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Evaluation of Geologic CO_2 Storage Potential at LG&E and Kentucky Utilities Power Plant Locations, Central and Western Kentucky

David C. Harris and John B. Hickman

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General Intermediate Technical

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Executive Summary

As part of a larger carbon-capture feasibility study, the Kentucky Geological Survey at the University of Kentucky evaluated five Kentucky coal-burning power-generation stations owned and operated by Louisville Gas and Electric–Kentucky Utilities, a subsidiary of PPL Corp. This work was undertaken to determine which generation station had the best potential for geologic CO_2 storage in order to select, design, and seek funding for an integrated carbon capture and storage demonstration project.

The sites evaluated were E.W. Brown Station (Mercer County), Ghent Station (Carroll County), Green River Station (Muhlenberg County), Mill Creek Station (Jefferson County), and Trimble County Station (Trimble County). Detailed geologic studies, including interpretation of seismic-reflection data, were completed to estimate CO_2 storage options, feasibility, and capacity. Various subsurface geologic maps and cross sections were made for each site and are included in the chapters that follow. The Trimble County and Ghent Stations were evaluated separately, but are discussed together in chapter 1 because of their close proximity and similar geology. Following the chapters on the individual locations, a list of site-selection criteria is included for comparison of the relative merits of these sites. The relative values used for each criteria type are somewhat subjective and are intended to be used as a guide for decision-making. Therefore, the specific needs of LG&E-KU may make the values of some criteria types a different priority than what is listed here.

Additional reflection-seismic data from around the Green River Station were purchased by LG&E-KU to improve mapping of faults near the site, which could affect containment of injected CO_2. These new data were interpreted and incorporated into the Green River evaluation. The rest of the data used for the study consisted of geophysical well logs, seismic data, and core data from databases maintained by KGS.

Figure E-1 illustrates the calculated storage capacity and the ranking score totals for each site. The ranking criteria and scores follow the four chapters describing the geology at each site. All of the sites with the exception of the E.W. Brown Station have potential for CO_2 to be injected and stored onsite to some degree. The geology at Brown is not favorable for onsite storage; however, an area 6 to 10 mi east of the site has the largest sequestration capacity of the five sites examined. Use of this area for CO_2 injection would require building a pipeline to transport CO_2 and securing the rights to use the subsurface pore space under private property. The potential storage reservoir for

the E.W. Brown Station is the only site that has sufficient geologic structure ("closure") to trap injected CO_2 and limit lateral migration.

The Ghent Station has the second-highest storage capacity of the studied sites, and injection wells could be drilled onsite using land and pore space owned by LG&E-KU. This avoids the need to lease rights to pore space from other property owners. The Ghent Station parcel is among the largest of the five sites, resulting in a large onsite storage volume. In addition, drilling depths at Ghent are shallower compared to the other sites, which would reduce drilling costs. The CO_2 injected at Ghent would probably migrate slowly updip to the northeast, and possibly under the Ohio River into Switzerland County, Ind.

The storage reservoir formation at Trimble County is the same as at Ghent, but the formation is deeper, and porosity (and thus storage capacity) is predicted to be lower. Well data are scarce near the Trimble County Station, making precise predictions of the geology under the site difficult. Estimated storage capacities are lower than at Brown or Ghent, and drilling depths would be greater. The CO_2 injected at Trimble County would probably also migrate slowly updip to the northeast, but because of the geometry of the Ohio River, it would remain in Kentucky for at least 14 mi.

The lowest CO_2 storage capacities estimated were at the Mill Creek and Green River Stations. Mill Creek Station is near an older hazardous-waste disposal well in Louisville that found poor injectivity in the deep Mount Simon Sandstone. This suggests limited porosity and storage capacity within the Mount Simon at Mill Creek Station. The Green River Station lies above a deep geologic basin where the only suitable injection zone is in carbonate rocks of the Knox Group. Although good injectivity was demonstrated in the Knox in a KGS research well in Hancock County, the limited deep-well data from

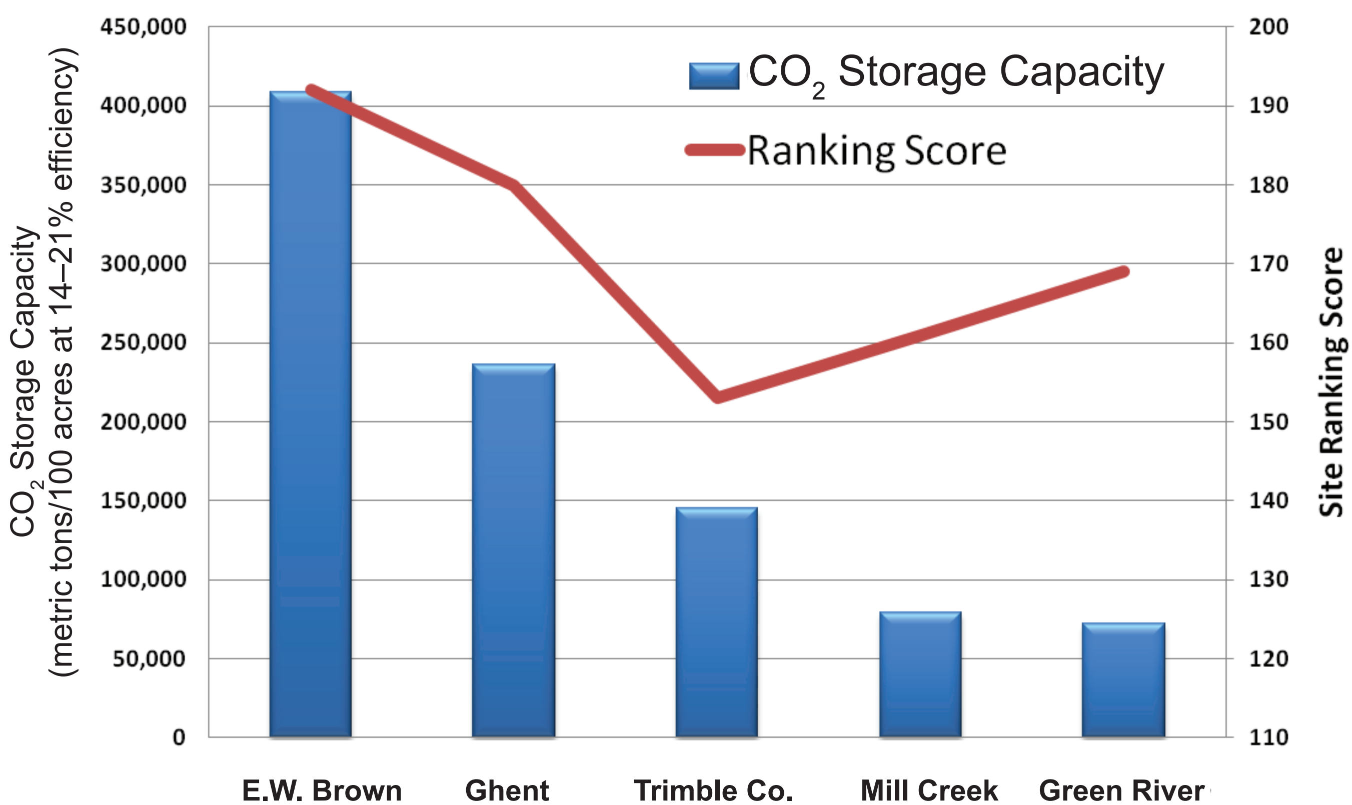

Figure E-1. Calculated CO_2 storage capacities and site ranking scores for the sites evaluated in this study. Capacities are metric tons of CO_2 for 100 acres. Storage efficiency factors of 14 percent (sandstone) and 21 percent (carbonate) of total pore volume were used. See p. 101–103 for site ranking score criteria.

Muhlenberg County indicate lower porosity values for this unit. Seismic data around Green River show that faulting (and possible leakage pathways) does not appear to be present near the site.

Calculated CO_2 storage volumes at all sites were scaled by published efficiency factors, which reduce total storage capacity because of various displacement factors that limit the pore space actually occupied by CO_2. Efficiency factors used range from 14 to 21 percent of the total pore space within the reservoirs.

Public perception regarding a carbon capture and storage project at each of the five sites was not scientifically evaluated as part of this project. The authors' personal opinions on possible public acceptance or resistance to a carbon capture and storage project were included in the ranking criteria. This was based primarily on the plant location and current land use in the area. We felt a demonstration project would be most acceptable in Muhlenberg County (Green River Station) because of the rural plant location, number of local coal-mining jobs, and long history of mining in the area. Ghent and Trimble County Stations are located in more developed, noncoal-producing areas, and have residential areas within a mile of the plant sites. This could lead to public opposition to a carbon capture and storage project because of the proximity of homes to the sequestration site. Mill Creek Station is located in an even more developed area, where concern about nearby homes could be a problem. E.W. Brown's off-site sequestration area is a primarily rural area, and site selection could focus on areas away from residences to avoid potential opposition.

In summary, the E.W. Brown Station has the highest CO_2 storage capacity, and a known trap in which to contain migration of the CO_2. However, the sequestration area is not located onsite, and will require a pipeline and access to privately held pore space.

The Ghent Station has a lower storage capacity, but should be more than adequate for a demonstration project located onsite. It has the shallowest depth of the five sites evaluated, which will significantly reduce drilling costs. Ghent appears to have the lowest geologic storage cost of any of the sites evaluated. Although deeper than Ghent and having lower porosity, the Trimble County Station should also have adequate storage volumes onsite for a demonstration project.

Chapter 1: Geologic CO_2 Sequestration Potential of the LG&E-KU Trimble County and Ghent Stations, Northern Kentucky

LG&E-KU CO_2 Sequestration Geologic Summary Sheet

Power Plant: Ghent **County:** Carroll **Geologic Basin:** Cincinnati Arch

Data Quality:	
Distance to nearest well control in reservoir:	4.7 mi
Wells to primary injection zone within 15-mi radius:	3
Distance to nearest core in injection zone:	14.7 mi
Distance to nearest good-quality seismic control:	14.5 mi
Reservoirs:	
Primary injection zone:	Cambrian Mount Simon Sandstone
Rock type:	sandstone (quartzarenite)
Drilling depth at plant site:	3,423 ft
Trapping mechanism:	regional dip (capillary and solution trapping)
Maximum reservoir pressure:	1,635 psi (hydrostatic)
Reservoir temperature:	100°F
Salinity of reservoir fluid:	200,000 ppm (estimated)
Reservoir thickness (gross/net):	301/160 ft
Average porosity:	12 percent
Average permeability:	200 md
Secondary injection zone:	none at this site
Confinement and Integrity:	
Primary confining zone:	Cambrian Eau Claire Shale
Rock type:	shale and dolomite
Thickness of primary confining zone:	560 ft
Height above primary injection zone:	0 (overlies injection zone)
Well penetrations of primary seal within 15-mi radius:	4
Secondary confining zone:	Ordovician Black River Limestone (High Bridge)
Rock type:	limestone
Thickness of secondary confining zone:	500 ft
Height above primary injection zone:	2,600 ft
Well penetrations of secondary seal within 15-mi radius:	16
Number of faults cutting primary seal within 15-mi radius:	0
Distance to nearest mapped fault:	15.6 mi
Storage Capacity:	
Calculated CO_2 storage capacity, primary injection zone:	1,688,924 metric tons/100 acres (assuming 100 percent total pore volume); 236,449 metric tons/100 acres (at 14 percent total pore volume)

Data compiled and interpreted from well records maintained by the Kentucky Geological Survey.

LG&E-KU CO_2 Sequestration Geologic Summary Sheet

Power Plant: Trimble County **County:** Trimble **Geologic Basin:** Cincinnati Arch

Data Quality:

Distance to nearest well control in injection zone:	26.6 mi
Wells to primary injection zone within 15-mi radius:	0
Distance to nearest core from injection zone:	34.3 mi
Distance to nearest good-quality seismic control:	35 mi

Reservoirs:

Primary injection zone:	Cambrian Mount Simon Sandstone
Rock type:	sandstone (quartzarenite)
Drilling depth at plant site:	3,900 ft
Trapping mechanism:	regional dip (capillary and dissolution trapping)
Maximum reservoir pressure:	1,888 psi (hydrostatic)
Reservoir temperature:	110°F
Salinity of reservoir fluid:	200,000 ppm (estimated)
Reservoir thickness (gross/net):	366/121 ft
Average porosity:	10 percent
Average permeability:	150 md
Secondary injection zone:	none at this site

Confinement and Integrity:

Primary confining zone:	Cambrian Eau Claire Shale
Rock type:	shale and dolomite
Thickness of primary confining zone:	560 ft
Height above primary injection zone:	0 (overlies injection zone)
Number of well penetrations of primary seal within 15-mi radius:	0
Secondary confining zone:	Ordovician Black River Limestone (High Bridge Group)
Rock type:	limestone
Thickness of secondary confining zone:	500 ft
Height above primary injection zone:	2,800 ft
Number of well penetrations of secondary seal within 15-mi radius:	5
Number of faults cutting primary confining zone within 15-mi radius:	1
Distance to nearest mapped fault:	13.2 mi

Storage Capacity:

Calculated CO_2 storage capacity, primary injection zone:	1,035,206 metric tons/100 acres (assuming 100 percent total pore volume); 144,929 metric tons/100 acres (at 14 percent total pore volume)

Data compiled and interpreted from well records maintained by the Kentucky Geological Survey.

Introduction

Geologic CO_2 sequestration potential was evaluated for an area surrounding the LG&E-KU Trimble County and Ghent Stations in Trimble and Carroll Counties, Ky. These plants are approximately 23 mi apart, and because of their proximity and similar geology, they have been evaluated together. Circular areas with a 15-mi radius around each plant were defined as the primary focus of the evaluation, but data from beyond 15 mi were also used because of limited data from the primary areas. The 15-mi-radius circles around the Trimble County and Ghent Stations overlap, as seen in Figure 1-1, supporting their combined evaluation.

