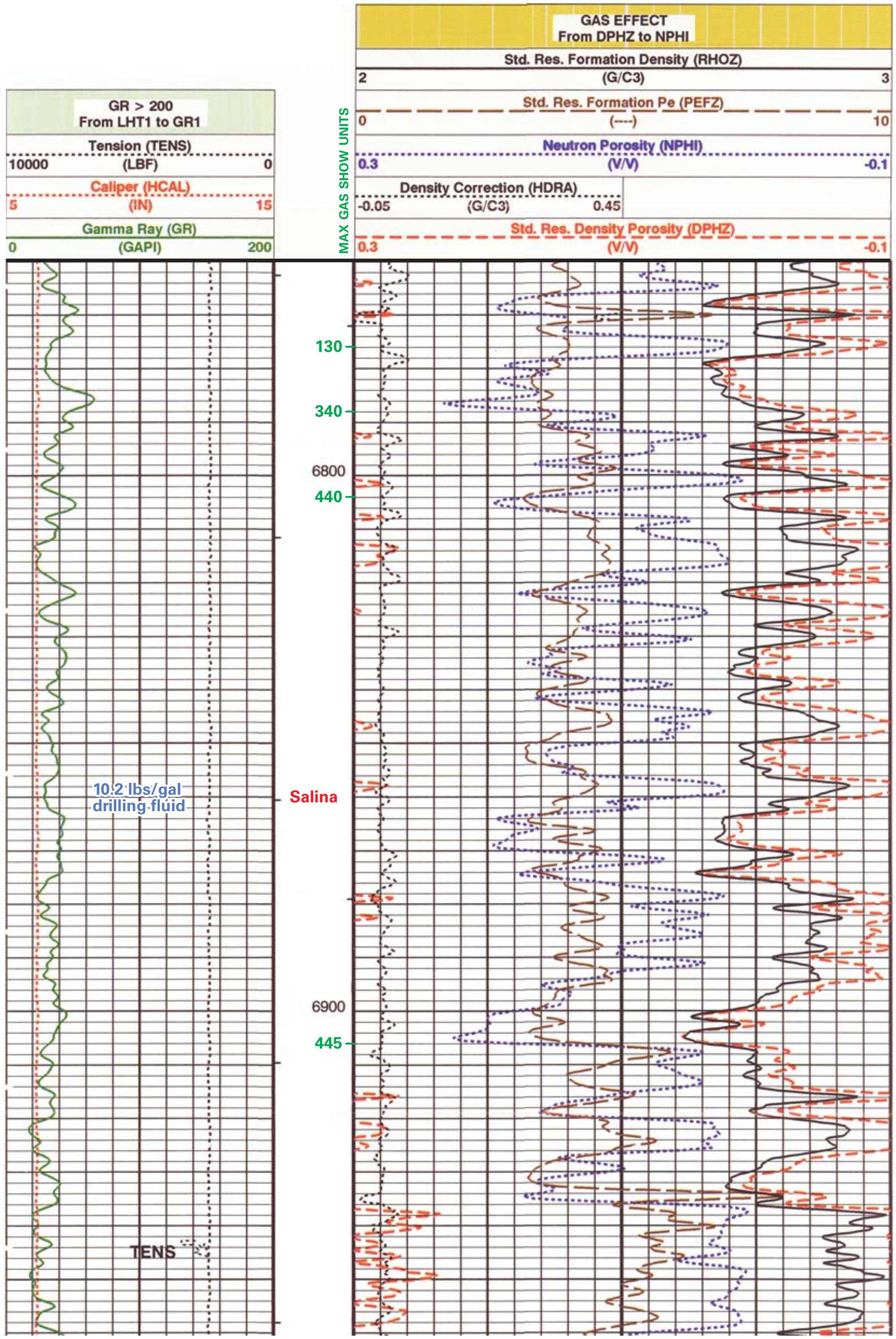


Figure 20.—Geophysical log response of the Salina interval exhibiting gas shows from the Burger Well (API number 3401320586).

6,350 ft. Some anhydrite is present and the lower section contains chert. A minor 76-unit gas show was detected at a depth of 6,300 ft, apparently from a low porosity limestone at a limestone-anhydrite bed boundary (fig. 21).

## 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 in 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 much of eastern Ohio, but sand thickness steadily increases to the southeast (figs. 22, 23). 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 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 of 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 approximately 20 gallons per minute at an intake pressure of 1,400 psi during the initial investigation stage (Pennsylvania Geological Survey, written comm.). The Oriskany in this well ranged from 5,250 to 5,426 ft. Average porosity and permeability were 5.2 percent and 2.2 md, respectively (Wickstrom and others, 2005).

The depth to the Oriskany Sandstone at the Burger Well is 5,921 ft with a total interval thickness of 33 ft (fig. 24). Based on well cuttings, the sandstone coarsens upward. The density-porosity log response shows a gradual increase in porosity from 3 to 7 percent throughout the interval. Four sidewall cores were collected from this interval at depths of 5,926; 5,935; 5,945; and 5,955 ft. A minor 15-unit gas show was detected at a depth of 5,928 ft.

## DEVONIAN HAMILTON GROUP AND WEST FALLS FORMATION

The Hamilton Group and West Falls Formation consist of dark to very dark grayish-brown, calcareous, organic-rich shale with traces of pyrite. These shales were deposited at the onset of the Acadian Orogeny in a partially restricted marine basin. The sediment source was the prograding Catskill Delta to the east; these units pinch out westward due to non-deposition upon a positive Cincinnati Arch (Roen and Walker, 1996). The basal unit of the Hamilton Group is the Middle Devonian Marcellus Shale, a transgressive black shale tongue. The Marcellus Shale is very fissile and is characterized by high natural radioactivity and low density. Core analysis of the Marcellus shale in Monongalia County, West Virginia, indicated high gas permeabilties (5 to 50 md) and gas storage capacity up to 26 Mcf (Randolph and Soeder, 1986). Disconformably overlying the Hamilton Group in the vicinity of the Burger site is the Rhinestreet Shale Member of the West Falls Formation. The Rhinestreet Member is another transgressive black shale tongue with similar characteristics to the Marcellus Shale. Gas production occurs from both the Marcellus and Rhinestreet Shales.

Drilling through the Hamilton Group is often problematic. Lost circulation due to the incompetent, fluid-sensitive shales of this interval is commonly reported. Also, the Hamilton is underpressured in this region, adding to drilling difficulties. These same characteristics also make the Hamilton a possible injection reservoir.

The depth to the Hamilton Group at the Burger Well is 5,583 ft (fig. 25). Numerous gas shows as high as 1,200 units were encountered while drilling through the 34-ft thick Marcellus Shale. Gas shows as high as 180 units were observed from the 20-ft thick Rhinestreet Shale Member of the West Falls Formation. The gas shows were short-lived and background gas concentrations returned once the individual black shale tongues were penetrated. One sidewall core was collected from the Hamilton Group at a depth of 5,616 ft.

# SIGNIFICANT OIL AND GAS HORIZONS

Carbon dioxide-assisted enhanced oil recovery 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 remaining 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 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, however, $CO_2$-assisted EOR may become an established practice in the region.

Carbon dioxide-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 ft or greater. Miscible flooding projects are more efficient at sweeping residual oil from reservoirs and can sequester much larger volumes of $CO_2$ than immiscible projects. Immiscible

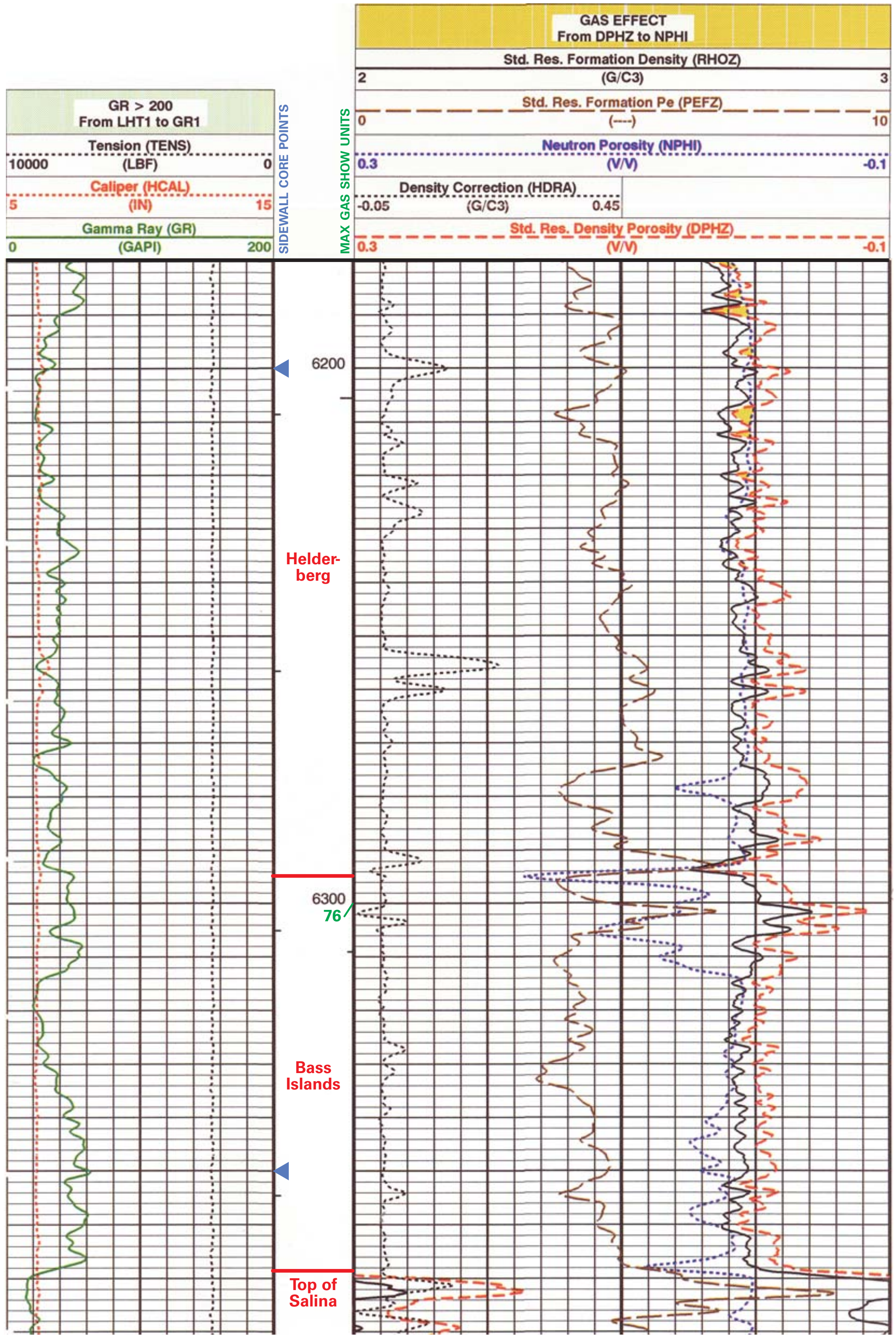


Figure 21.—Geophysical log response of the Bass Islands Dolomite from the Burger Well (API number 3401320586). Note the locations of sidewall cores and a minor gas show.

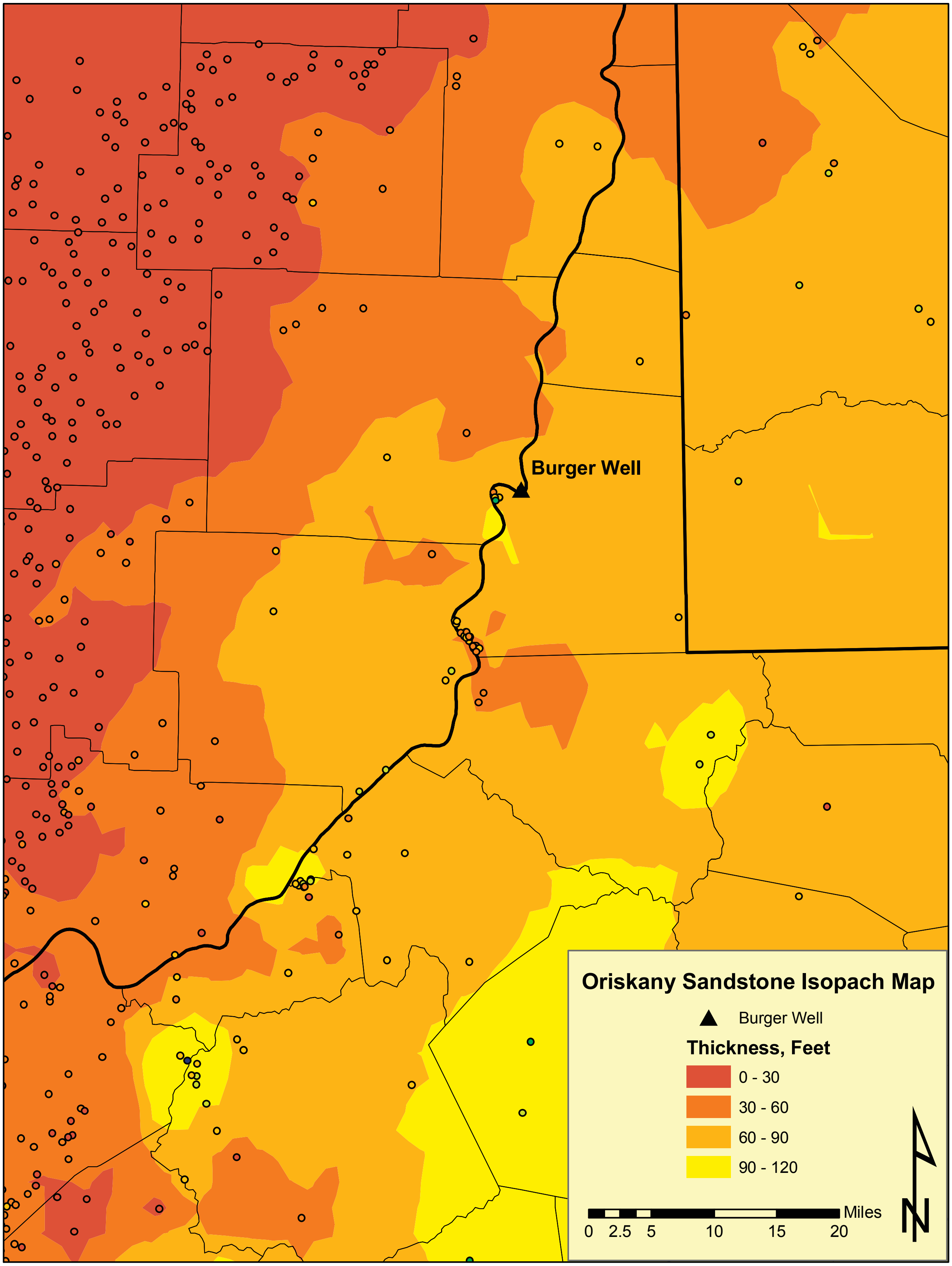


Figure 22.—Isopach (thickness) map of the Oriskany Sandstone within the Ohio, Pennsylvania, and West Virginia region. Also shown is the location of major (>100,000 tons per year) point sources of $CO_2$.

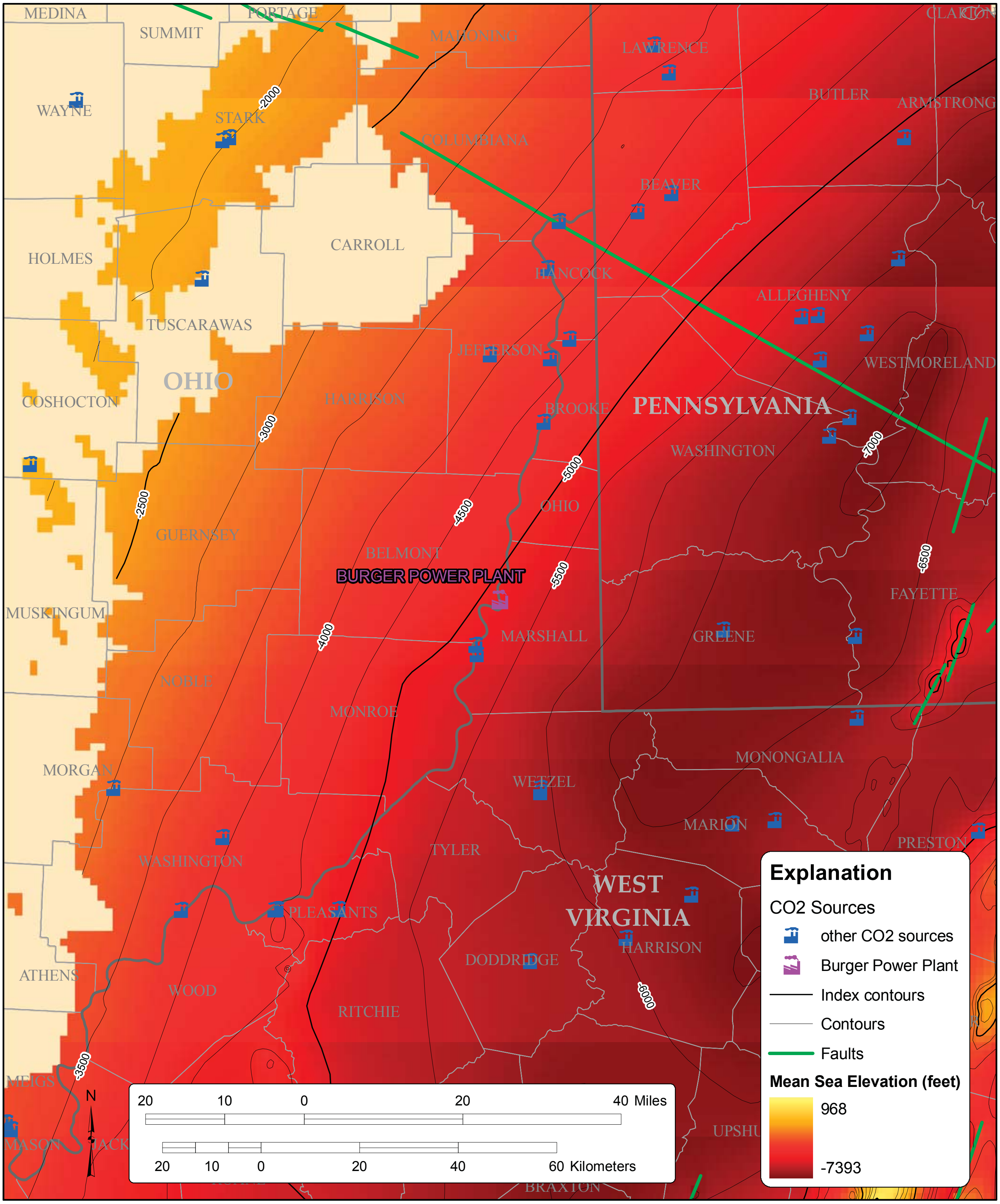


Figure 23.—Structure contour map on the top of the Oriskany Sandstone within the Ohio, Pennsylvania, and West Virginia region. Also shown is the location of major (>100,000 tons per year) point sources of CO2. (Map elements taken from Wickstrom and others, 2005.)

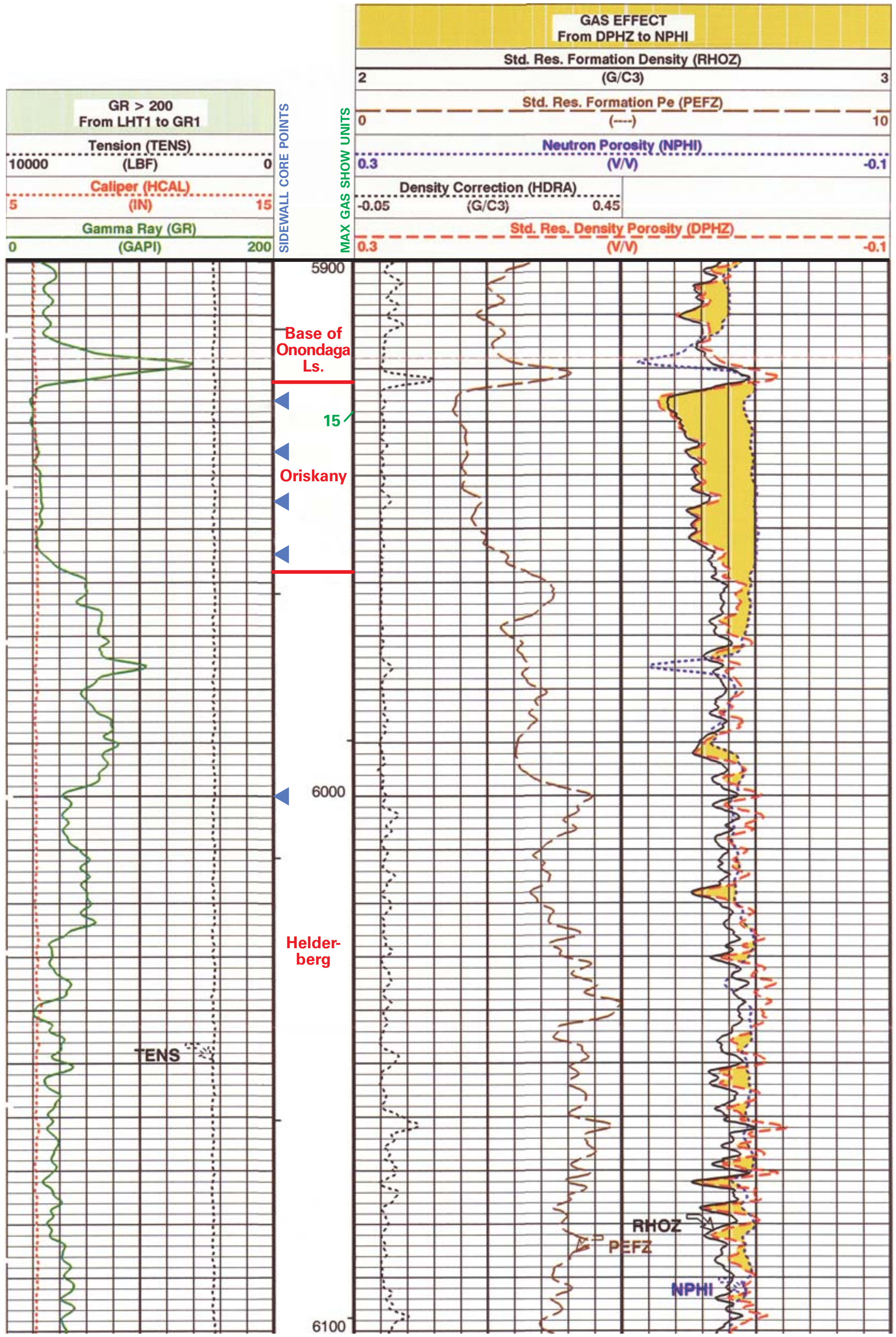


Figure 24.—Geophysical log response of the Oriskany Sandstone from the Burger Well (API number 3401320586). Note the locations of sidewall cores and a minor gas show.