The following data were compiled for the evaluation:

1. The 7.5-minute topographic and geologic quadrangle maps for the Bethlehem (Trimble County) and Vevay South (Ghent) quadrangles
2. Locations of all petroleum-exploration and waste-disposal wells penetrating the Cambrian-Ordovician Knox Group or deeper formations (Kentucky and Indiana Geological Surveys)
3. Formation tops for geologic units from the top of the Ordovician to the Precambrian

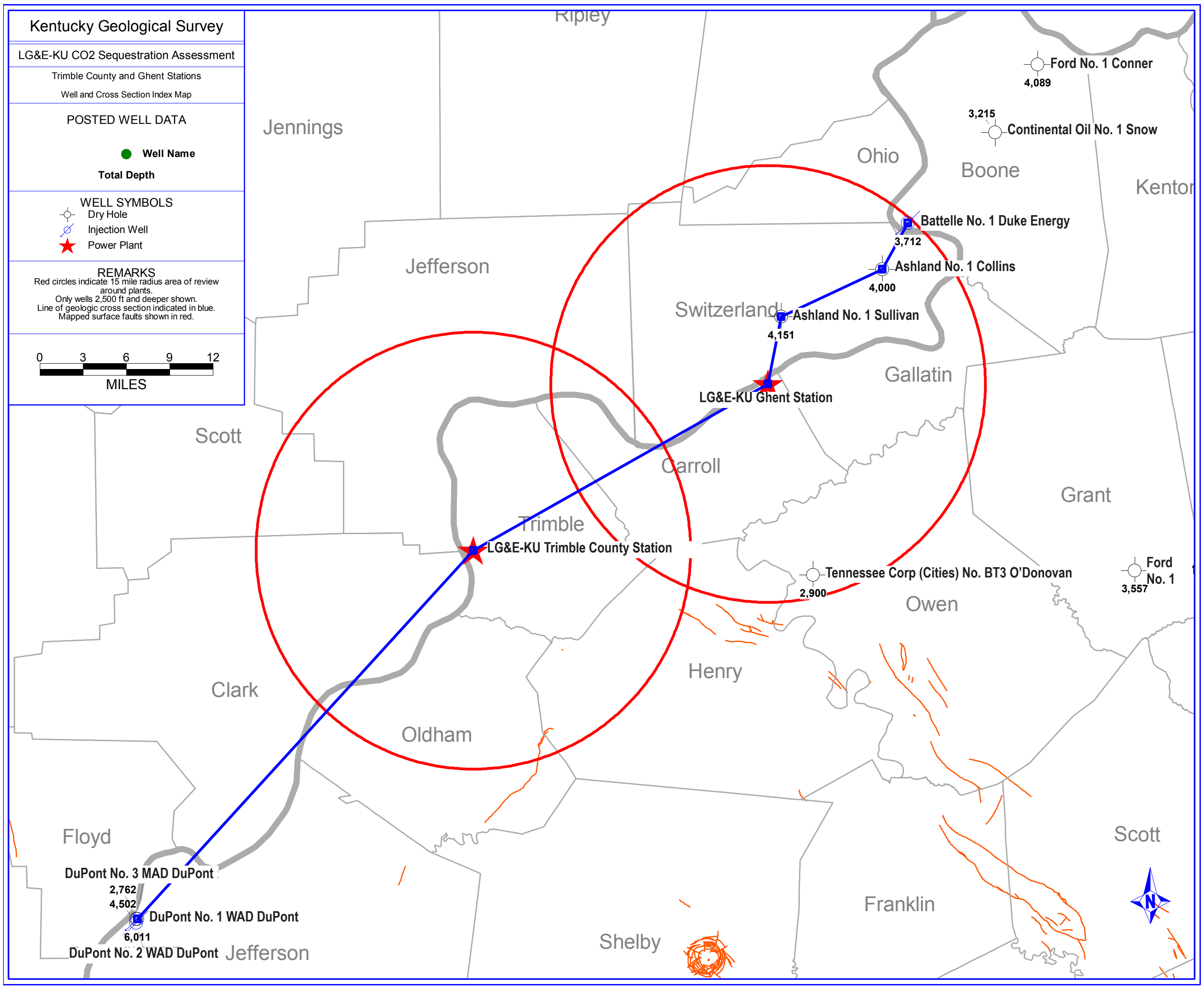

Figure 1-1. Locations of Trimble County and Ghent Stations in northern Kentucky. Heavy gray line is the Ohio River, separating Indiana from Kentucky. Bold red circles are 15-mi radii around each station. Wells deeper than 2,500 ft are shown. Blue line is the location of the southwest-northeast cross section shown in Figure 1-12. Surface fault traces indicated by thin red lines.

(Kentucky and Indiana Geological Surveys)
4. Available digital geophysical logs for Knox and deeper wells (Kentucky and Indiana Geological Surveys)
5. Core analyses (porosity and permeability) for Mount Simon Sandstone and Eau Claire Formation
6. Reflection-seismic data (two lines in Boone County, Ky., at the Duke East Bend Station)

Within the 15-mi radius around the Ghent Station, three wells have been drilled that penetrate the entire Paleozoic sequence, ending in Precambrian rocks. These wells provide the key geologic data used in this assessment. Two wells were drilled in Switzerland County, Ind., by Ashland Oil, and well logs from these wells were used. In 2009, a CO_2 injection test well was drilled by Battelle Memorial Institute at the Duke Energy East Bend Station in Boone County, Ky., as part of the U.S. DOE–funded Midwest Regional Carbon Sequestration Partnership (www.mrcsp.org). This well was drilled to test the Cambrian Mount Simon Sandstone, the same reservoir zone that underlies Ghent and Trimble County. Data from this well were used for this evaluation, including core analyses, formation image logs, and injection data. All of these wells penetrated the primary injection zone and overlying seal.

The 15-mi area around the Trimble County Station lacks any wells below 2,500 ft, the depth required for supercritical-phase CO_2 storage. The deepest well in the area went to 2,496 ft (Oldham County), ending in the Knox Supergroup. No other wells were drilled deeper than 2,500 ft to the southwest of Trimble County until the DuPont waste-disposal wells were drilled in Louisville (Jefferson County). DuPont drilled three deep wells at their Louisville neoprene plant for hazardous-waste disposal. Data from the DuPont wells have been included in the Trimble County/Ghent evaluation.

Geologic Setting and Surface Geology

Trimble and Carroll Counties lie on the west flank of the Cincinnati Arch, a broad anticline that separates the deep Illinois Basin in western Kentucky from the Appalachian Basin in eastern Kentucky. The arch developed in Middle Ordovician time, and rock units deposited prior to this time have been tilted to the west toward the Illinois Basin. Rocks deposited from the Middle Ordovician and later were influenced to some extent by the growing arch, but for the interval of interest in this study, the arch had no effect on thickness or lithology.

The Ghent Station is located in the Vevay South 7.5-minute quadrangle, and the quadrangle's geology was mapped by Swadley (1973). The Trimble County Station is located in the Bethlehem 7.5-minute quadrangle, and the quadrangle's geology was mapped by Swadley (1977).

The Ghent and Trimble County power plants are located on unconsolidated sediments deposited along the Ohio River (Figs. 1-2a, b). These sediments are Quaternary (Pleistocene) in age, and interpreted as glacial outwash deposits. Ordovician bedrock is exposed in the hills and bluffs to the east of each station. Rocks near the Ghent Station in Carroll County consist of Ordovician shales and limestones assigned to the Kope, Fairview, Grant Lake, and Bull Fork Formations as mapped by the USGS (Fig. 1-2a). For the Trimble County Station, slightly younger Ordovician rocks are exposed, including the Drakes Formation and Lower and Middle Silurian Osgood Formation, Brassfield Formation, and Laurel Dolomite on hilltops (Fig. 1-2b).

Surface geology does not have a direct impact on carbon sequestration potential, since CO_2 injection will occur much deeper. However, the abundance of low-permeability shales in the near-surface Upper Ordovician rocks would serve as secondary confining layers in the unlikely event CO_2 were to migrate through the deeper primary seals.

The surface geology will affect the design and implementation of shallow groundwater-monitoring wells that may be required by the U.S. EPA for an underground injection permit. The presence of unconsolidated glacial outwash along the Ohio River at both sites allows relatively inexpensive construction of monitoring wells. The EPA UIC permit will likely require monitoring down to the base of the underground source of drinking water, which may require drilling into bedrock. However, the Upper Ordovician interval below

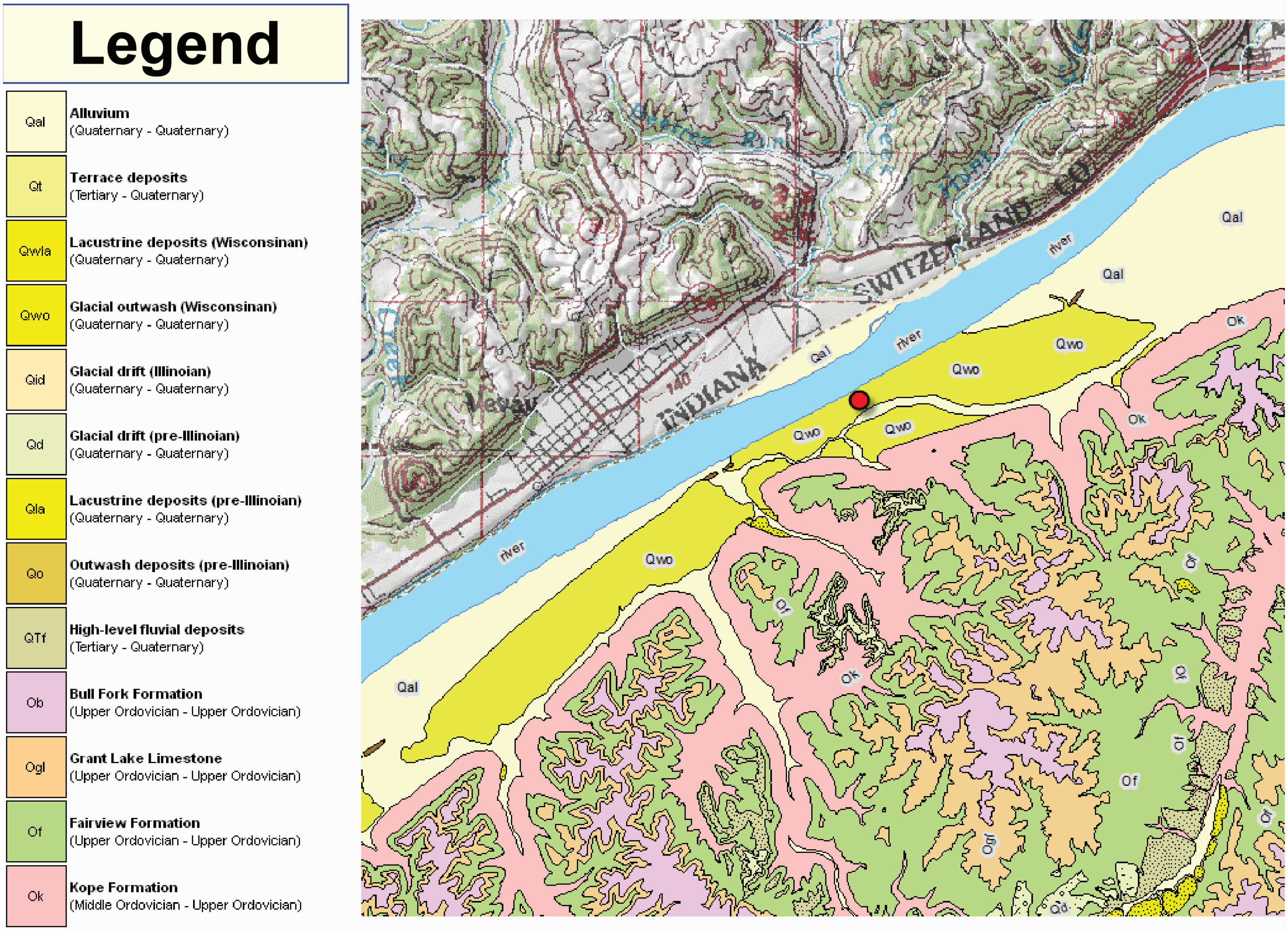

Figure 1-2a. Geology of part of the Vevay South and Vevay North 7.5-minute quadrangles (Swadley, 1973). The Ghent Station (red dot) is located on unconsolidated Pleistocene glacial outwash (Owo). Hills to the south of the station are underlain by Upper Ordovician shales and limestone.

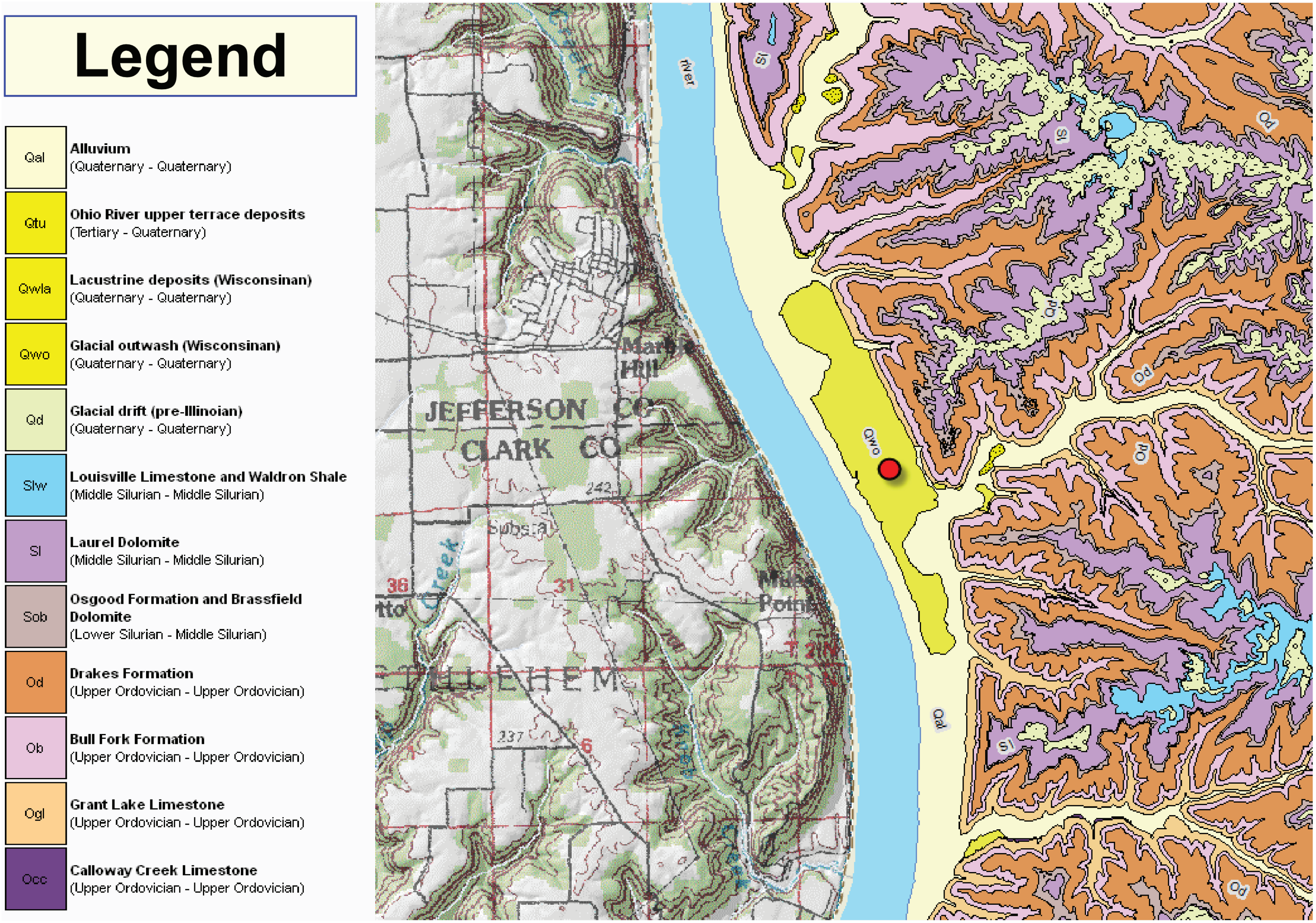

Figure 1-2b. Geology of part of the Bethlehem 7.5-minute quadrangle showing the location of the Trimble County Station (red dot) (Swadley, 1977). The station is located on unconsolidated Pleistocene sediments, mapped as glacial outwash (Owo). Hills to the east of the station are underlain by Upper Ordovician shales and limestone and Silurian dolomite and shale.

the unconsolidated sediments may not be suitable for groundwater monitoring because of low porosity and permeability. Both geologic maps (Swadley, 1973, 1977) cite very hard groundwater with some salt occurrence, and the lack of groundwater in wells drilled on ridges and hillsides. Monitoring wells would likely be confined to the Ohio River alluvium and glacial deposits, larger creek valleys, and the Kentucky River Valley.

Stratigraphy and Structure

Geologic storage of carbon dioxide is confined to depths greater than 2,500 ft below the surface so that CO_2 exists in the supercritical, or dense, phase. Supercritical CO_2 has properties of both a liquid and a gas, but much higher density than gaseous CO_2. In the Trimble and Carroll County area, this 2,500-ft depth falls within the Cambrian-Ordovician Knox Supergroup. Geologic formations below 2,500 ft in this area include the basal part of the Knox, the Upper/Middle Cambrian Eau Claire Formation and Middle Cambrian Mount Simon Sandstone, and Precambrian Middle Run Formation (Fig. 1-3). These formations are briefly described below, from oldest to youngest.

Precambrian Middle Run Formation

The Middle Run has been penetrated in five wells in northern Kentucky and adjacent Indiana. The Precambrian basement in the study area consists of sedimentary rocks assigned to the Middle Run Formation, in contrast to the igneous and metamorphic rocks typically encountered in the basement in other parts of Kentucky. The Middle Run consists of fine-grained, red lithic sandstones, and minor siltstone and shale. It was deposited in nonmarine fluvial environments in a fault-bounded rift basin (Drahovzal and others, 1994). The top of the Middle Run is an erosional unconformity, formed during a long period of exposure and nondeposition between the Precambrian and Paleozoic Eras. The sandstone is well cemented and lacks porosity and permeability in all of these wells. It has no potential for carbon sequestration in the study area, but forms the lower confining layer for the overlying Mount Simon Sandstone.

The Precambrian unconformity surface dips to the west in the study area, consistent with the trend of the Cincinnati Arch (Fig. 1-4). This structure map is based on the few wells that penetrate the Precambrian surface in the area. As such, it should be considered a general representation of the structure of the area. This map indicates that the depth to basement is about 4,361 ft (–3,888 ft subsea) at the Trimble County Station, and 3,777 ft (–3,289 ft subsea) at the Ghent Station. This would be the maximum depth required for an injection well, with Ghent lying about 600 ft updip (shallower) from Trimble County at the Precambrian level.

Cambrian Mount Simon Sandstone

The Cambrian Mount Simon Sandstone unconformably overlies the Precambrian Middle Run Formation in most of the study area. Farther to the southwest in Louisville, the Mount Simon overlies Precambrian igneous rocks. The Mount Simon Sandstone is predominantly quartz-rich, and because of its depth and porosity, is the primary CO_2 injection zone in the study area. The Mount Simon has been encountered in five wells in the study area. Cores from the Mount Simon Sandstone are available from two of these wells: the Battelle Duke Energy well and the DuPont waste-injection well in Louisville. Porosity and permeability data measured in these cores are described further in the Reservoir Quality section.

Using available well data for the area, structure and thickness maps for the Mount Simon were constructed. Other studies have used data from seismic lines outside this study area to map the extent of the Mount Simon Sandstone across Kentucky. The broader regional data show the Mount Simon thickens to the north and northwest, and pinches out toward the south (Fig. 1-5) (Greb and Solis, 2010). The zero thickness line from the map by Greb and Solis (2010) has been used in the Trimble/Ghent maps made for this study. The zero thickness line runs across the southeastern corner of the map area, and has been used to constrain the structure and thickness maps for this study. This zero thickness line has been interpreted from limited data, and should be considered approximate. The Mount Simon is known to be absent in several wells in central Kentucky, but the mapped pinchout should be considered a preliminary limit that may be revised with new data.

The top of the Mount Simon is at 3,233 ft in the Battelle No. 1 Duke Energy well, and deepens

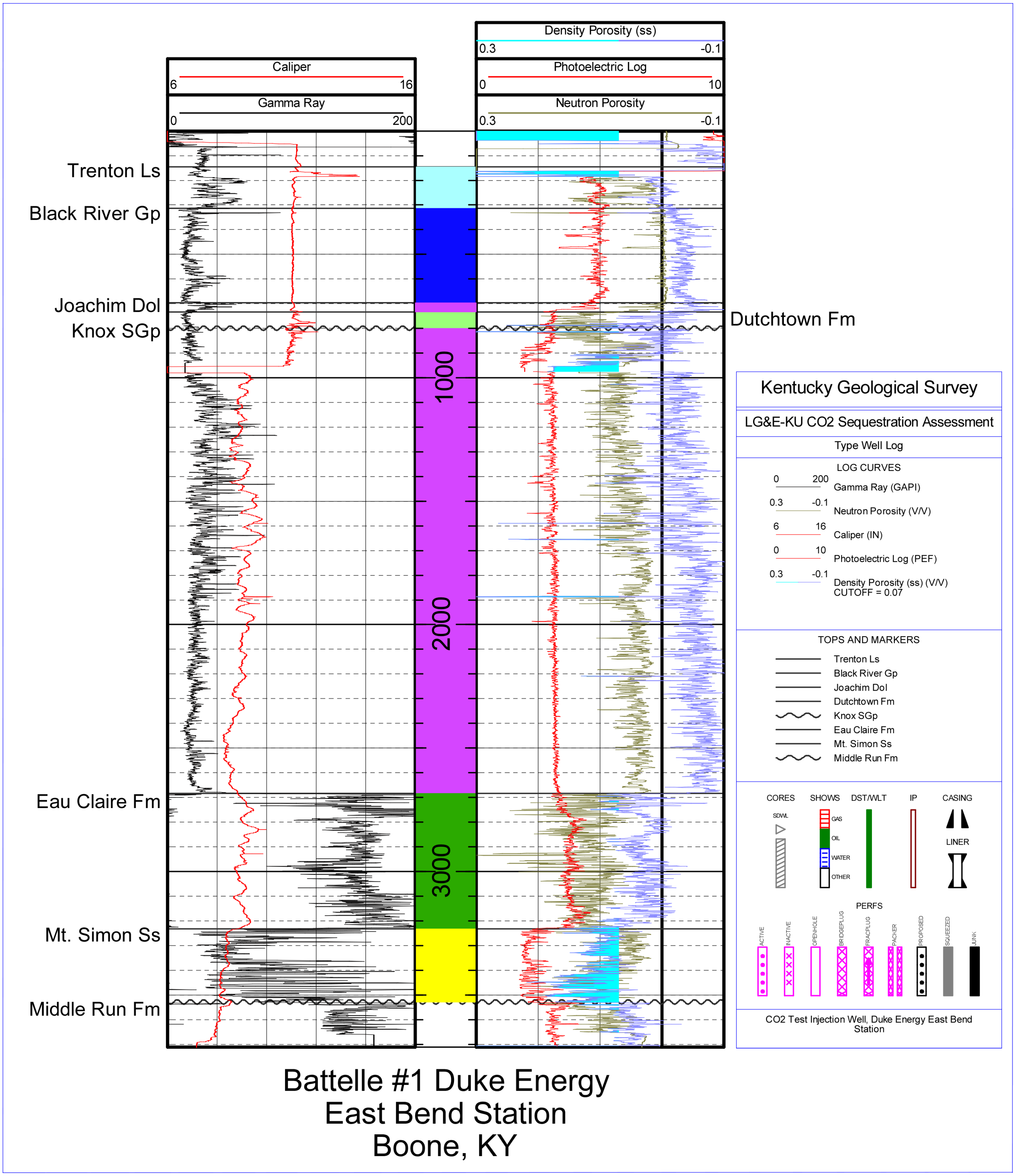

Figure 1-3. Geophysical log for the Battelle No. 1 Duke Energy well at the East Bend Station in Boone County, Ky. Stratigraphic units are labeled. Cored intervals are marked on the right edge of the depth column, and the CO_2 injection zone is marked on the left side of the depth column in the Mount Simon Sandstone. The density-porosity log is shaded blue in the Mount Simon interval where porosity is greater than 7 percent, the minimum porosity considered in CO_2 capacity calculations.

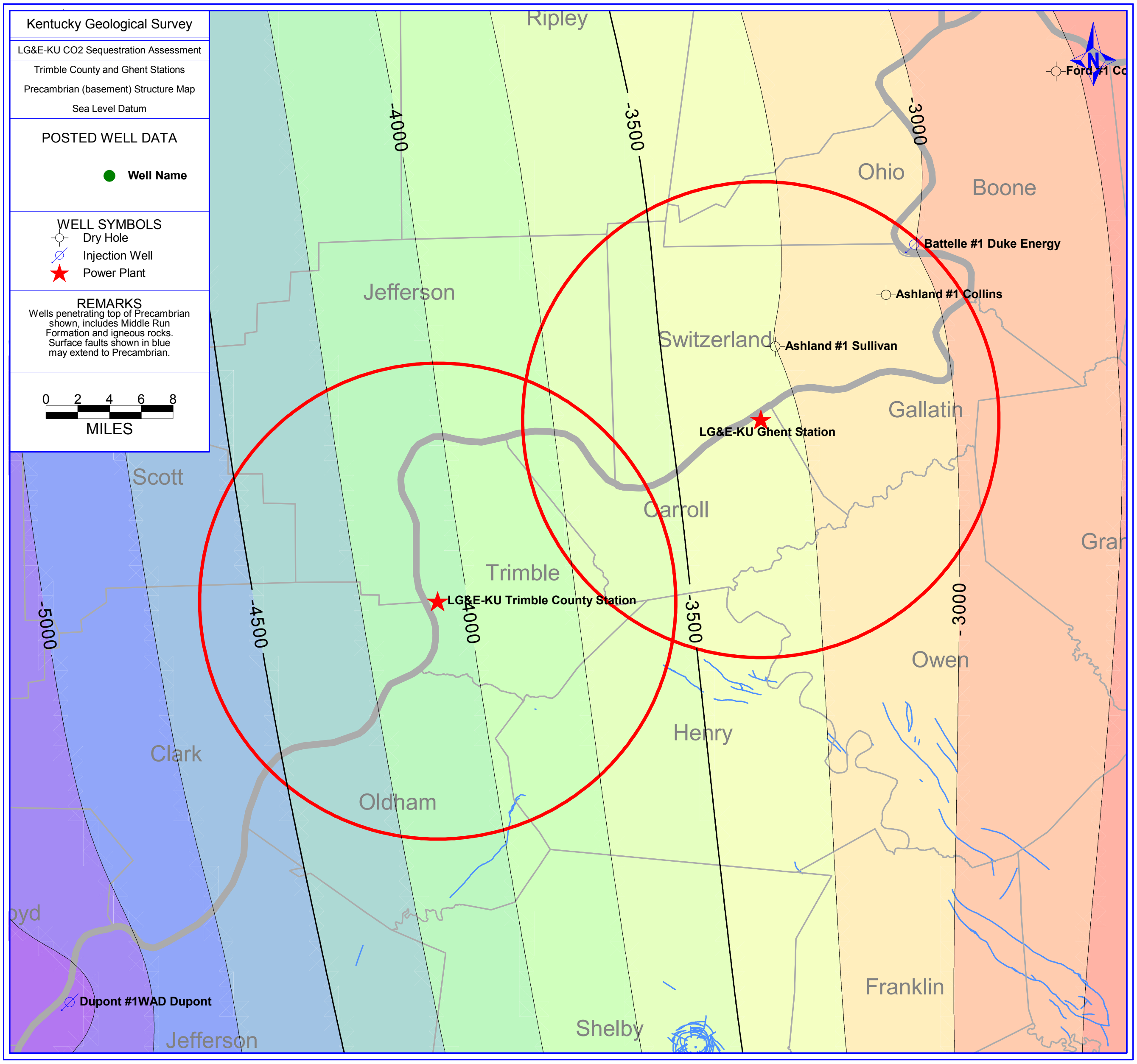

Figure 1-4. Structure on top of the Precambrian basement surface (feet below MSL). In the study area this is the top of the Middle Run Sandstone or igneous rocks. The Precambrian surface deepens to the west-southwest. Blue lines are faults mapped at the surface, which may extend to the Precambrian level.

to the southwest to 5,098 ft in the DuPont well in Louisville (Fig. 1-6). The Mount Simon Sandstone ranges in thickness from 297 to 748 ft across the same area (Fig. 1-7). The Mount Simon may have suitable porosity and permeability at both stations to allow injection and storage of CO_2. One thousand tons of CO_2 were successfully injected in the Duke Energy well in 2009.