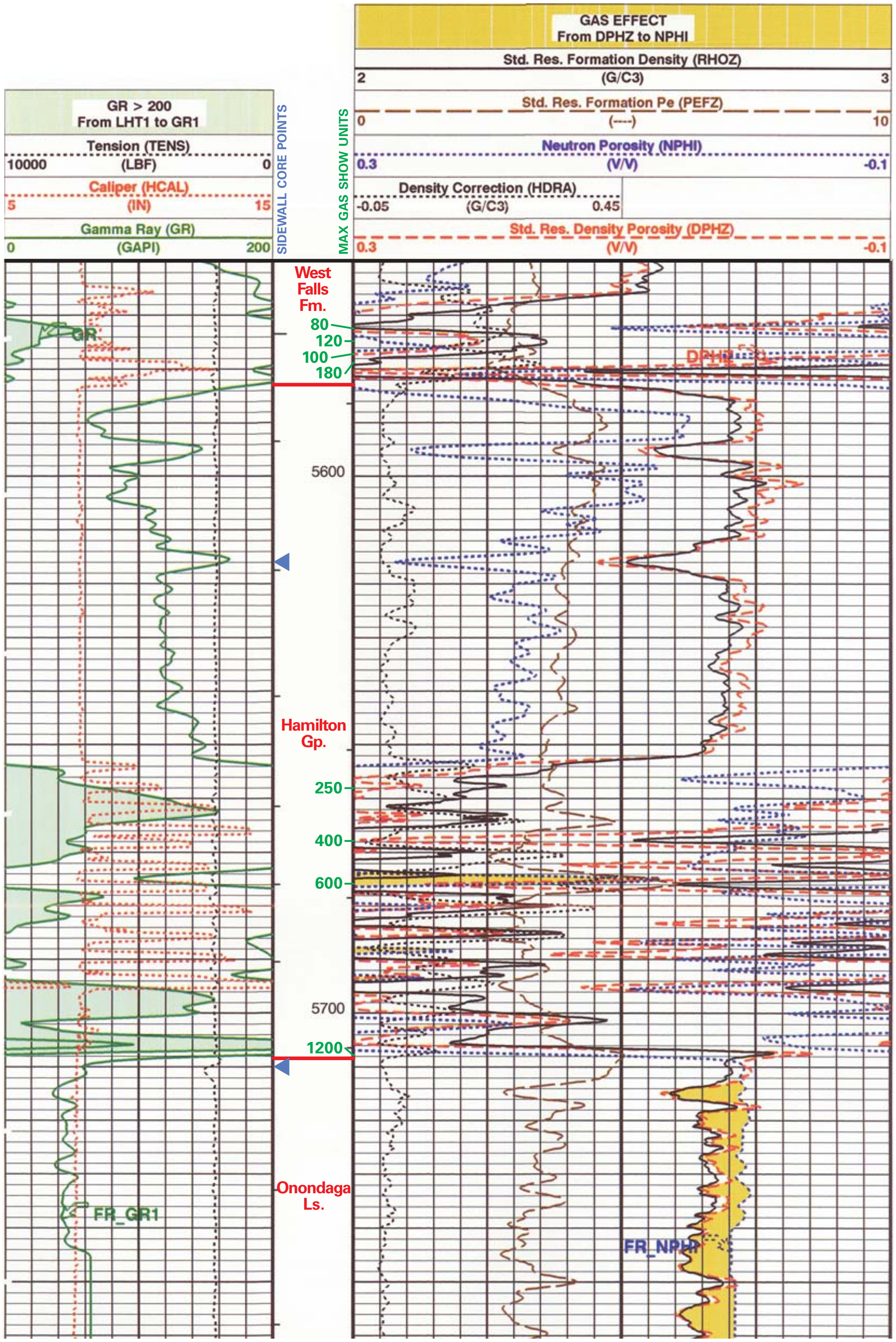


Figure 25.—Geophysical log response of the Hamilton Group and lower West Falls Formation from the Burger Well (API number 3401320586). Note the locations of sidewall cores and multiple strong gas shows.

projects are technically feasible for recovering additional oil, but the ultimate fate of injected $CO_2$ is less certain and would be of lower volume than in miscible projects; therefore, immiscible EOR is not under consideration by the MRCSP for sequestration projects.

For many decades, extensive mining of shallow coal resources and the ownership of oil and gas lease rights have prevented most oil and gas exploration on a large swath of land along the Ohio River near the Burger site. 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 in figure 26, there is a large area near the Burger site with relatively few oil-and-gas fields deeper than 2,500 ft, as compared to surrounding regions. Miscible EOR operations using $CO_2$ from the Burger plant will require transporting $CO_2$ out of the area with few oil-and-gas fields.

The sub-sections below describe, by stratigraphic unit, the oil fields with significant miscible EOR potential that are in close proximity to the Burger site. Approximately 67 known oil-and-gas fields occur within the AOR and many of these produce hydrocarbons from multiple geologic horizons (fig. 27; Appendix C). Producing depths range from 800 to 7,300 ft, although most production has been shallow.

Three natural gas storage fields are also found within the AOR (fig. 28). The Majorsville-Heard gas field of Marshall County, West Virginia and Greene County, Pennsylvania was activated in 1943 for gas storage in the Mississippian "Big Injun" sandstone (at a depth of 1,640 ft) and the Devonian siltstones and sandstones (at a depth of 2,700 ft) (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 Formation (at a depth of 2,040 ft) and Mississippian Big Injun sandstone (at a depth of 2,300 ft), 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.

Detailed descriptions of many potential oil and gas plays in the AOR are present in Roen and Walker (1996). Oil and gas plays deeper than the Lower Silurian are not discussed herein, mainly because the closest 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, there is potential for deep hydrocarbon production to be discovered in the area from the Trenton Limestone, Black River Limestone, St. Peter Sandstone, Knox Group and/or the Conasauga Group. The following oil and gas plays are discussed for the AOR:

## LOWER SILURIAN "CLINTON-MEDINA"/ TUSCARORA SANDSTONE

Since the 1970s, the oil-and-gas horizon containing "Clinton-Medina" sandstone has been the most drilled horizon in Ohio. Ohio has 186 Clinton-Medina sandstone fields with approximately 60,000 wells that have produced over 5 trillion cubic feet (tcf) of gas (McCormac and others, 1996), yet no Clinton/Tuscarora pools or fields are present within the 20-mile radius AOR. Hydrocarbon production (initial production reported at 100 mcfg, 1 bo, and 2 bw) from the Clinton/Tuscarora sandstone was reported from one well located 19 miles northeast of the Burger site (API number 3401320485). Production history for this well is unknown.

Figure 29 shows the stratigraphic correlations using geophysical well logs of the Clinton-Medina sandstones across southeastern Ohio. The density logs in figure 29 illustrate an increase 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 reliant on natural fractures and hydrofracing for economic gas production. It might be necessary to hydrofrac the unit to open sufficient permeability for injection operations; however, it is unclear if artificial fracturing will be allowable in $CO_2$ injection wells in the region, as permit requirements are currently under study by the U.S. EPA.

## 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) describe a typical producing Lockport patch reef, imaged with seismic reflection data. This under-explored deeper formation of the Appalachian Basin warrants examination with 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 (fig. 27). This well pool was discovered in 2001 and produces at a depth of 7,350 ft. 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 southwest of the Burger Power Plant site. Core analyses (from API number 3412121561 well) 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-ft 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, 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. Geophysical log density ranges from 2.60 to 2.70 g/cc for wells within the AOR over a 10 to 100-ft interval thickness. A density porosity electric log from a well 8 miles northwest of the Burger Power Plant site (API number 3401320553) indicates an Oriskany zone 12 ft thick with an uncorrected 6 to 8 percent porosity.

The Oriskany Sandstone in the Burger Well is a coarsening upwards interval with a net sandstone thickness of 33 ft and an uncorrected porosity up to 7 percent (fig. 24). 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 injection analysis within the Burger Well.

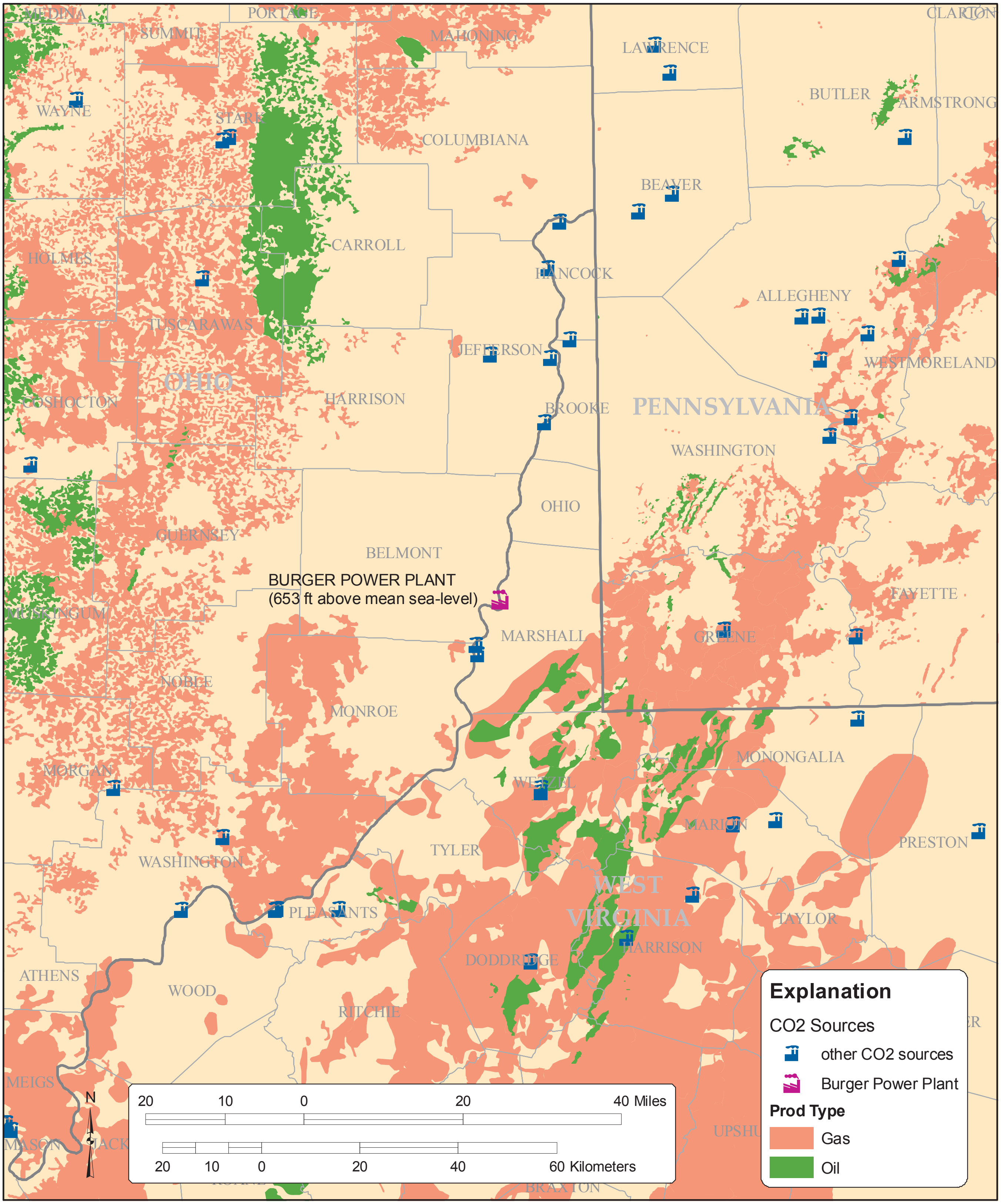


Figure 26.—Map showing the locations of oil and gas fields producing from depths greater than 2,500 feet within the Ohio, Pennsylvania, and West Virginia region.