The Trimble County and Ghent sites lie intermediate in depth between the DuPont waste-disposal well to the southwest and the Duke Energy East Bend well to the northeast. Interpolating depth and thickness data from wells, depth to the top of the Mount Simon is estimated to be 3,898 ft (–3,425 ft subsea) at Trimble and 3,423 ft (–2,935 ft subsea) at Ghent (Fig. 1-6). The inferred pinchout line for the Mount Simon was used to clip the

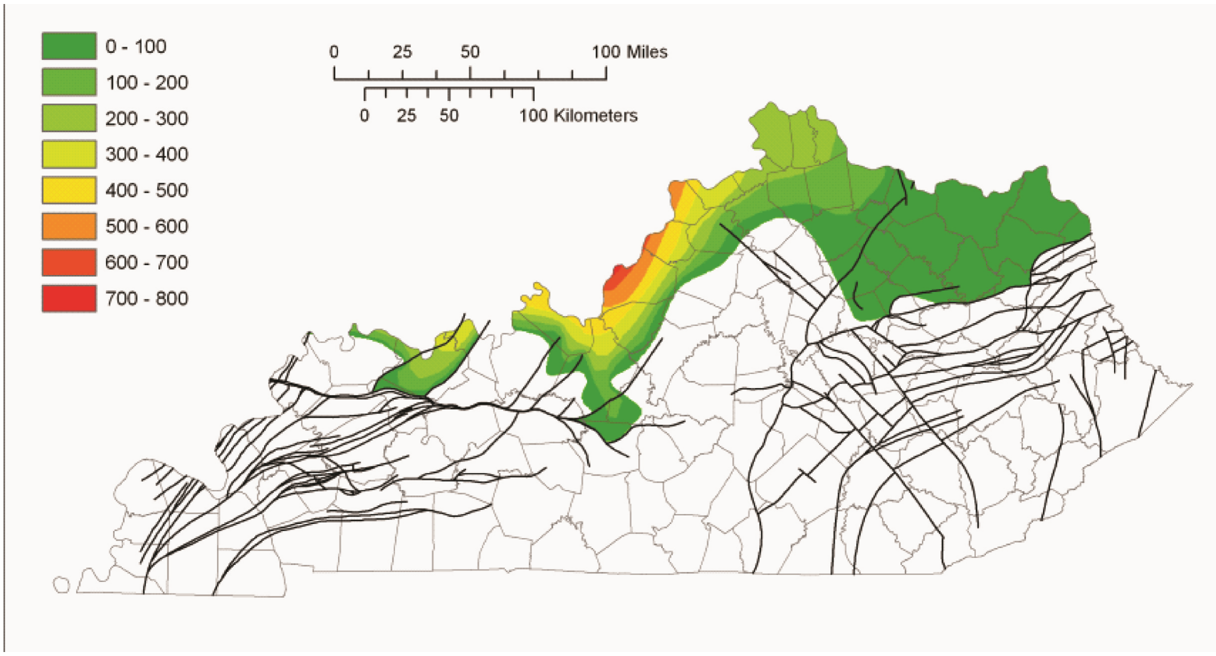

Figure 1-5. Thickness of the Mount Simon Sandstone in Kentucky. Interpretation based on seismic and well data. Contours in feet. From Greb and Solis (2010).

structure contours at the zero edge. The isopach (thickness) map (Fig. 1-7) shows thinning of the Mount Simon Sandstone toward the southeast. Its thickness is estimated to be 366 ft at Trimble and 301 ft at Ghent. The isopach map was interpreted from the nearby well data, and the zero thickness line drawn on the regional map. The greater projected thickness at the Trimble Station is because of its closer proximity to the DuPont waste-disposal well in Louisville, where the Mount Simon is 748 ft thick.

Cambrian Eau Claire Formation

The Eau Claire Formation directly overlies the Mount Simon Sandstone and is predominantly composed of green and gray marine shale, with some interbedded dolomite. In the Duke Energy East Bend well, the Eau Claire Formation is 549 ft thick and was cored from 2,825 to 2,855 ft. The Eau Claire Formation was also cored in the DuPont No. 1 WAD well in Louisville, from 4,409 to 4,459 and 4,842 to 4,871 ft. The Eau Claire has very low porosity and permeability and is the primary confining layer (seal) for CO_2 injected into the Mount Simon below (Fig. 1-8).

Figure 1-9 is a structure map on the top of the Eau Claire. The Eau Claire deepens to the southwest into the deeper parts of the Illinois Basin. The top is projected to be at 2,870 ft (–2,382 ft subsea) at Ghent and 3,423 ft (–2,950 ft subsea) at Trimble County. The top of this confining layer is deeper than the minimum depth for supercritical CO_2 at both sites.

Cambrian-Ordovician Knox Supergroup

The Knox Supergroup is divided into an upper dolomite unit, the Beekmantown Dolomite, and the lower Copper Ridge Dolomite, separated by sandstone or a quartzose dolomite unit (Rose Run Sandstone) that is poorly developed in this area. The top of the Knox is a regional erosional unconformity that formed when the Knox was uplifted above sea level during the Early Ordovician. The Knox is approximately 2,000 ft thick in the study area. The Knox contains scattered porous and permeable intervals separated by impermeable dolomite. It has injection potential in deeper parts of Kentucky (such as the KGS No. 1 Marvin Blan research well in Hancock County) and was used as a hazardous-waste injection zone at the DuPont chemical plant in Louisville. Porous zones in the Knox have also been used for natural-gas storage by LG&E near the study area, in Grant and Oldham Counties (Ballardsville and Eagle Creek

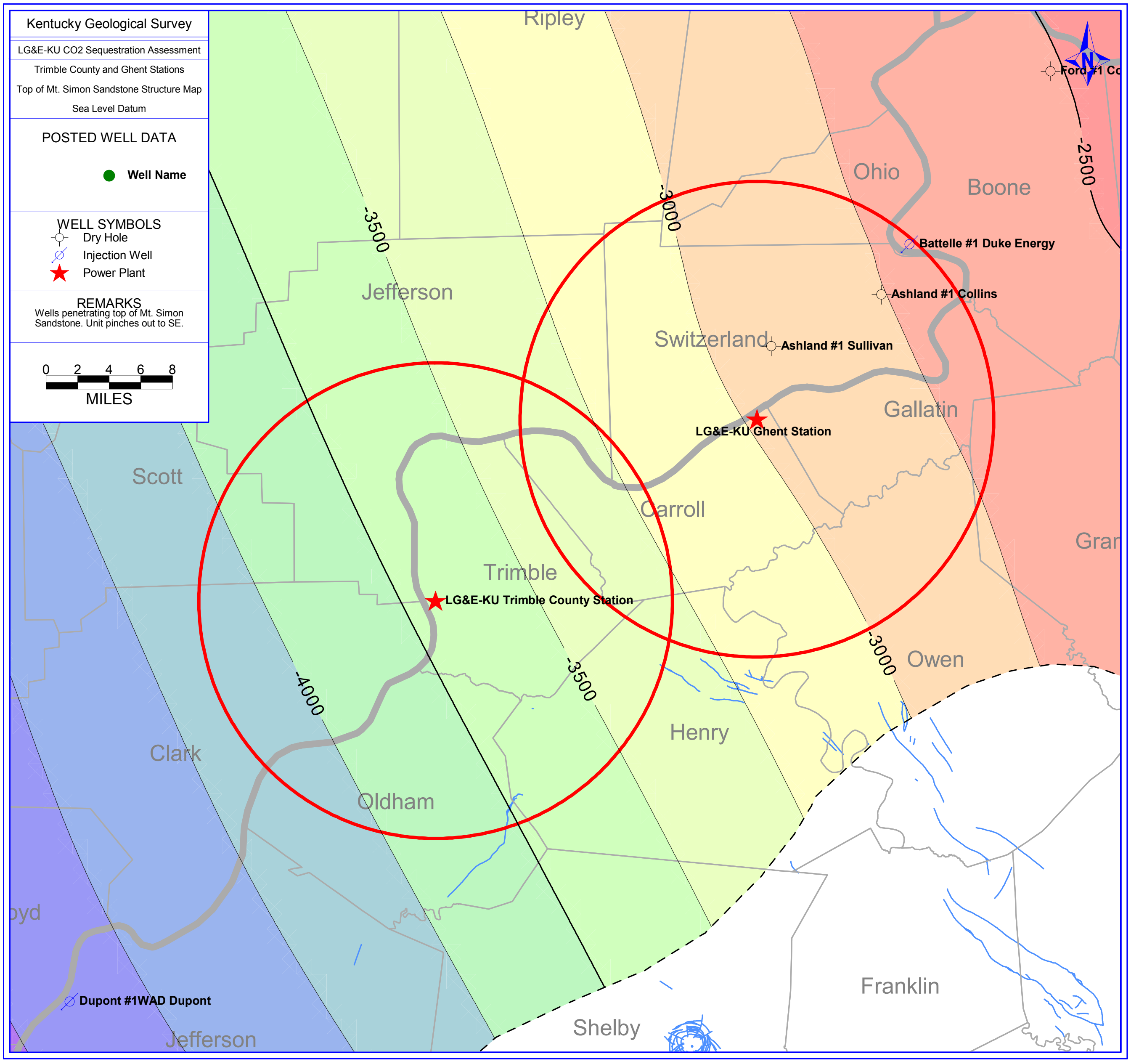

Figure 1-6. Structure on top of the Cambrian Mount Simon Sandstone. Contour interval is 250 ft. The dashed line in the southeastern part of the map is the inferred pinchout of the Mount Simon to the south (Greb and Solis, 2010).

storage fields). These storage fields are now abandoned, and the porous zones used in these fields are too shallow for CO_2 storage.

In the study area, much of the Knox lies above the 2,500-ft depth limit for CO_2 to be in a supercritical phase. The lower part of the Knox (below 2,500-ft depth) is also not a viable injection target, since the primary seal (containment zone) above the top of the Knox is well above the 2,500-ft depth required to keep CO_2 in a supercritical phase.

The Knox is the shallowest interval mapped in this evaluation. Figure 1-10 is a structure map on the top of the Knox. Many more wells have been drilled to the top of the Knox than to the deeper horizons, and thus more data are available for the Knox structure map. The Knox dips to the west, with the projected top of the Knox at about 1,077 ft (–604 ft subsea) at Trimble County and 849 ft (–361 ft subsea) at Ghent.

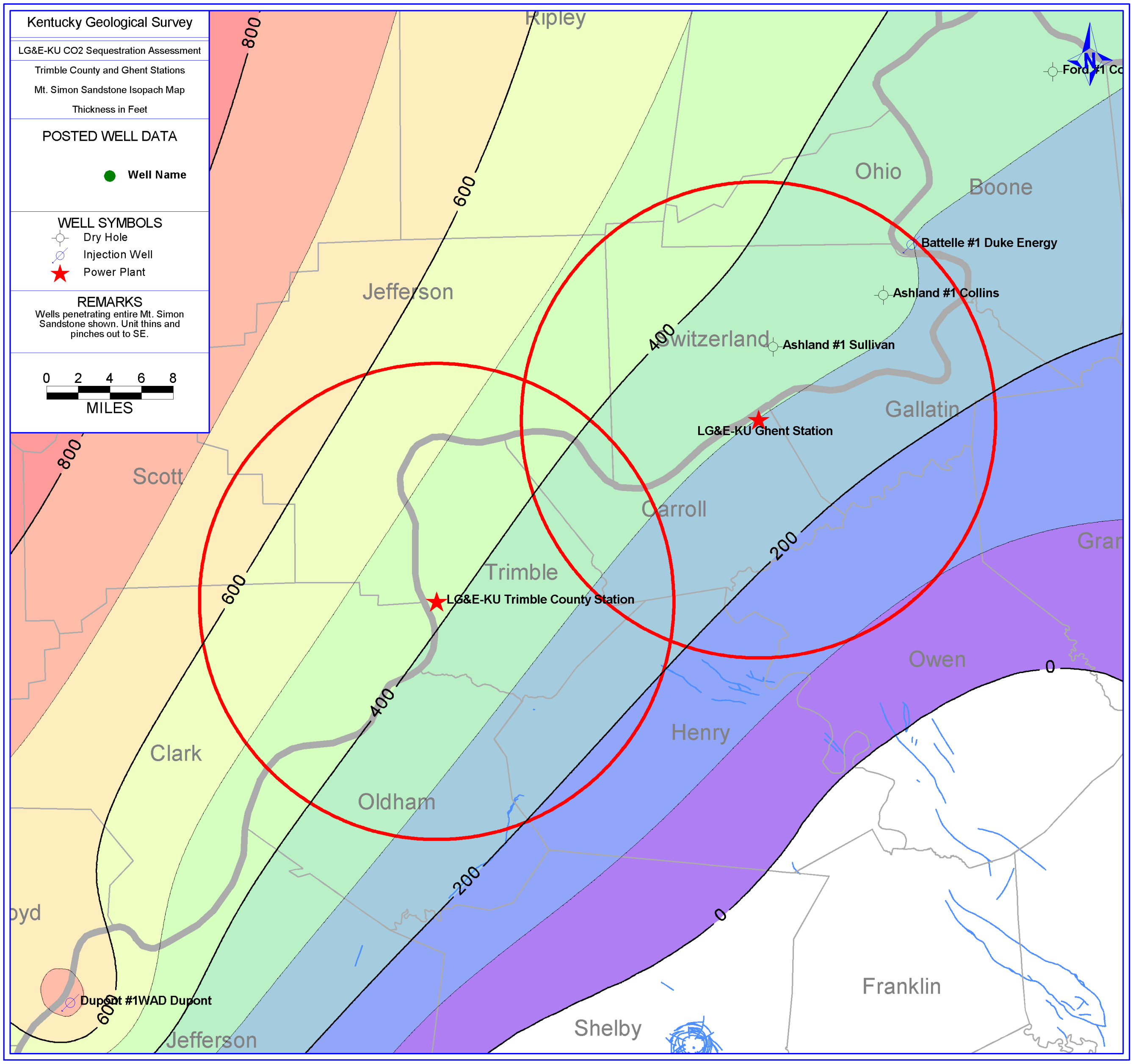

Figure 1-7. Thickness of the Cambrian Mount Simon Sandstone. Contour interval is 100 ft. The Mount Simon thins to the southeast and thickens to the west into the Illinois Basin. The Mount Simon is interpreted to pinch out at the zero contour line. This interpretation is based on data from several older seismic lines, and should be regarded as an approximate location.

The Knox isopach map (Fig. 1-11) shows that the unit thins by more than 1,000 ft from southwest to northeast across the study area. This thinning is primarily caused by erosional truncation at the top of the Knox during exposure after Knox deposition. This thinning is also illustrated on the regional cross section, Figure 1-12. The Knox is interpreted to be 2,300 ft thick at Trimble County and 2,034 ft thick at Ghent.