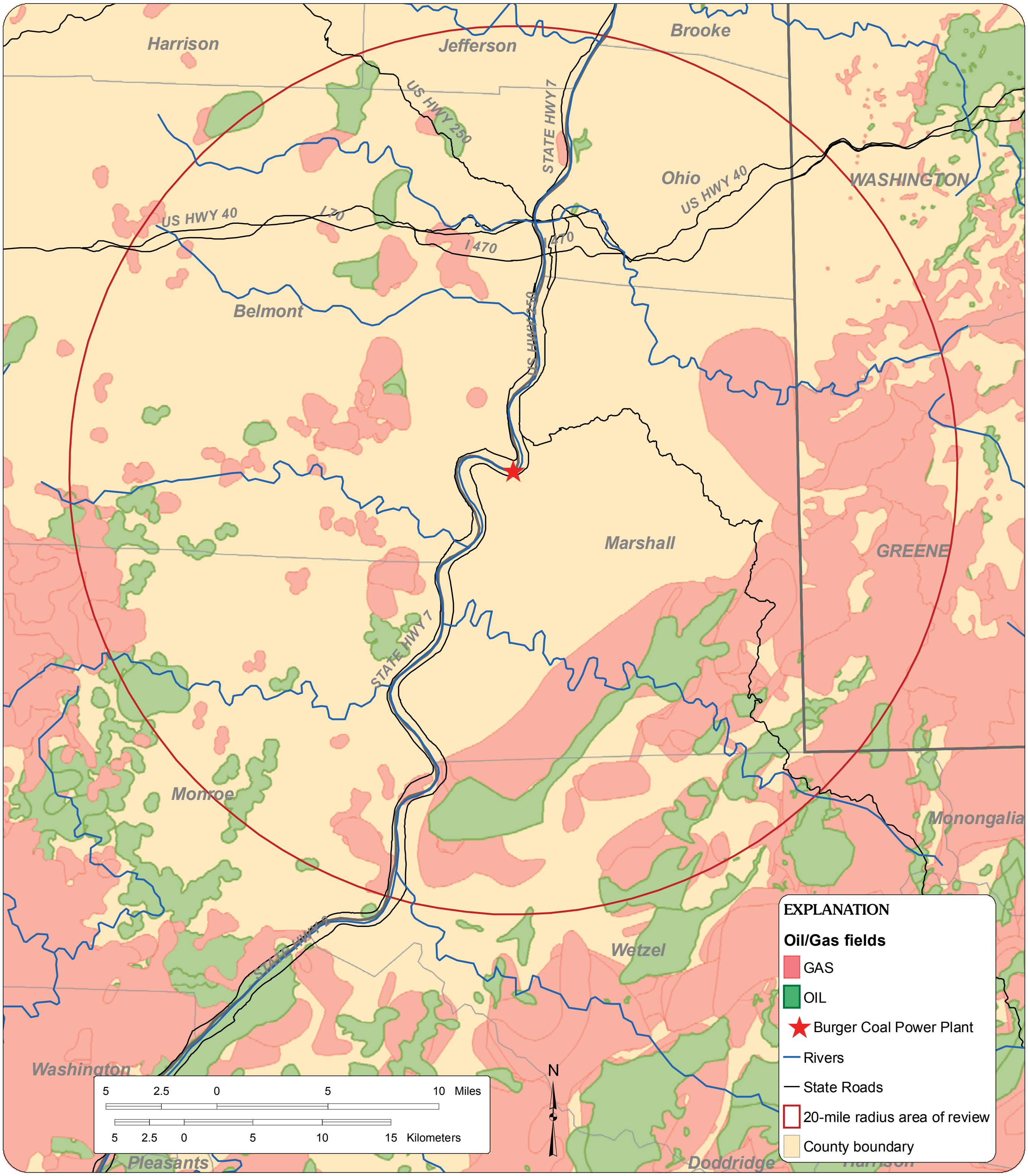


Figure 27.—Map showing the locations of all oil and gas fields within the Burger site AOR.

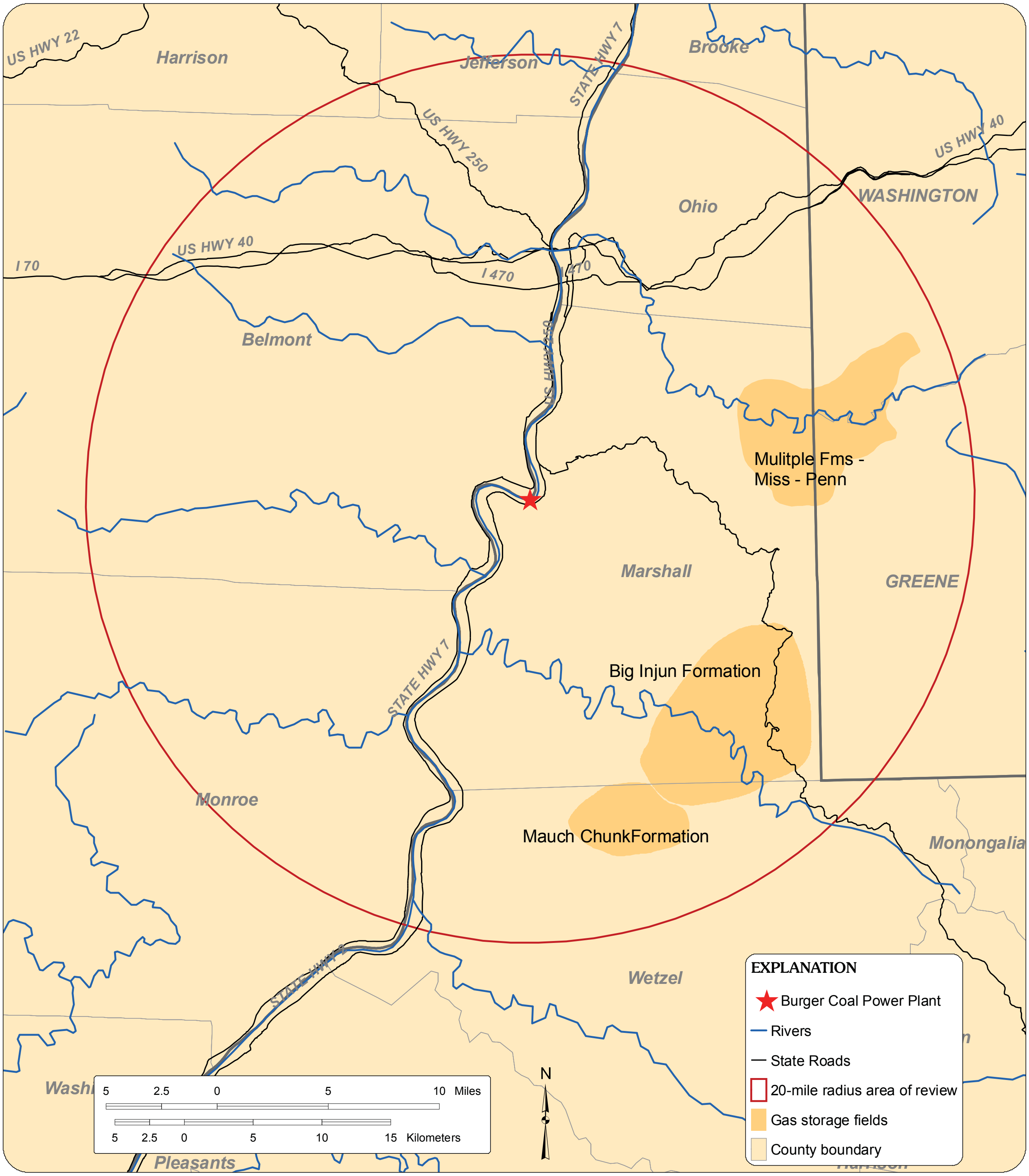


Figure 28.—Map showing the locations of natural gas storage fields within the Burger AOR.

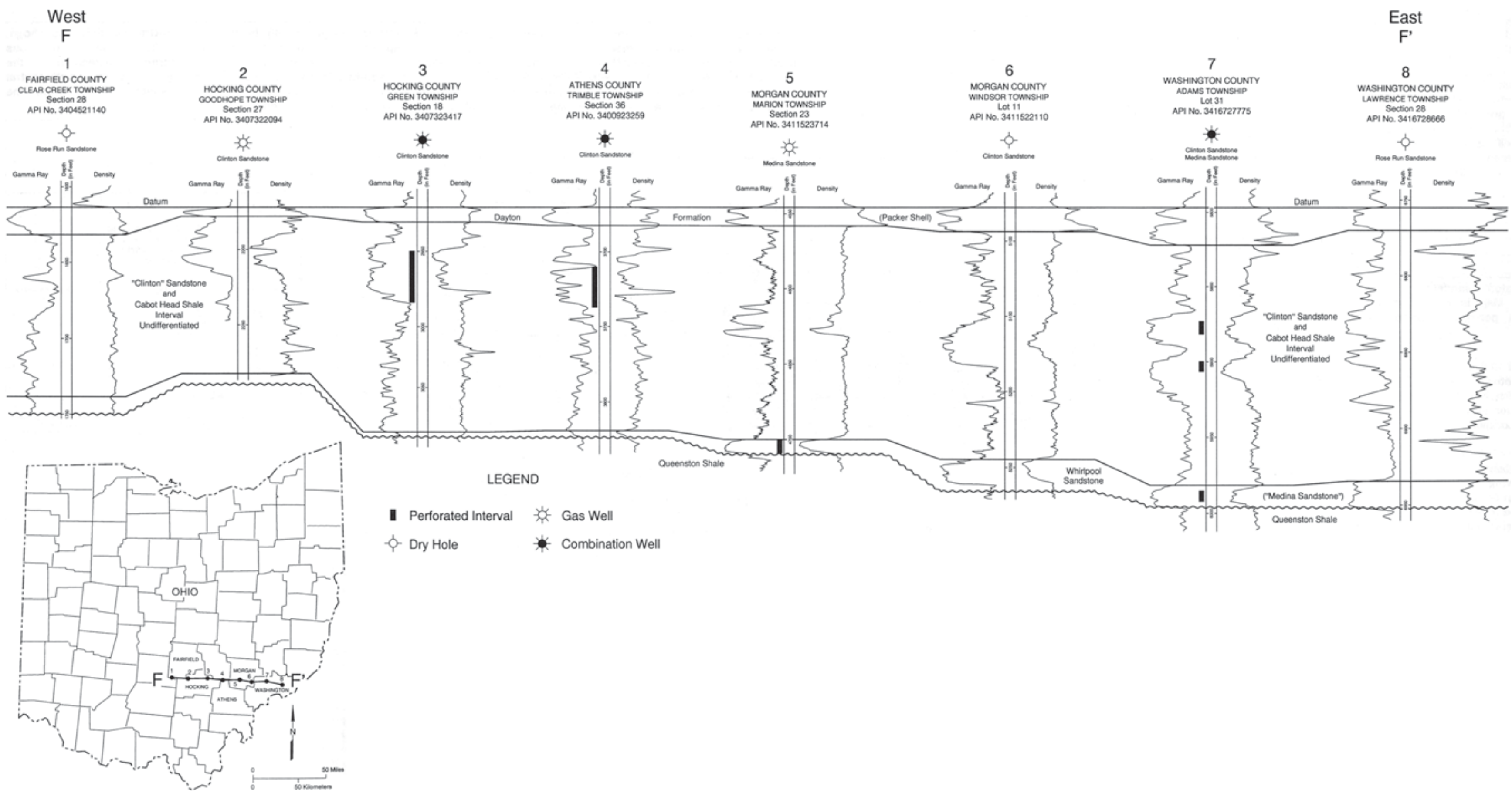


Figure 29.—Stratigraphic cross section showing the Lower Silurian "Clinton-Medina" sandstone geophysical well log correlations across Sugar Grove and Sharon fields of southeastern Ohio (modified from McCormac and others, 1996).