Ordovician Dutchtown Formation and Joachim Dolomite

The Dutchtown Formation and Joachim Dolomite are dolomite intervals that contain variable amounts of shale and overlie the Knox unconformity. They are equivalent to the Wells Creek Dolomite in Ohio, and are partly gradational with the St. Peter Sandstone. They generally have low porosity and permeability. They would provide additional

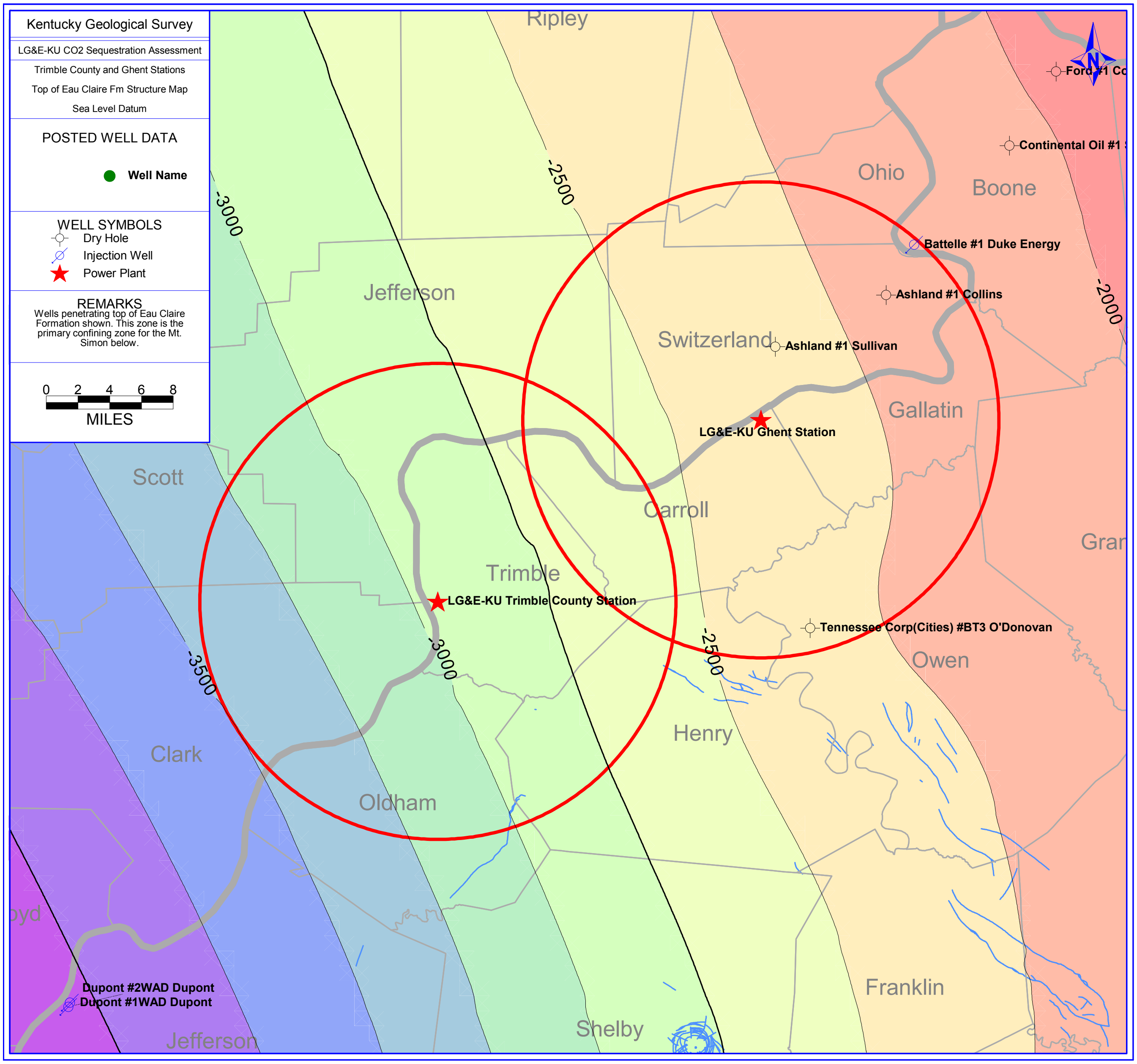

Figure 1-8. Thickness of the Eau Claire Formation. Shale and minor dolomite in this formation are more than 550 ft thick at both sites, providing an excellent seal for CO_2 injected into the underlying Mount Simon Sandstone.

confinement for CO_2 injected in deeper zones. The formations were not mapped in detail.

Ordovician Black River Group and Trenton Limestone

The Trenton Limestone and Black River Group together form a shallow secondary confining zone (seal) for CO_2 injected into the deeper Mount Simon Sandstone. These rocks are composed of limestone, minor dolomite, and interbedded shale. The interval typically has very low porosity and permeability unless fractured. In the Battelle No. 1 Duke Energy well, these formations have a combined thickness of 550 ft, with the top of the Trenton Limestone at 145 ft and the top of the Black River at 313 ft (depths below surface). On surface geologic maps for the area, the Trenton is named the Lexington Limestone (Swadley, 1973).

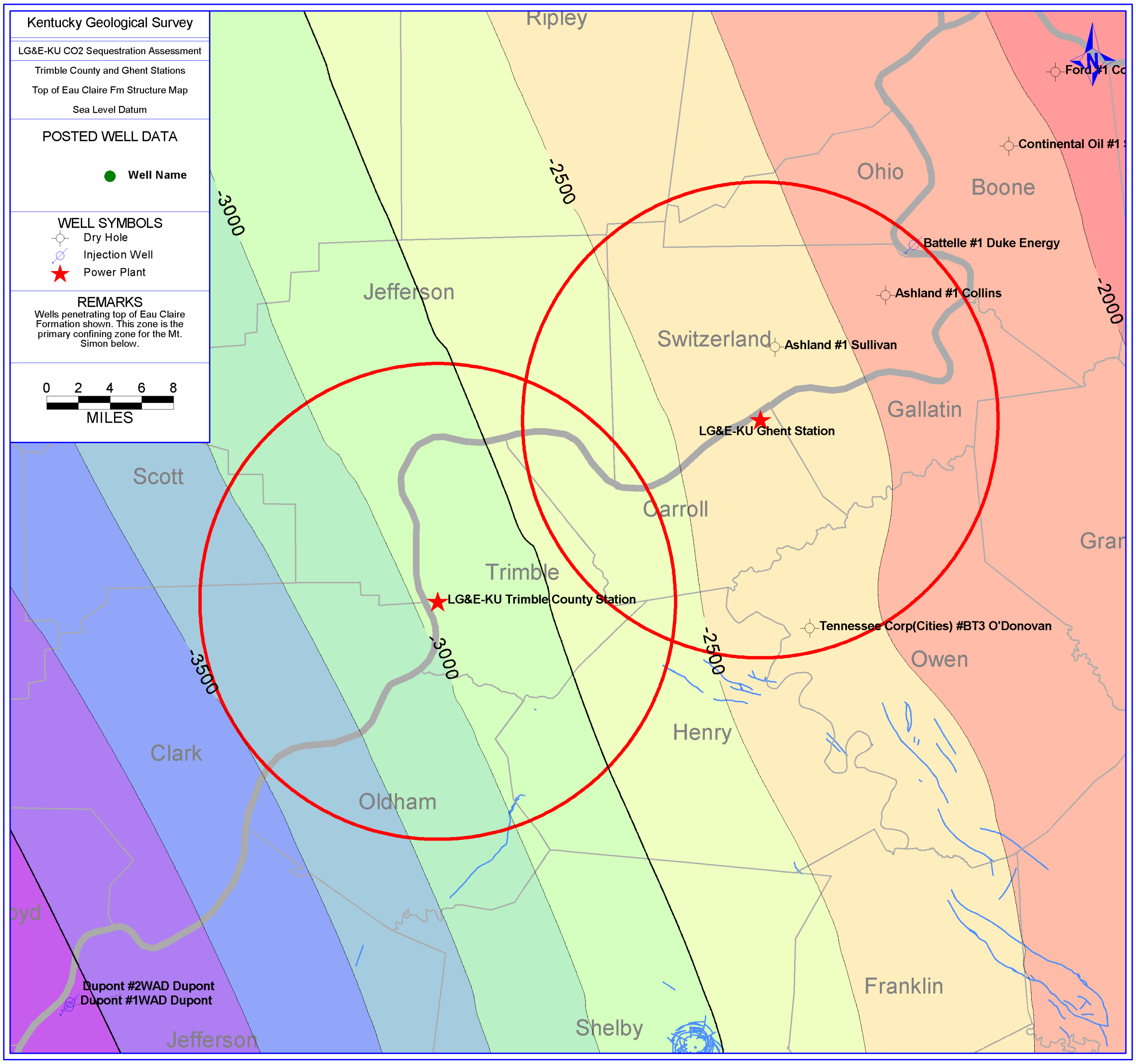

Figure 1-9. Structure on top of the Cambrian Eau Claire Formation. Contour interval is 250 ft. The structure dips to the southwest.

Near-Surface Formations

Formations at and near the surface in the study area include several Upper Ordovician units above the Trenton. Around Ghent, these include the Point Pleasant (Calloway Creek), Kope, Fairview Formation, Grant Lake Limestone, and Bull Fork Formation. Near the Trimble site, in addition to these formations, younger rocks are present, including the Late Ordovician Drakes and Early and Middle Silurian Osgood and Brassfield Formations and Laurel Dolomite. Because of their shallow depth, these units were not mapped in detail, but most of them will provide additional confining zones.

Deep Faults and Available Seismic Data

The only seismic data for the area are two short lines acquired at the Duke Energy East Bend Station prior to drilling of the CO_2 injection well

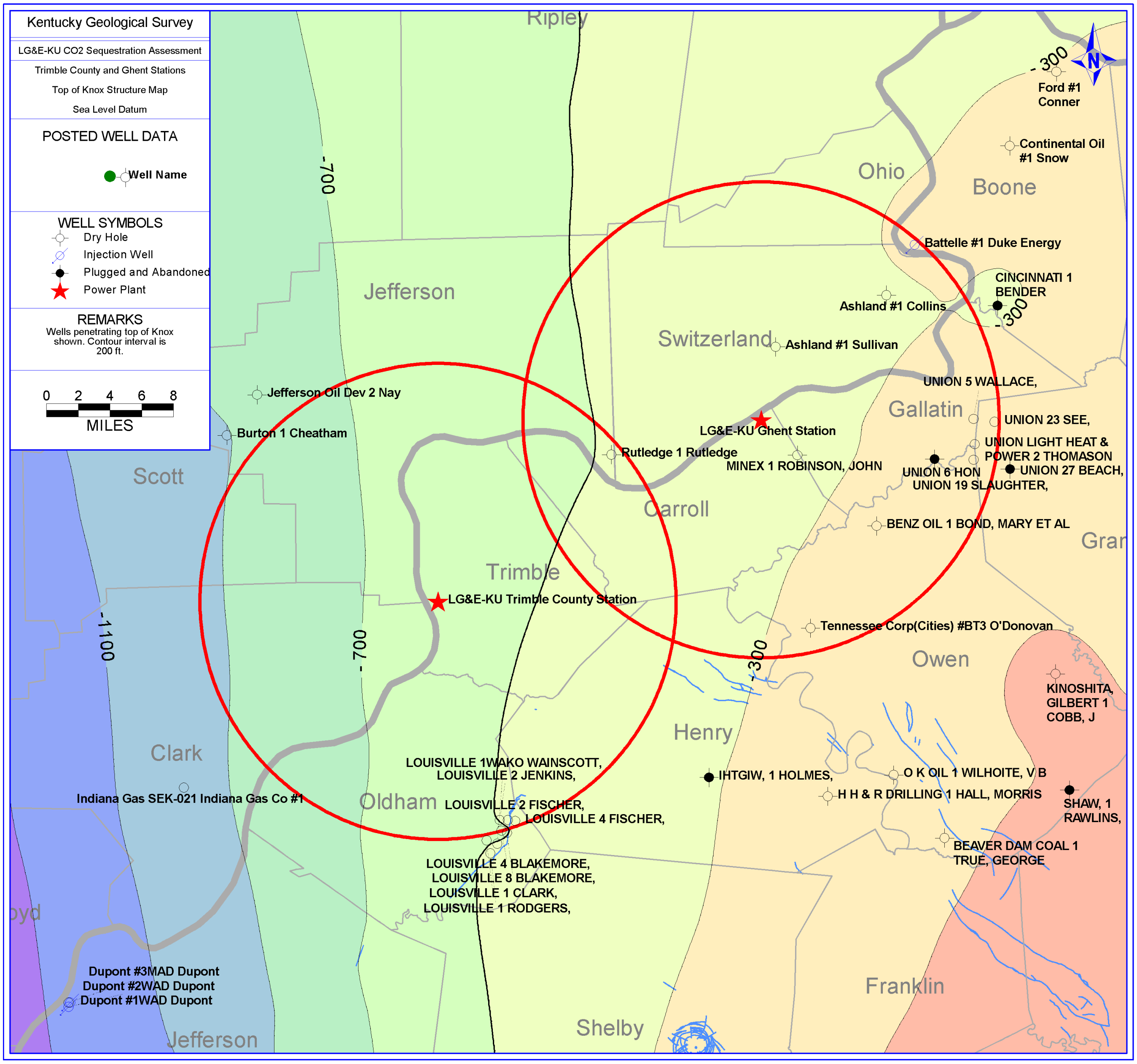

Figure 1-10. Structure on the top of the Knox Supergroup. Contour interval is 100 ft. The top of the Knox is a regional erosional surface, and the structure dips more westerly than in underlying formations. The upper part of the Knox is too shallow for carbon storage in this area.

in 2009. These lines show no faults near the East Bend site. Faults have been mapped at the surface near the study area, and are shown in blue on Figures 1-1 and 1-4. Only two of these faults are located within 15 mi of a plant site. The Ballardsville Fault crosses the southern edge of the 15-mi radius around the Trimble County site. This fault is in Oldham County and forms the trap and southeastern boundary of the former Ballardsville gas storage field, operated by LG&E. This natural-gas field was discovered in 1931 and later converted to gas storage in 1964 (Luft, 1977). Gas was stored in porous dolomite in the Knox Supergroup at depths around 1,250 ft. The fact that the Ballardsville Fault forms the southeastern boundary of the gas storage field indicates it is a seal, at least at shallow depths. Kepferle (1977) reported gas bubbles rising out of a stream bed about a mile southeast of the fault, but

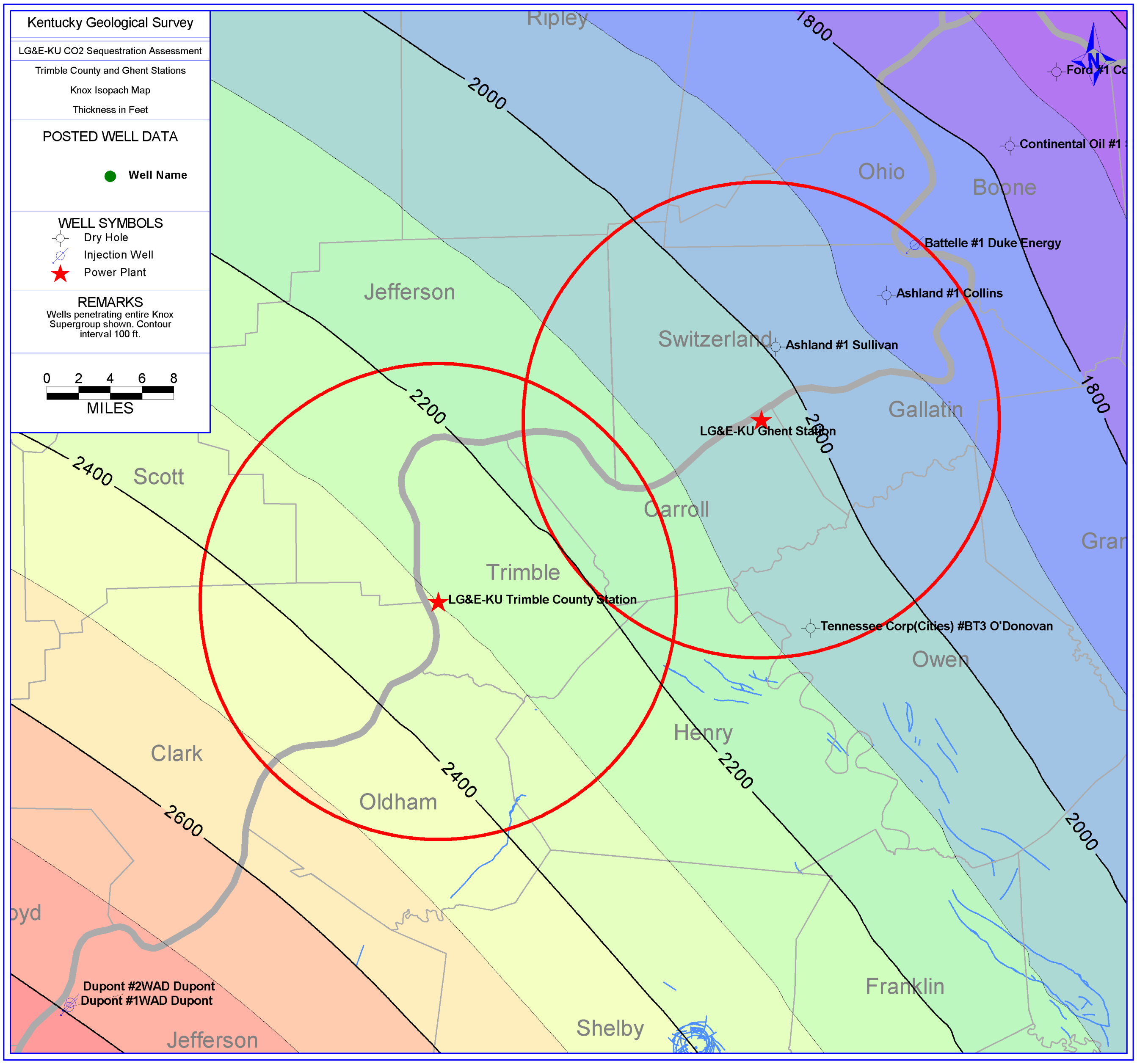

Figure 1-11. Thickness of the Knox Supergroup. The Knox thins to the northeast because of erosion on the post-Knox unconformity.

because of the distance, this seems to be unrelated to the fault or gas storage field.