## UPPER DEVONIAN SILTSTONES AND SANDSTONES

Hydrocarbon production from Appalachian Basin Upper Devonian siltstones and sandstones, including significant volumes of oil, began in 1859 with cumulative production estimated at approximately 20 Tcf (Boswell, 1996) (fig. 30). Fields productive from both Devonian siltstone and sandstone reservoirs are known within the AOR (fig. 30) by such drillers' names as "Fifth Sand," "Thirty-Foot," "Gordon," and "Gantz" (these units are found in the Chagrin Shale interval shown in fig. 3). The dominant productive area is more than 10 miles southeast of the 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 at this site are at an average depth of 2,570 ft (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 extent, thickness, porosity and permeability of these siltstones vary laterally and are poorly defined in the vicinity of the Burger Power Plant site. Several Chagrin siltstone units were encountered in the Burger Well at depths ranging from 2,250 to 2,850 ft. Twelve feet of net siltstone with a neutron porosity greater than 6 percent was present in the lowermost siltstone unit (2,804–2,834 ft). A total of 12 sidewall cores were collected from the Devonian shales; two of these cores were from the Chagrin Formation.

## LOWER DEVONIAN BEREA SANDSTONE

In the Appalachian Basin, 151 productive fields have been discovered in the Berea Sandstone and its equivalents with an estimated cumulative production of 1.9 Tcf (Tomastik, 1997). The Berea Sandstone produces from 17 pools within the AOR (fig. 31). The nearest reservoir data for the Berea are from a site approximately 30 miles to the north-northwest of the Burger site and indicate a porosity range of 10.1 to 15.4 percent and permeability range of less than 0.1 md to 2.7 md over a 6-ft interval (core analyses from API number 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 in the Burger Well is 1,822 ft with a thickness of 28 ft and 3 ft of net sandstone. Within the AOR, Berea sandstone thickness ranges from less than 10 ft to 20 ft, and porosity determined from geophysical logs 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 limestones and sandstones is present in the AOR (fig. 32). The Greenbrier/Newman limestones ("Big Lime" from driller terminology in Pennsylvania and West Virginia; Maxville Limestone of Ohio) 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 in this report only to partially explain the large number of shallow penetrations in the area. Depth to the Lower and Upper Mississippian sandstones and 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 Mcf, the cumulative production for the Allegheny Group in the Appalachian Basin is estimated at 181 Bcf (Hohn, 1996).

Pottsville Group sandstones have produced hydrocarbons since the late 1800s 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 33 shows the current and historical production areas from both the Pennsylvanian Allegheny and Pottsville Groups in the AOR. These reservoirs are mentioned in this report 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 in about 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 for production. 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 Burger site that may have sufficient thickness (greater than 12 inches) and depth (greater than 500 ft) for consideration as testing targets for enhanced recovery of methane by $CO_2$ injection. Three of these coals, the No. 6, No. 5, and No. 4, were encountered in the Burger Well. The No. 6 coal occurs at a depth of 810 ft below the surface and ranges from 24 to 42 inches thick. The No. 5 and No. 4 coals occur at 50 and 90 ft, respectively, below the No. 6 coal and range from 12 to 36 inches thick. Additional coals occur at depths of 924; 963; and 1,012 ft with thicknesses in the 12 to 48 inch range. 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. 34), especially below the No. 4 coal. Hence, predicting or even anticipating exact lithologic content in this part of the geologic section, especially for coal beds only a few feet thick (and for a single pilot-project well) is uncertain given the next 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; however, using conservatively low gas-content values, the DGS estimates the state's producible CBM reserves at

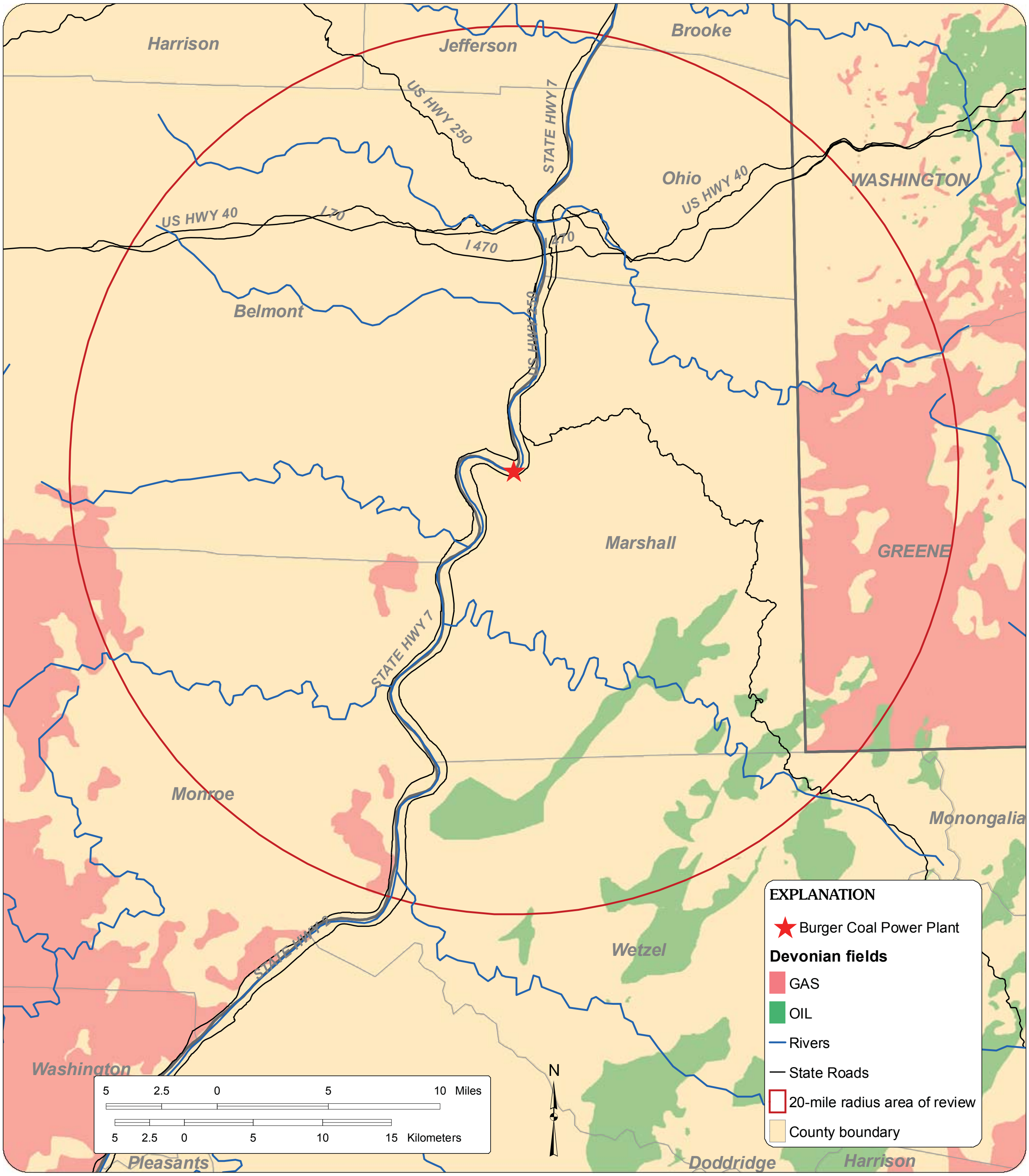


Figure 30.—Map showing the locations of oil and gas fields producing from the Devonian Shales and upper Devonian siltstones and sandstones within the Burger site AOR.

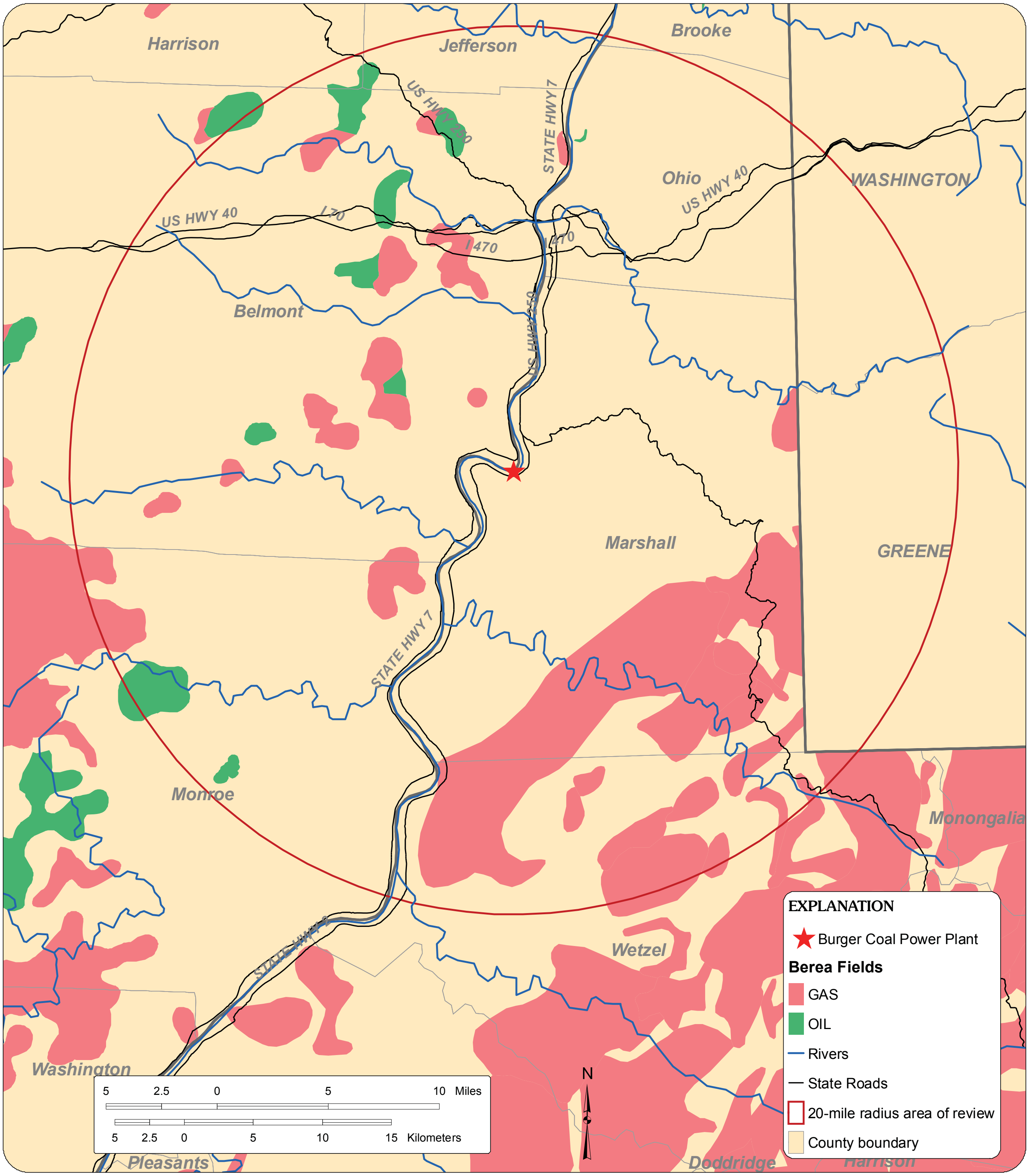


Figure 31.—Map showing the locations of oil and gas fields producing from the lower Devonian Berea Sandstone within the Burger site AOR.

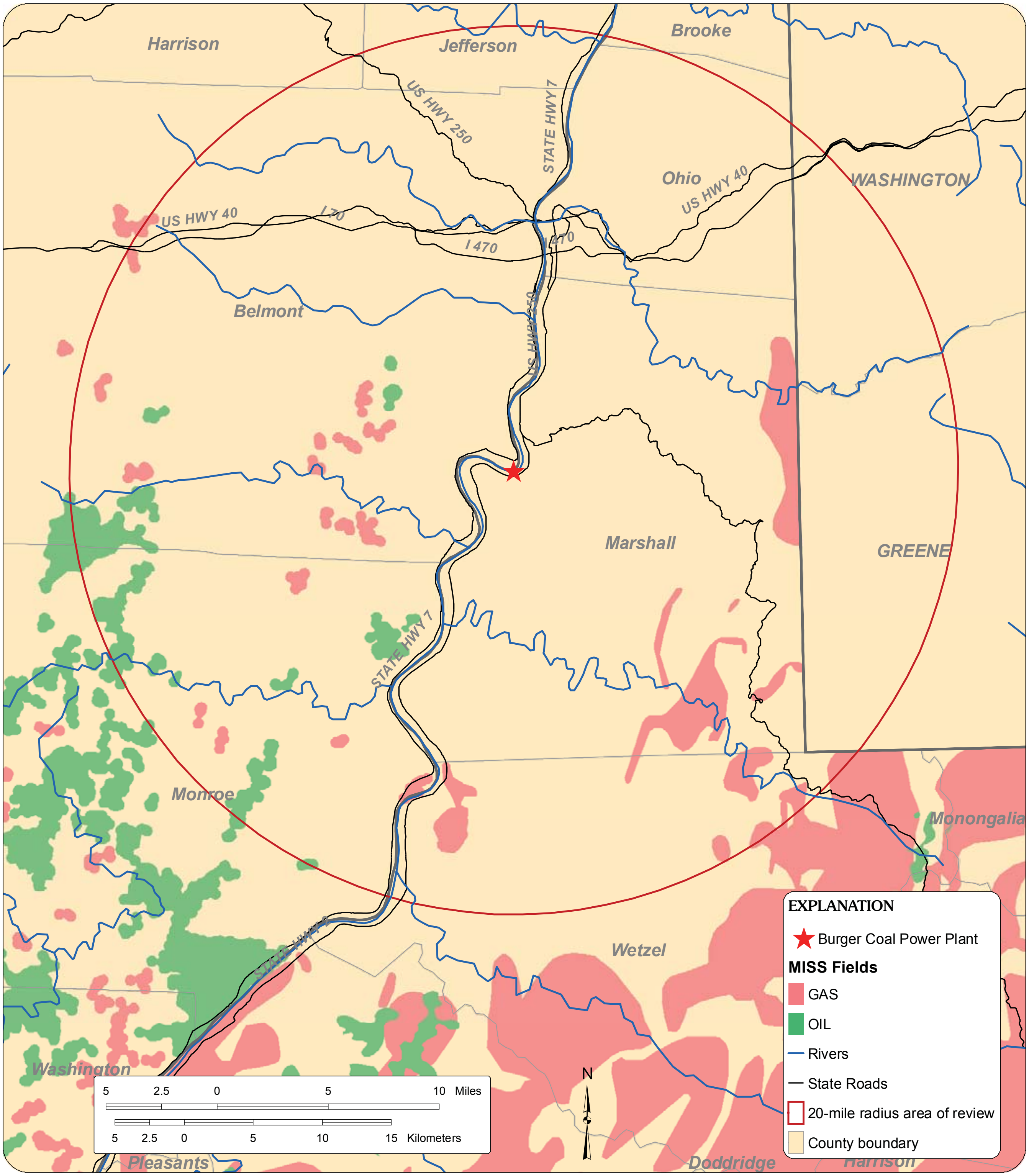


Figure 32.—Map showing the locations of oil and gas fields producing from the Mississippian limestones and sandstones within the Burger site AOR.

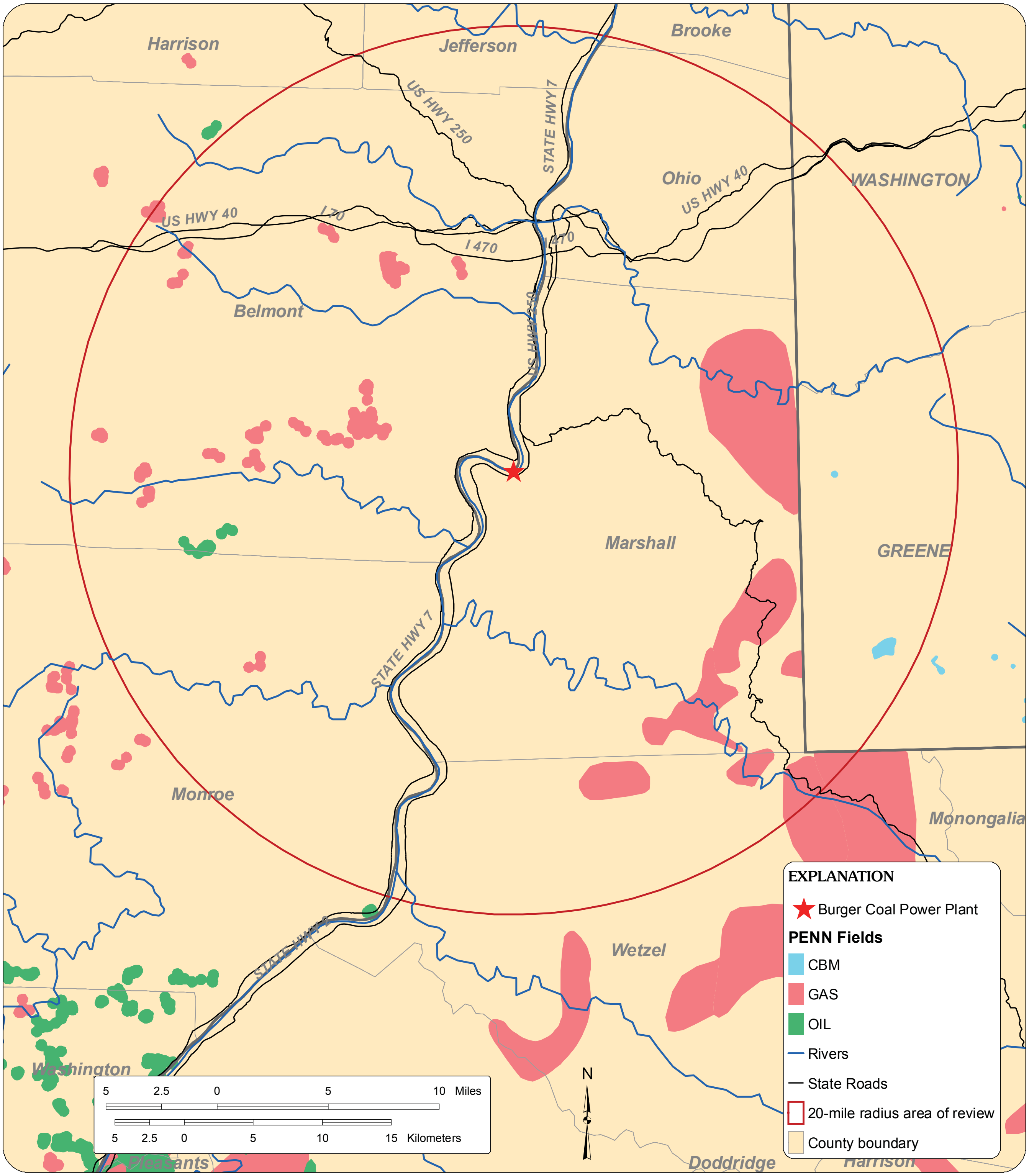


Figure 33.—Map showing the locations of oil and gas fields producing from the Pennsylvanian sandstones within the Burger site AOR.

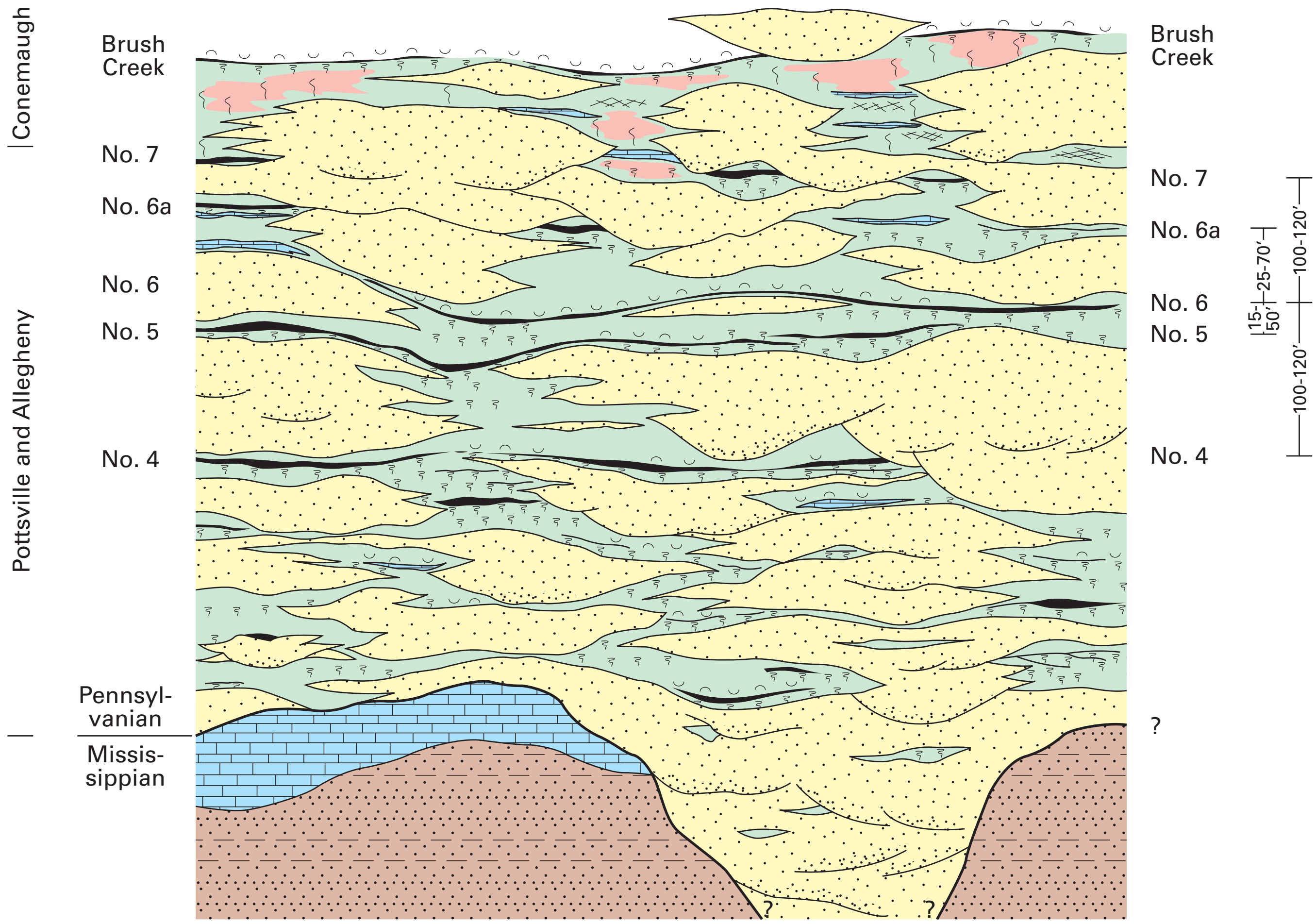


Figure 34.—Schematic cross section of coal-bearing strata near the Burger site illustrating the discontinuous nature of the units and lithologies. Numbered units refer to the numbered coals of Ohio. Right-hand column numbers give approximate distance between key coal beds. Surface elevation at the site is approximately 670 ft. The main coal mined near the site is the No. 8 (Pittsburgh), which is found at an approximate elevation of 480 ft above sea level. The base of the Conemaugh Group (shown in illustration) is approximately 520 ft below the No. 8 coal.