There is also a northwest-southeast trend of faults that occur to the southeast of the plant sites. These faults define a graben, or downdropped fault block, in Franklin County in the Switzer quadrangle, and this has been named the Switzer Graben. The faults continue to the northwest into Owen and Henry Counties, but are more discontinuous. As mapped at the surface, one fault extends 0.2 mi across the southeastern edge of the 15-mi radius around the Trimble County site. The fault trend could extend farther to the northwest in the subsurface, but there are no seismic or well data to suggest this.

Reservoir Quality and Injection Zone Thickness

In order to calculate carbon sequestration capacity, the average porosity and thickness of the

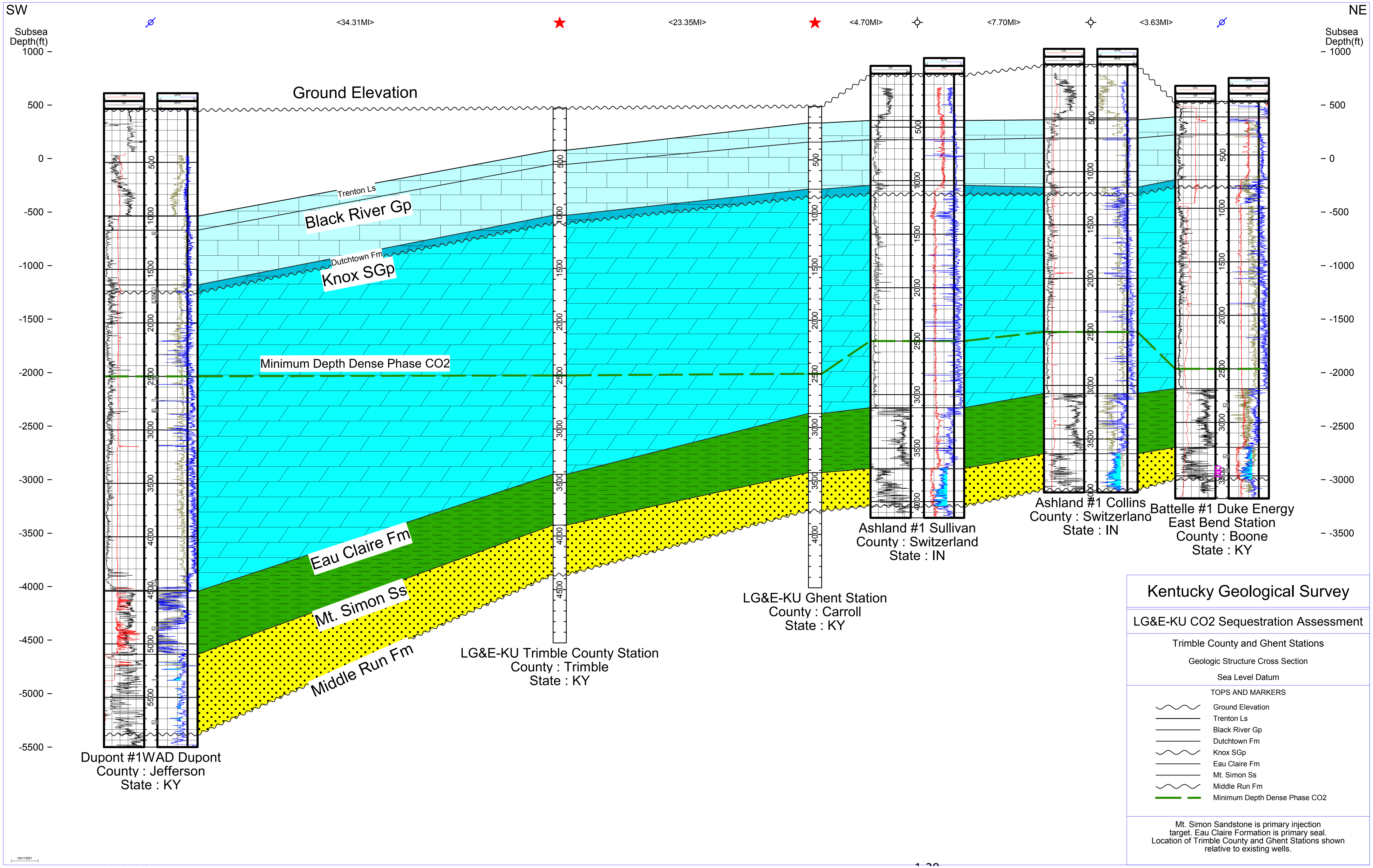

Figure 1-12. Southwest-northeast regional structure showing well logs for deep wells and the location of the Ghent and Trimble County Stations. The Mount Simon deepens to the southwest. Well logs include the gamma-ray in the left track, and density and neutron-porosity logs in the right track. The density-porosity log is shaded blue where porosity is greater than 7 percent in the Mount Simon Sandstone. The Eau Claire Formation is the primary seal for the underlying Mount Simon, and extends across the entire area.

storage zone are required. Since there are no wells drilled to the Mount Simon Sandstone at the Ghent and Trimble County plant sites, exact porosity data are not available. As such, reasonable estimates for porosity and net injection zone thickness were calculated from nearby well control. Data from the Duke Energy East Bend CO_2 injection test well were especially helpful, since high-quality well logs and core data are available from this well drilled in 2009.

Regional Porosity Trends

As in many sandstones, porosity in the Mount Simon Sandstone decreases with increasing burial depth. This is primarily because of cementation and compaction, and is a result of increased temperature, pressure, and the amount of time the rocks have been buried. A substantial set of Mount Simon porosity and permeability data from across the Midwest has been published by Medina and others (2011). Cross-plots of porosity versus depth in this paper establish a general correlation between porosity and depth. We found a dramatic decrease in porosity at depths below 7,000 ft. This depth generally corresponds to a porosity value of 7 percent, although the data vary significantly.

Porosity varies significantly in the Mount Simon within the current study area, and correlates with burial depth (Fig. 1-13). The DuPont No. 1 WAD well in Louisville was drilled to more than 6,000 ft to test the Mount Simon for hazardous-waste injection. Initial injection tests in the Mount Simon determined it lacked sufficient porosity and permeability for commercial waste disposal. An alternate zone in the shallower Knox Dolomite was eventually used as the injection zone. The average depth of the Mount Simon in the DuPont well is 5,600 ft, and the average log-derived sandstone porosity is 6.5 percent. The regional depth/porosity correlation proposed by Medina and others (2011) suggests that the Mount Simon has about 8.4 percent porosity at 5,600 ft. This means that the DuPont well has lower porosity than predicted for its depth. The reason for this is not known, but the DuPont well provides a deep control point that must be considered for prediction of porosity at the Trimble County and Ghent sites.

Northeast of Trimble County and Ghent are three wells in which the Mount Simon is much shallower than in Louisville. In the two Ashland Oil wells in Switzerland County, Ind., and the Duke Energy East Bend well in Boone County, Ky., the Mount Simon occurs at depths of 3,400 to 3,900 ft. In these three wells the average log-derived sandstone porosity is 13 percent, double that at Louisville. The Ghent and Trimble County sites lie intermediate between the poor porosity at Louisville and the much higher porosity in Boone and Switzerland Counties (Fig. 1-13). The methodology for estimating porosity and reservoir thickness at the two sites is discussed below.

Site-Specific Porosity Estimates

Both well-log and core porosity data were used to estimate porosity at Ghent and Trimble County. Core measurements are the most accurate method of determining porosity and permeability. Core-derived porosity and permeability data for the Mount Simon are available from cores at the Duke Energy East Bend well and the DuPont No. 1 WAD well in Louisville.

Core data are not available for all wells, and cores typically are cut for a limited interval within the Mount Simon. Thus, the best zones are not always cored. Porosity (but not permeability) data are also derived from downhole well logs, especially the bulk-density log. Logs provide a continuous data set for the entire formation, but are not as accurate as core data. A total of four wells with density logs were used to estimate sandstone porosity at the plant sites (the DuPont and Duke Energy wells, and the two Ashland Oil wells in Switzerland County, Ind.).

Core data from the Duke Energy East Bend and the DuPont No. 1 WAD well (Louisville) are presented in Figures 1-14 and 1-15. The porosity and permeability versus depth plots (Figs. 1-14a, b) also include data from the overlying Eau Claire Formation core from East Bend. The Mount Simon core data help to illustrate the range of porosity and permeability in the area. There is considerable variation in porosity and permeability within the limited depth range of the cores. Despite this, the DuPont core data show overall lower porosity and permeability than the cores at East Bend. As discussed previously, this is related to the greater burial depth.

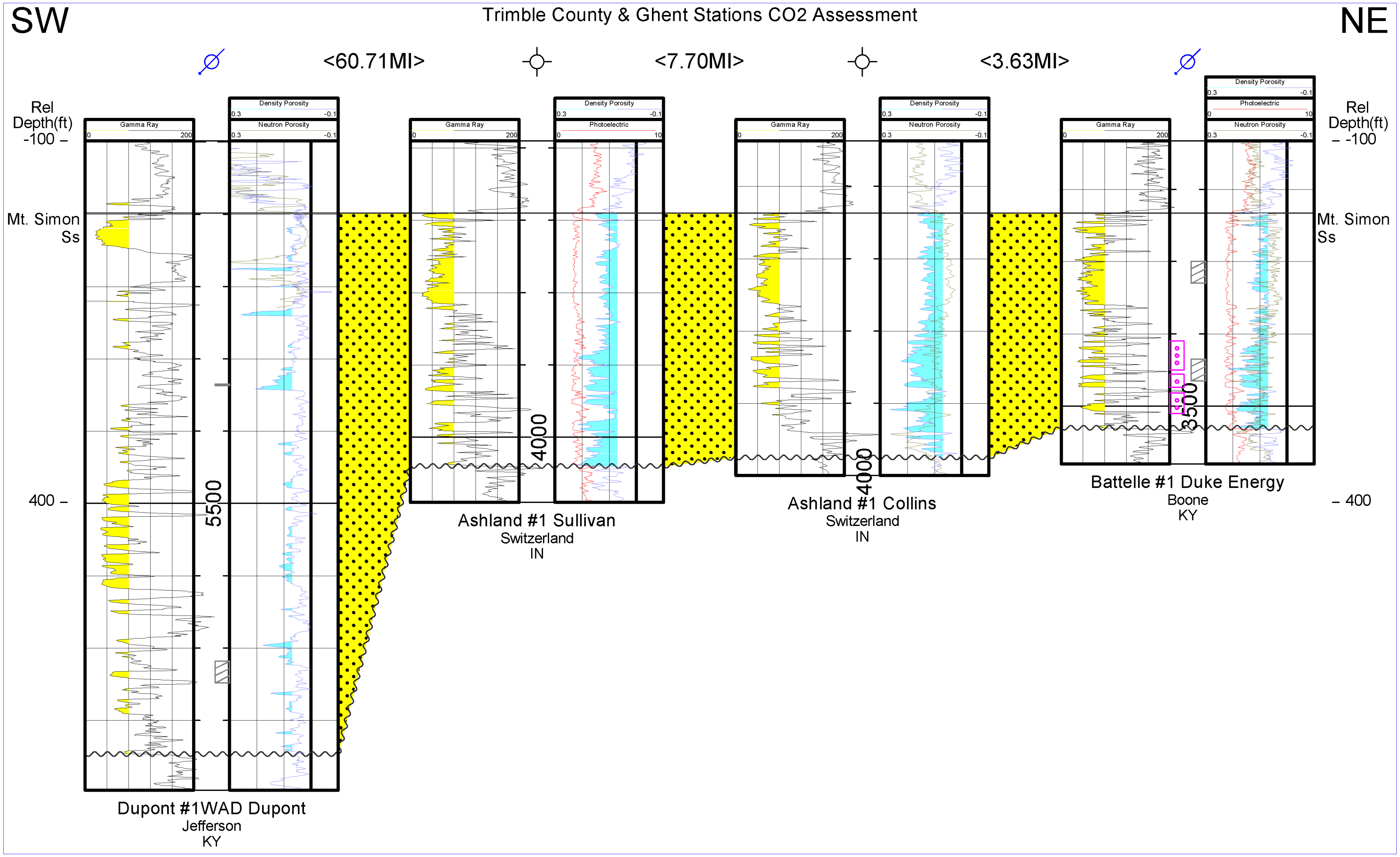

Figure 1-13. Detailed well-log cross section of Mount Simon Sandstone from Louisville (SW) to Rabbit Hash, Ky. (NE), illustrating variation in porosity and thickness. Logs are spaced evenly, and the section is flattened on the top of the Mount Simon, with depths shown in the center track. The density-porosity log in the right track is shaded blue where porosity is greater than 7 percent. The gamma-ray log in the left track is shaded yellow where the gamma-ray is less than 80 units (clean sandstone). The three shallow wells have significant sandstone intervals with porosity above 7 percent, whereas the deeper DuPont well in Louisville has very little porosity greater than 7 percent. The Ghent and Trimble County sites lie in the 60-mi gap between the DuPont and Ashland Sullivan wells. Cored intervals are indicated between the DuPont and Ashland Sullivan wells. Cored intervals are indicated by the diagonally striped boxes on the right side of the depth tracks. The CO_2 injection zone in the East Bend well is indicated by the red box with circles on the left side of the depth track.

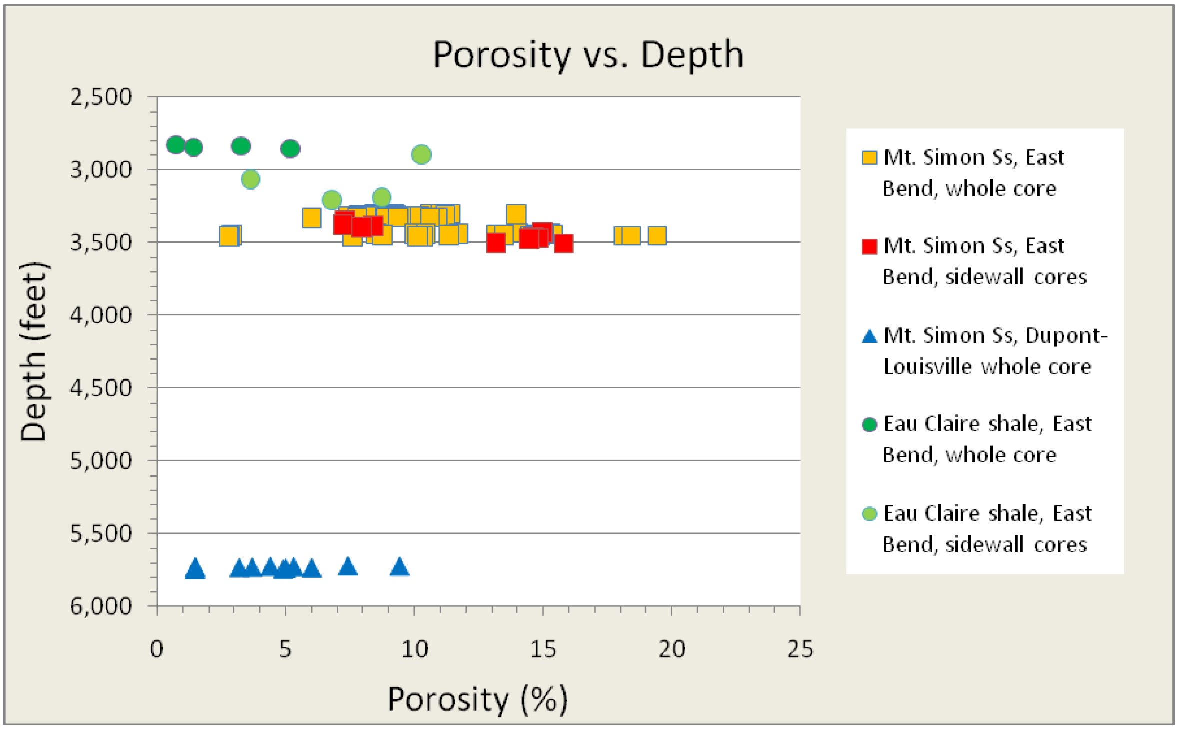

Figure 1-14a. Core porosity versus depth below surface for Mount Simon Sandstone (reservoir) and Eau Claire Formation (seal) core from the Duke East Bend and DuPont No. 1 WAD wells. Mount Simon porosity in the DuPont cores is significantly lower because of deeper burial depth. Average porosity for East Bend sidewall cores is 11.9 percent; for East Bend whole core plugs, 10.4 percent; and for the DuPont core plugs, 4.3 percent.

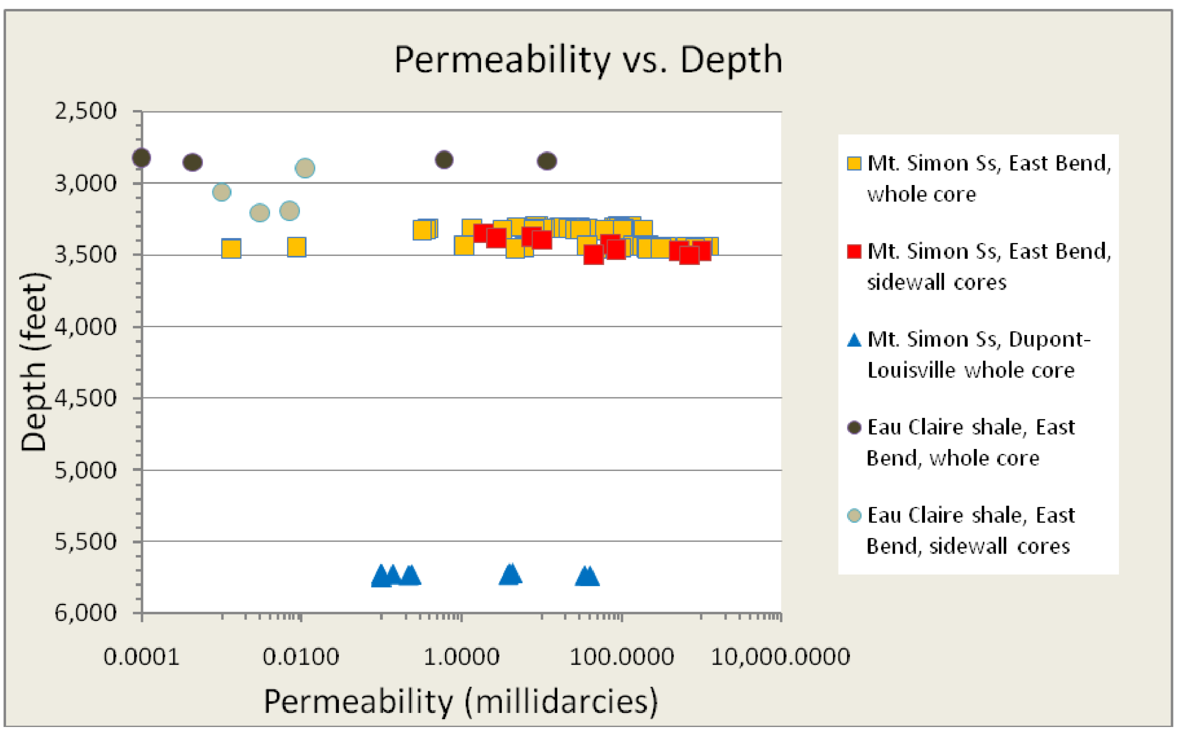

Figure 1-14b. Core permeability versus depth below surface for Mount Simon Sandstone and Eau Claire Formation. Permeability is quite variable, but is lower in the DuPont cores and in the Eau Claire shales. Average permeability for the East Bend sidewall cores is 246 md; for East Bend whole core plugs, 143.4 md; and for the DuPont core plugs, 6.1 md.

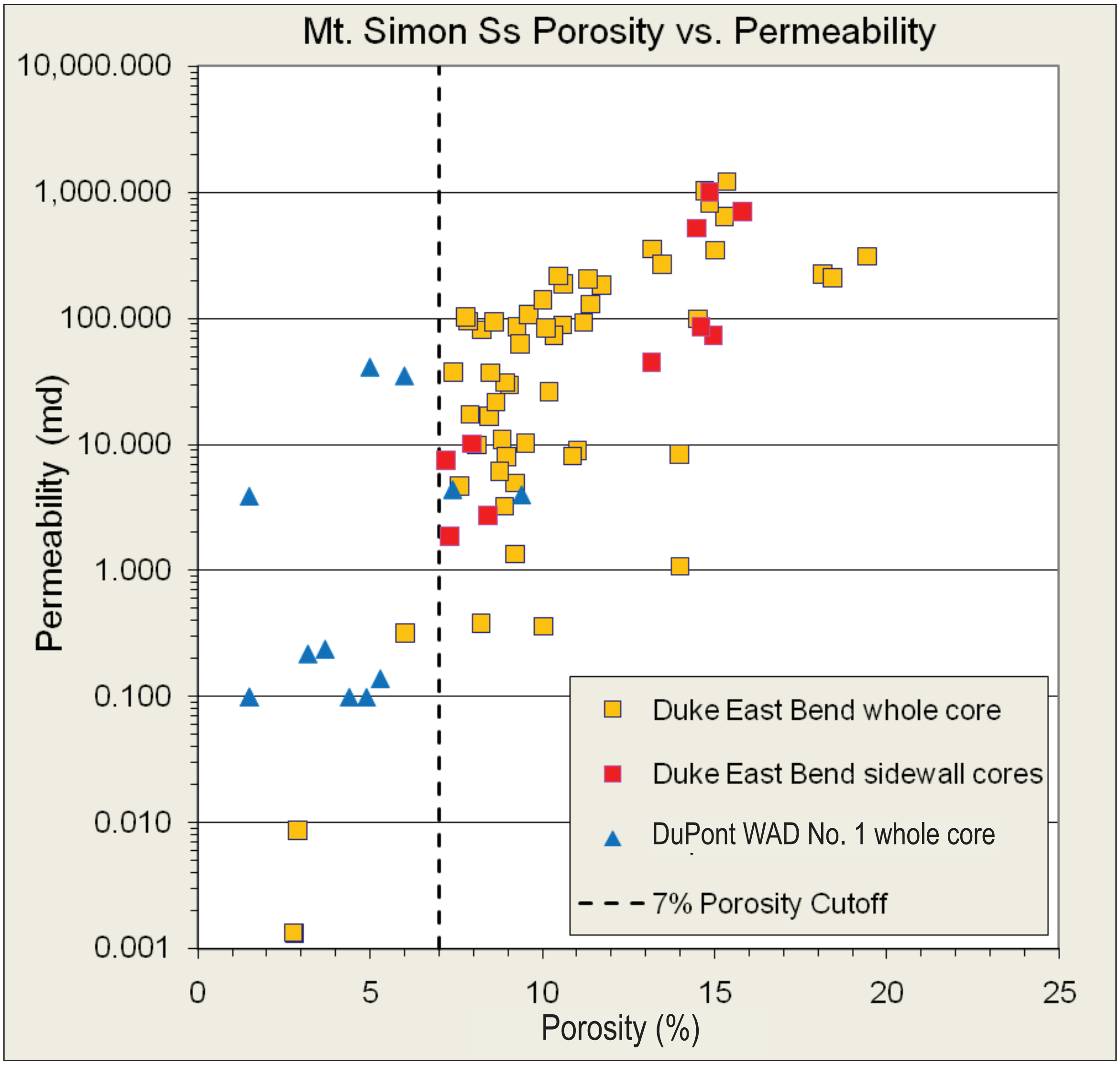

Figure 1-15. Mount Simon Sandstone core porosity versus permeability plot for the Duke East Bend and DuPont No. 1 WAD wells. In general, permeability decreases rapidly below 7 percent porosity, and this trend was the basis for the 7 percent porosity cutoff used to calculate net reservoir thickness.

Plotting porosity versus permeability illustrates the positive correlation between the two measurements (Fig. 1-15). This plot allows a minimum porosity to be interpreted for sandstone with acceptable permeability for injection. Because porosity can be measured with downhole logs and permeability cannot, this cutoff allows the thickness of rock with suitable porosity and permeability for injection to be summed from porosity-log data alone.

Based on the core data in Figure 1-15, a minimum porosity of 7 percent was chosen as the porosity cutoff in this area. The 7 percent porosity line separates the majority of the East Bend data (permeability greater than 10 md) from the DuPont core data, where injection was not successful. Medina and others (2011) also used a 7 percent porosity cutoff for the Mount Simon across the Midwest in their calculation of CO_2 sequestration capacities. Their cutoff, based on a much larger data set, is supported by the core data used in this study.

Calculation of Net Porous Sandstone

Once a porosity cutoff was chosen, the footage of net porous sandstone and average porosity of sandstones above the cutoff was determined for use in CO_2 capacity calculations. Because the Mount Simon Sandstone contains thin shales and some argillaceous sandstones with poor reservoir quality, only clean sandstone was included in the net sandstone calculation. The gamma-ray log is the best discriminator of clay and shale, and a cutoff of 80 API gamma-ray units was used to identify clean sandstone. Intervals with 80 or less API gamma-ray units were classified as sandstone. This 80 API unit cutoff is very close to the 75 API cutoff used by Medina and others (2011) in their Mount Simon study.

A log analysis program (Petra) was used to calculate the number of feet of Mount Simon in each well with a gamma-ray reading of less than 80 API units, and density porosity (calculated using a sandstone matrix) greater than or equal to 7 percent. The results of the net sandstone calculation are shown in Table 1-1. Average log porosity and total porosity-feet (thickness of void space) were also calculated. Gross thickness is the total Mount Simon thickness. A net-to-gross sandstone ratio was calculated for each well to allow a similar thickness to be calculated at the Trimble County and Ghent sites using the total mapped thickness. The net-to-gross ratio ranges from 0.57 at East Bend to 0.15 in the Louisville DuPont well, reflecting the decrease in porous sandstones with increasing depth. Average log-derived porosity of the net sandstone interval ranges from 14.4 percent in the Ashland Collins well to 8.7 percent in the DuPont well.

Table 1-1 also includes calculated data for the Ghent and Trimble County sites. The gross thickness was taken from the thickness map of the Mount Simon at each location (Fig. 1-7). Then a net sandstone footage was calculated using the net-to-gross ratios determined from the four analog wells. For the Ghent site, a ratio of 0.53 was used, because the site is very close to the Ashland Sullivan well. This yields a net sandstone estimate for Ghent of 160 ft. The Ghent site is slightly deeper than the Sullivan well (see cross section, Figure 1-12), so a slightly lower average porosity of 12 percent was assigned. This is essentially the same average porosity as at the Duke East Bend well.

Estimates for the Trimble County site are more difficult because there are no wells to the Mount Simon within a 15-mi radius of the plant. Trimble County is intermediate in depth between the DuPont well in Louisville (34 mi southwest) and the three shallower wells about 35 mi to the northeast. The predicted gross thickness of the Mount Simon at Trimble County is 366 ft (Fig. 1-7). A net-to-gross ratio of 0.33 was used for Trimble County, intermediate between 0.53 in the Ashland wells and 0.15 in the DuPont well. This yields a predicted net sandstone thickness of 121 ft. Average porosity at Trimble County is estimated to be 10 percent, again chosen as an intermediate value between the DuPont well to the southwest and the three shallower wells. The porosity predicted for Trimble County is reduced because of the poor porosity at the DuPont well. Comparison with regional data suggests the DuPont well has lower porosity than it should for its depth (Medina and others, 2011). If this is a local anomaly, Trimble County may have better porosity than the conservative number used here.