2–5 trillion cubic feet of methane. Although there is 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. 33).

## CARBONACEOUS SHALES

The Burger AOR also contains widespread, thick deposits of carbonaceous shales. These shales are often multifunctional, acting as seals for underlying reservoirs, source rocks for oil-and-gas reservoirs, and unconventional gas reservoirs themselves. Both the Ordovician shale and the Devonian shale intervals below the site contain thick sequences of organic shale; however, only the Devonian Shale interval is within the range of economic drilling depths for this site, which is less than 9,000 ft. 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. 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 benefit, 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 production is present within the AOR (fig. 30). 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 siltstone units in this portion of the Appalachian Basin very difficult. However, most of the production in this portion of the Basin 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 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 the Marcellus Shale Member of the Hamilton Group. Six sidewall cores were collected from the darker organic-rich interval of the Devonian Shale, one core from the lower Hamilton Group, and five cores from the West Falls and Java Formations.

Depth to top of the Devonian Shale at the Burger Power Plant is 1,850 ft. Total thickness of Devonian Shale at the Burger Power Plant site is 4,858 ft. Depth to the base of the shale interval (top of Onondaga Limestone) interval is 5,708 ft. Multiple gas shows were encountered from organic-rich, low density intervals within the Hamilton Group (fig. 25). Based on the mudlog description, the estimated total black shale thickness at the Burger Well is 540 ft. A total of twelve sidewall cores were collected through the Devonian shales.

## 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 $CO_2$ (fig. 3). 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; projecting core analyses for cap rocks over 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. 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 ft of tight shale and carbonates of the Clinton Group, Lockport Dolomite and Salina Group carbonates and evaporites (minus cavern development from nearby solution mining). Drillers often refer to the thick carbonates above the Clinton-Medina/Tuscarora sandstone as the “Big Lime.” The Bass Islands Dolomite and Helderberg Limestone interval is a cap rock of 411 ft of carbonates beneath the Oriskany Sandstone possible injection reservoir. The Onondaga Limestone, a potential cap rock above the Oriskany, consists of 415 ft 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 ft 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, increasingly upward, complex assemblage of Mississippian and Pennsylvanian shale, carbonates, coal, and sandstone. The approximate thickness of these highly variable lithologies is 1,800 ft. Net effective thickness, excluding the uppermost ground water reservoir zone is in excess of 1,000 ft. Elimination of shallow speculative and possible injection reservoirs effectively either adds reservoirs as buffer zones or potential cap rock to the lowermost prospective injection reservoir. Using the Clinton-Medina as an example, as much as 8,200 ft of potential cap rock and buffer zones exists.

A total of 25 sidewall cores were collected from both caprock and reservoir units in the Burger Well. These cores will be analyzed for permeability and will be petrographically described to characterize the prospective cap rocks and buffer zones at the Burger Well site.

## STRUCTURAL GEOLOGY NEAR THE BURGER SITE

Depth to the Precambrian basement at the Burger site is estimated to be approximately 14,000 ft; the estimate is based on very sparse deep well control and from 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 normal faults down to the southeast with displacement increasing on individual faults farther to the southeast towards the main border fault of the Trough (fig. 11). Little data are available on the deep structure of the area. Therefore, the acquisition and analysis of seismic reflection profiles across the immediate area are of vital importance to identify local faulting.

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:

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 mechanisms for lithologic spatial patterns; moreover, numerous summaries on the structural influence in various coal-forming basins are found in Lyons and Rice (1986). In the AOR, several indirect lines of evidence 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 approximately 2 miles northwest of the site. The monocline is parallel to and 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 County 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 makes a second abrupt change in course direction 165 degrees to the southeast. This second river diversion occurs where the Ohio River intersects the northeast-trending monocline (item 1 above), a structural feature that may be the controlling element for the second diversion of the river course. The 2-mile, northwest-trending section of the Ohio River that occurs between these prominent river bends 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 Louden-

ville synclines and Martinsville anticline) on the shallow Pennsylvanian strata several miles south of the Burger site. These features parallel the monocline and faulting noted in item 1.

4. A dome structure with about 50 ft 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 suggests subsurface faulting has occurred along this trend and influenced the distribution of sediments during the Upper Carboniferous.
7. 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 being northeast-southwest and northwest-southeast. The structural irregularities noted above 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.

## SEISMIC REFLECTION DATA

The nearest public domain seismic reflection data for the Burger site is the Ohio Consortium for Continental Reflection Profiling (COCORP) line, 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 contain the reflection records from the Paleozoic and shallow Precambrian, are 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 COCORP line 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 of the eastern mid-continent 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, which may be useful in the 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 of the AOR.

## 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. As of June 2006, 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 drilled that were reported in public records from Ohio, Pennsylvania, and West Virginia. There are three deep wells drilled deeper than Ordovician Trenton Limestone within 30 miles, one of which was drilled into the 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 ft into the Cambrian Knox Group. The nearest moderately deep wells are within approximately 2.5 miles west of the site, where 13 wells were drilled to approximately 6,600 ft 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 importance of drilling the test well in order to proceed with reasonable modeling of potential injection reservoirs. Appendix D is a general list of known deep well tests by formation 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 ft 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 in figure 35. Two Class II injection wells are found within the AOR. The well in Monroe County, Ohio (API number 3411121559) injects brine into the Mississippian "Big Injun" sandstone (Appendix E). The well in Wetzel County, West Virginia (API number 4710301415) was drilled to a total depth of 2,360 ft. 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 well 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 2.5 miles west of the Burger Power Plant site (figs. 4 and 35). Thirteen wells have been drilled to about 6,500 ft to remove an uppermost halite bed of the Salina. Very few data, other than some well locations, are 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 searchable format, nor is there an inventory of the information. It is suggested that an effort be 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

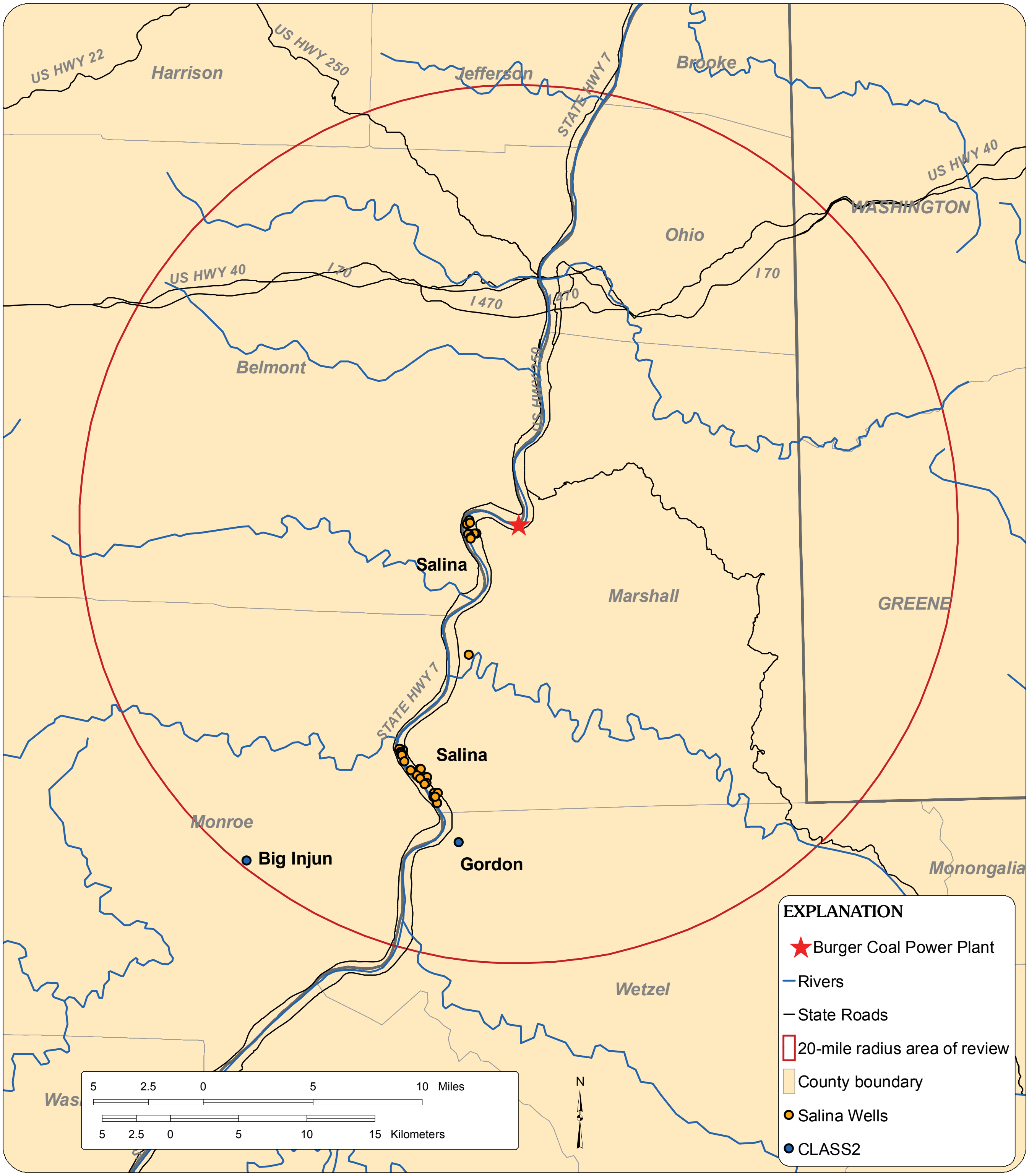


Figure 35.—Map showing the locations of class II (brine) and class III (solution mining) injection wells within the Burger AOR.

reported in Moundsville, West Virginia (French, 1963). This well has not been located through the current data search. The thickness of solution-mined Salina halite beds 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 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 have extraordinary porosity and permeability that would make them potential $CO_2$ storage caverns. However, more site data is necessary to determine the safety and potential volume of such a consideration.

## 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 USGS National Earthquake Information 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 36 is a map showing all recorded earthquake locations and their 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: <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 in historic times. The nearest significant earthquakes were the January 31, 1986, Lake County earthquake (5.0 mbLg) at a distance of approximately 124 miles from the site and the September 25, 1998, Pymatuning earthquake (5.2 mbLg) at a distance of approximately 112 miles from the site. The NCEER catalog also lists a West Virginia earthquake from 1824 at a distance of approximately 21 miles 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 a lack of accurate technology and 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 USGS Peak Acceleration (% g) map, with a 2 percent probability of exceedance in 50 years (2002). The above data suggest that the site has a very low probability of significant seismic risk.

## SUMMARY

Prior to drilling the Burger Well, available literature, petroleum well and storage field data, well and core descriptions and analyses, and coal information were compiled and analyzed for the 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 of the tri-state AOR. Core tests and analyses of prospective injection reservoirs and cap rocks were non-existent or not known to be available for public use.

Other than shallow stratigraphic core hole tests, only one well is known 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. In the AOR, only 59 wells have been drilled into or deeper than the Devonian-age Onondaga Limestone. 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 well site, additional deep stratigraphic data exist that can be used to project data about these deeper units into the site area. Many of the deeper wells have geophysical logs available in public records. The nearest well penetrating Precambrian rocks occurs 30 miles northwest of the Burger Power Plant. Conventional industry-acquired seismic data is not known within the AOR. Additional data is also lacking on formation pressure, brine/formation fluid samples, and mineralogy in the AOR.

Maps of oil and gas plays in the AOR are provided to assist in understanding their potential impact on $CO_2$ sequestration. Approximately 67 oil-and-gas pools/fields are within the AOR (fig. 27; Appendix C)). Many of these areas produce hydrocarbons from multiple horizons at depths that range from 800 to 7,300 ft 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 of these data is dependent on time available to create stratigraphically consistent data sets. It is not likely that geologic conditions similar to the well-developed reservoirs in current and abandoned storage fields in West Virginia and Pennsylvania exist at the Burger 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 for wells drilled prior to the Burger Well.

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; 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). Oil and gas plays deeper than the Lower Silurian Clinton/Tuscarora sandstone are not discussed, as these plays are considered “ultra-deep” and 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; however, 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.

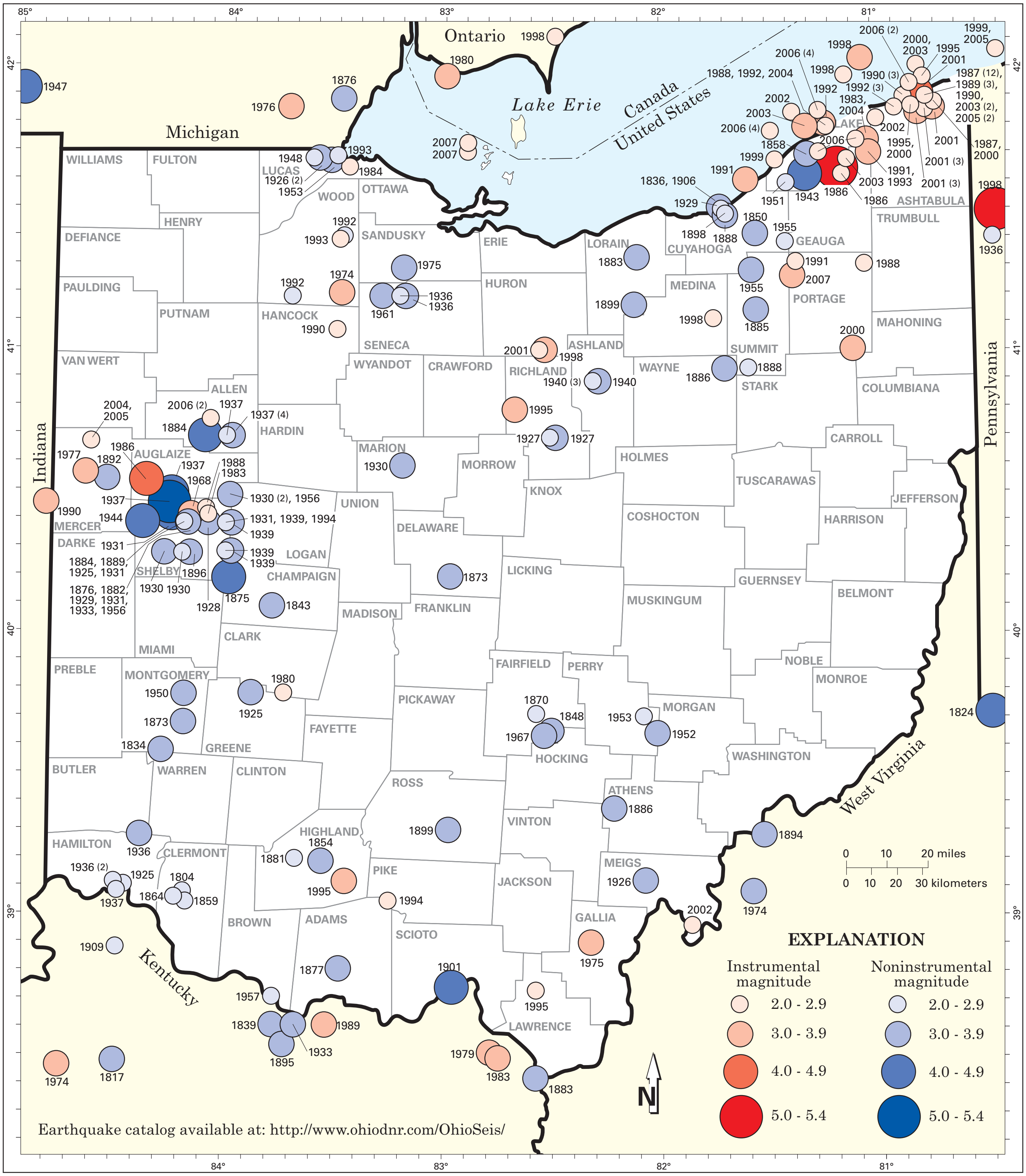


Figure 36.—Map of Ohio and surrounding areas showing known earthquake locations and relative magnitude (from Hansen, 2002). *Earthquake Epicenters in Ohio and Adjacent Areas* can be accessed through the Ohio Seismic Network's website: <http://www.ohiodnr.com/OhioSeis/>.

A minimum depth of approximately 2,500 ft 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 unmineable coal beds, and perhaps organic shales, do not require this depth constraint since $CO_2$ is adsorbed in organic-rich zones rather than being stored in pore spaces.

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 2.5 miles updip of the site. Presently, the extent and thickness of Salina halite removal, potential roof collapse, and cumulative salt production is unknown. It is likely that pilot $CO_2$ injection testing of the Salina and nearby zones, such as the Bass Islands or Oriskany Sandstone, will be proposed for the Burger Well. Burger Well pilot test information and all data from both publicly available regulatory agencies and private industrial operators concerning solution-mining operations should be thoroughly analyzed and modeled before the Burger Well proceeds with a larger injection program. Should the pilot injection tests show that the Salina or nearby units are favorable for $CO_2$ sequestration, extensive investigations and modeling should be required to ensure integrity of the prospective operations prior to permitting.

Figure 37 summarizes the rock section penetrated in the Burger Well. This diagram indicates the depths of stratigraphic intervals and identifies both confining units and potential sequestration target zones in the Burger Well. The black shales of the Hamilton Group appear favorable as potential reservoir rock based on their drilling characteristics; the thickness of the low-density, organic-rich intervals; and strong gas shows encountered during drilling. The Clinton sandstone and Oriskany Sandstone are also potential sequestration reservoirs because developed sandstones with porosity were encountered in both intervals. Good gas shows in the Salina Group and Lockport Formation indicate effective porosity in porous dolomite zones. Bass Islands Dolomite is a lower potential sequestration target at this location due to the lack of porosity development and only a minor gas show. Upper Devonian through Pennsylvanian shale, siltstones, and sandstones also show lower potential due to minimal gas shows and shallow depths. Approximately 10 net feet of deep unmineable coal beds beneath the site could be considered possible injection zones; however, the lateral extent of these coals are unknown and the discontinuous nature of overlying confining units may limit the effectiveness of a shallow seal. Potential buffer zones, which in part are represented by possible reservoirs that would not be used for injection, could combine with cap rock units to reduce the potential of vertical fluid migration. Cap rock units in the Burger Well generally appear very favorable (low porosity and well developed thickness), which is relatively predictable from well log analyses tied to core and testing data from great distances, giving good credence to the lateral continuity of these units.

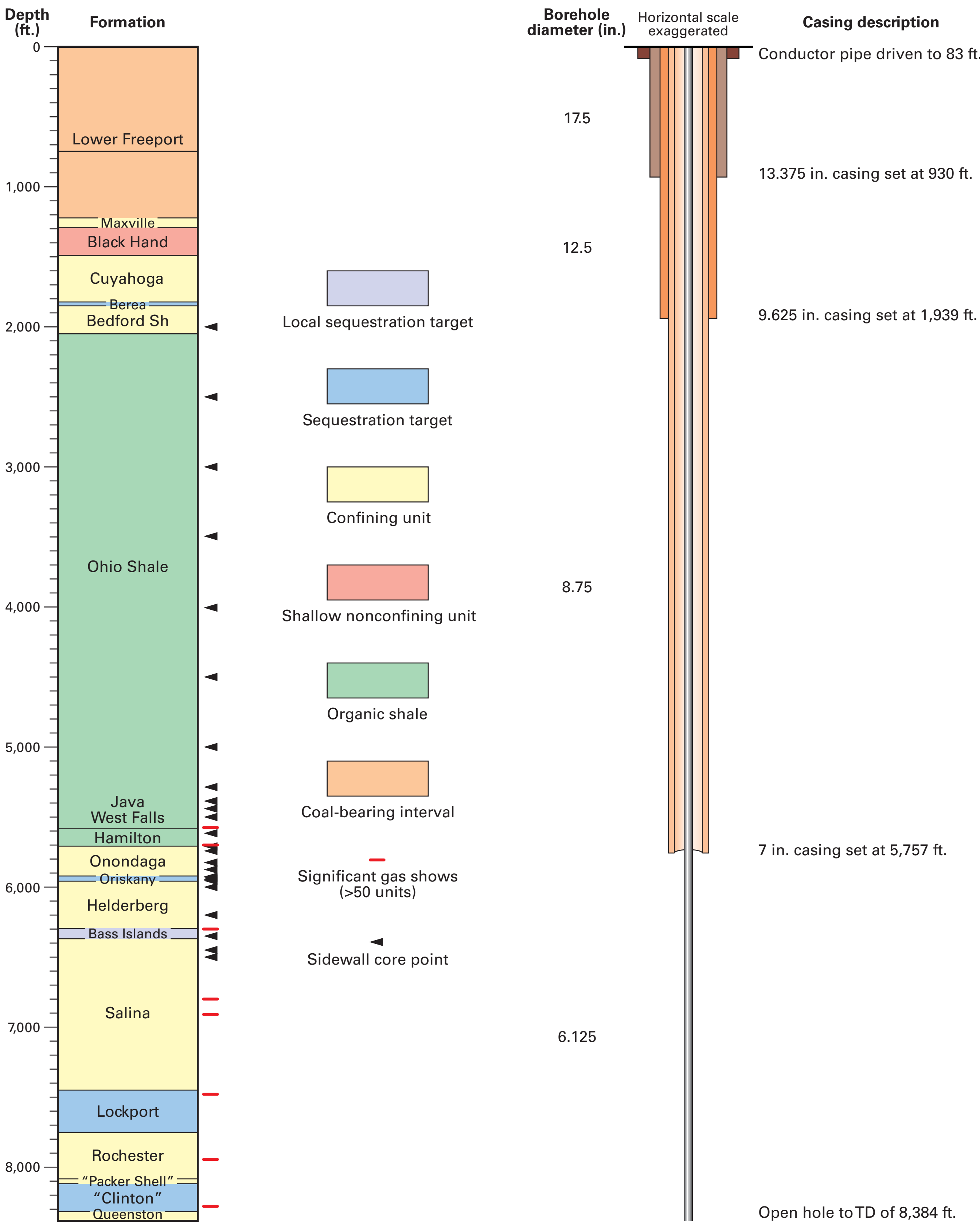


Figure 37.—Burger Well summary diagram showing potential injection zones, confining units, sidewall core locations, and significant gas shows.

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