Table 1-1. Mount Simon reservoir data.

Mount Simon Sandstone Well-Log Data	*Average Depth (below surface, ft)*	*Gross Thickness (ft)*	*Net Porous Sandstone < 80 Gamma-Ray and > 7% Porosity (ft)*	*Net-to-Gross Ratio*	*Average Log Porosity of Net Porous Sandstone (%)*	*Porosity Feet*
Duke Energy East Bend	3,400	297	170.0	0.57	11.90	20.3
Ashland Collins	3,800	338	178.0	0.53	14.40	25.6
Ashland Sullivan	3,900	350	186.0	0.53	13.40	25.0
DuPont No. 1 WAD	5,600	748	111.5	0.15	8.70	9.6
Calculated data						
Ghent Station	3,650	301	160.0	0.53	12.00	19.2
Trimble County Station	4,200	366	121.0	0.33	10.00	12.1

CO_2 Capacity Calculations

Using compiled and calculated data, CO_2 storage volume was calculated. CO_2 storage capacity is based on the porosity, thickness, and acreage of the injection zone, and density of the injected CO_2. CO_2 density is a function of reservoir pressure and temperature. The Mount Simon interval is deep enough for supercritical-phase CO_2 injection at both Ghent and Trimble County. CO_2 density calculations were made using the CO_2 properties calculator at the MIDCARB project Web site: www.midcarb.org/calculators.shtml. The Midcontinent Interactive Digital Carbon Atlas and Relational dataBase was produced by a research consortium composed of the state geological surveys of Illinois, Indiana, Kansas, Kentucky, and Ohio, funded by the U.S. Department of Energy.

Calculated CO_2 densities are shown in Table 1-2. CO_2 density is higher at Ghent than at Trimble County despite the shallower depth. This is because of the lower reservoir temperature.

The following parameters are required inputs to calculate CO_2 storage capacity:

Reservoir pressure: assumed hydrostatic and calculated at 0.433 psi/ft for the reservoir depth

Temperature: taken from well-log data in Boone and Jefferson Counties

Reservoir thickness: the net porous sandstone thickness as calculated above

Reservoir area: standard area of 100 acres

Reservoir porosity: the average porosity for the net reservoir footage

The equation for CO_2 storage capacity, modified from Medina and others (2011), is:

$$SC=A_n * h_n * \Phi_n * \rho_{CO2} * \dot{\varepsilon}/1{,}000$$

where SC is the storage capacity in metric tons, A_n is the area in square meters, h_n is the net reservoir thickness, Φ_n is the average porosity of the net reservoir, ρ_{CO2} is the density of CO_2 at reservoir conditions, and $\dot{\varepsilon}$ is the storage efficiency factor (discussed below).

The Ghent Station has a higher storage capacity than the Trimble County Station, because of greater reservoir thickness, higher porosity, and higher CO_2 density. The reservoir parameters used and CO_2 capacities calculated are shown in Table 1-3.

Efficiency of CO_2 Storage

The storage capacity equation used above includes an efficiency factor, which reduces the CO_2 storage capacity. This factor is applied because 100 percent of the available pore volume is never completely saturated with CO_2 because of fluid characteristics and geologic variability within the reservoir.

Litynski and others (2010) calculated efficiency factors for carbon storage in various reservoir types that account for factors that reduce the volume of CO_2 that can be stored. These factors include:

Table 1-2. Calculated CO_2 density at reservoir conditions.

CO_2 Density	*Reservoir Pressure (psi)*	*Reservoir Temperature (°F)*	*CO_2 Density (lb/ft³)*	*CO_2 Density (kg/m³)*
Ghent	1,600	100	44.5	713.14
Trimble County	1,800	110	43.3	693.60

Table 1-3. Input parameters and calculated CO_2 storage capacity for a 100-acre area at 100 percent and 14 percent storage efficiencies.

Site	*Net Reservoir Thickness (ft)*	*Net Reservoir Thickness (m)*	*Porosity*	*CO_2 Density (kg/m³)*	*CO_2 Capacity at 100% Efficiency (metric tons)*	*Storage Efficiency Factor*	*CO_2 Capacity at 14% Efficiency (metric tons)*
Ghent	160	48.8	0.12	713.14	1,688,924	0.14	236,449
Trimble County	121	36.9	0.10	693.60	1,035,206	0.14	144,929

Geologic Factors

- Net-to-total area ratio of a basin suitable for sequestration
- Net-to-gross thickness ratio of a reservoir that meets minimum porosity and permeability requirements
- Ratio of effective to total porosity (fraction of connected pores)

Displacement Factors

- Areal displacement efficiency: area around a well that can be contacted by CO_2
- Vertical displacement efficiency: fraction of vertical thickness that will be contacted by CO_2
- Gravity: fraction of reservoir not contacted by CO_2 due to buoyancy effects
- Displacement efficiency: portion of pore volume that can be filled by CO_2 due to irreducible water saturation

Combining all of these factors using a Monte Carlo simulation results in a probability range of total efficiency factors of 0.51 to 5.4 percent (P_{10} to P_{90} range) (Litynski and others, 2010). For the purposes of this assessment, we can assume the *geologic* factors are equal to 1. In our 100-acre unit, the net to total area is the same, the net to gross thickness has already been calculated and used in the calculation, and for clastic reservoirs (sandstones) we can assume that the porosity is well connected with a ratio of effective (connected) porosity to total porosity equal to 1. Litynski and others (2010) calculated efficiency factors for just the *displacement* factors separately, and for sandstone reservoirs they range from 7.4 to 24 percent, with a P_{50} (most likely) efficiency factor of 14 percent. This means the most likely case is that 14 percent of the pore space can be filled with CO_2. The range of storage volumes using the probabilistic efficiency factors for each site is shown in Table 1-4.

The application of an efficiency factor significantly reduces the storage capacities, but is necessary to determine reasonable volume estimates.

Summary

Both Ghent and Trimble County Stations have good potential for geologic storage of CO_2 beneath the site property. The Mount Simon Sandstone is the only formation with suitable porosity and permeability at the depths required for supercritical-phase sequestration. Excellent confinement for injected CO_2 is provided by the Eau Claire Formation, which is more than 500 ft thick.

Geologic data control for Ghent is good, with several wells to the reservoir within a 15-mi radius, including the Duke Energy East Bend CO_2 injection well. The proximity of the East Bend well to Ghent lowers the risk of finding a suitable reservoir, and excellent core, log, and engineering data are available from this research project. Two short seismic lines were acquired at the East Bend site, almost 15 mi from Ghent. Although helpful in mapping, these lines are not close enough to characterize the Ghent site. There are no surface faults mapped within a 15-mi radius. Ghent has a higher calculated CO_2 storage volume per acre than Trimble County because of shallower depth and higher porosity, which results in a higher net reservoir thickness. The Mount Simon structure map (Fig. 1-6) indicates that injected CO_2 would migrate slowly to the northeast, parallel to the Ohio River. Migration of some CO_2 under the river into Indiana is possible, but this would depend on the volume of CO_2 injected and the length of time. If this is a concern, an injection simulation could be run to predict the CO_2 plume size and direction over time. KGS does not currently have this modeling capability, but it may be available in the near future.

The Trimble County site has very similar geology to Ghent, but geologic data are scarcer. There are no wells to the Mount Simon within a 15-mi radius of the site. The Mount Simon Sandstone is likely to be thicker at Trimble than at Ghent, but it lies about 500 ft deeper, resulting in less porosity and thinner net reservoir thickness. The Trimble

Table 1-4. Range of probabilistic storage volumes using DOE's displacement efficiency factors for clastic reservoirs (Litynski and others, 2010).

Site	*Minimum Volume (metric tons/100 acres) $\dot{\varepsilon}$ = 7.4% (P_{10})*	*Most Likely Volume (metric tons/100 acres) $\dot{\varepsilon}$ = 14% (P_{50})*	*Maximum Volume (metric tons/100 acres) $\dot{\varepsilon}$ = 24% (P_{90})*
Ghent	124,980	236,449	405,342
Trimble County	76,605	144,929	248,449

County site is closer to Louisville, where a waste-disposal well was unable to establish commercial-rate injection in the Mount Simon. Reservoir quality is thought to be adequate for injection at Trimble County, but with lower storage volumes predicted than at Ghent, and with a higher level of risk because of the lack of nearby data. The Eau Claire Formation seal is good and similar to that at Ghent, but there are mapped surface faults that just cross the 15-mi buffer to the east and south of the site. These faults do not appear to continue toward the site, but seismic data would be necessary to confirm their extent in the subsurface. The dip of the Mount Simon is similar to that at Ghent, but because of the location of the Ohio River, injected CO_2 migrating northeast (updip) from Trimble County would remain in Kentucky for at least 14 mi. Depending on volumes and rates of injection, part of the CO_2 plume could grow to the southwest (downdip) of the plant site, under the river. As at Ghent, injection simulations could be run to predict the size and shape of the CO_2 plume over time.

Using the most likely storage volumes at each site, the following volume of CO_2 could be stored at each site, using property owned by LG&E-KU (Table 1-5).

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Table 1-5. Total storage volume onsite assuming 100 percent use of LG&E-KU property.

Site	*CO_2 Storage Volume (metric tons per acre)*	*Total Property Size (acres)*	*Total Onsite Storage Volume (metric tons)*
Ghent	2,364	2,178	5,149,866
Trimble County	1,449	2,192	3,176,841

Chapter 2: Geologic CO_2 Sequestration Potential of the LG&E-KU Green River Station, Western Kentucky

LG&E-KU CO_2 Sequestration Geologic Summary Sheet

Power Plant: Green River **County:** Muhlenberg **Geologic Basin:** Illinois Basin

Data Quality:	
Distance to nearest well control in reservoir:	3.0 mi (partial penetration)
Wells to primary injection zone within 15-mi radius:	4
Distance to nearest core in injection zone:	10.7 mi
Distance to nearest good-quality seismic control:	3.6 mi
Reservoirs:	
Primary injection zone:	Cambrian-Ordovician Knox Group
Rock type:	dolomite with interbedded sandstones
Drilling depth at plant site:	6,421–8,000 ft
Trapping mechanism:	regional dip (capillary and solution trapping)
Average reservoir pressure:	3,300 psi (assuming 100,000 ppm TDS)
Reservoir temperature:	130°F
Salinity of reservoir fluid:	100,000 ppm
Reservoir thickness (gross/net):	36/11.1 ft
Average porosity:	9.7 percent
Average permeability:	1.2 md (calculated)
Secondary injection zone:	none at this site
Confinement and Integrity:	
Primary confining zone:	Maquoketa Shale
Rock type:	shale and siltstone
Thickness of primary confining zone:	545 ft
Height above primary injection zone:	875 ft
Well penetrations of primary seal within 15-mi radius:	6
Secondary confining zone:	Devonian New Albany Shale
Rock type:	black shale
Thickness of secondary confining zone:	225 ft
Height above primary injection zone:	2,690 ft
Well penetrations of secondary seal within 15-mi radius:	43
Number of faults cutting primary seal within 15-mi radius:	7 (fault zone segments)
Distance to nearest mapped fault:	6.8 mi
Storage Capacity:	
Calculated CO_2 storage capacity, primary injection zone:	345,515 million metric tons/100 acres (assuming 100 percent efficiency) 72,558 metric tons/100 acres (at 21 percent efficiency)

Data compiled and interpreted from well records maintained by the Kentucky Geological Survey.

Introduction

Geologic CO_2 sequestration potential was evaluated for an area surrounding the LG&E-KU Green River Station in Muhlenberg County, Ky. A circular area with a 15-mi radius around the plant was defined as the primary focus of the evaluation, but data from beyond 15 mi were also used because of limited data from the primary area (Fig. 2-1).

The following data were compiled for the evaluation:

1. The 7.5-minute topographic and geologic quadrangle maps for the Central City East, Central City West, Equality, and Livermore quadrangles
2. Locations of all petroleum-exploration and waste-disposal wells penetrating the Upper Ordovician Maquoketa Shale or deeper formations
3. Formation tops for geologic units from the top of the Ordovician to the Middle Cambrian strata
4. Available digital geophysical logs for Knox and deeper wells
5. Reflection-seismic data, including the purchase and interpretation of three new profiles in Ohio, Muhlenberg, and Hopkins Counties, Ky.

Within the 15-mi radius around the Green River Station, four wells have been drilled that penetrate the target reservoir (Knox Group), including one well (Conoco No. 1 Turner) that penetrates the entire Paleozoic section, ending in Precambrian rocks. These wells provide the key geologic data used in this assessment. Geologic data relating to the injection zone from the Kentucky Geological Survey No. 1 Marvin Blan well in Hancock County, Ky., were also used, even though the well is 23 mi outside the project radius. The data from this more distant well were added to the review because of the quality and quantity of the subsurface data acquired at this research well. Core analyses, formation image logs, and injection data were available from this well. All of these wells penetrated the primary injection zone (Knox Group) and overlying seal (Maquoketa Shale).

Geologic Setting and Surface Geology

The Green River Station is located in the southernmost Illinois Basin, within the Moorman Syncline. This east–west-trending syncline (concave-upward fold structure) within Mississippian, Pennsylvanian, and Quaternary strata is a sag feature that formed above the Cambrian Rough Creek Graben. The borders of the Rough Creek Graben are formed by basement-rooted fault systems: the Rough Creek Fault System to the north (exposed in McLean and Ohio Counties; Figure 2-1) and by the Pennyrile Fault System to the south (Christian, Muhlenberg, and Butler Counties; Figure 2-1). Despite the numerous exposed faults in the study area, no evidence has been found to suggest that any of these faults have been active since the Permian Period (more than 250 million years ago).

The Green River Station is located on the western edge of the Central City East 7.5-minute quadrangle, and a geologic map for this quadrangle by Palmer (1972) was published by the U.S. Geological Survey. The station is located on unconsolidated Quaternary alluvium sediments (Fig. 2-2). The hills northwest of the station are underlain by Middle to Upper Pennsylvanian sandstones, siltstones, shales, limestones, and coal of the Patoka Formation (Pp in Figure 2-2). The area in green to the south of the station is hills formed by sandstone, shale, and coal of the Lower to Middle Pennsylvanian Shelburn Formation (Psh in Figure 2-2). The change in colors in the map area northwest of the station (Livermore quadrangle) in Figure 2-2 represents a slightly different stratigraphic classification system, and not an abrupt change in surface geology. Surface geology does not have a direct impact on carbon sequestration potential, since carbon dioxide injection will occur at much deeper depths. More information about these quadrangle maps and units is available online at kgs.uky.edu/kgsmap/KGSGeology/viewer.asp.

The surface geology will have an impact on the design and implementation of shallow groundwater monitoring wells that will be required by the U.S. EPA for an underground injection control permit. The presence of unconsolidated alluvium along the Green River should reduce the

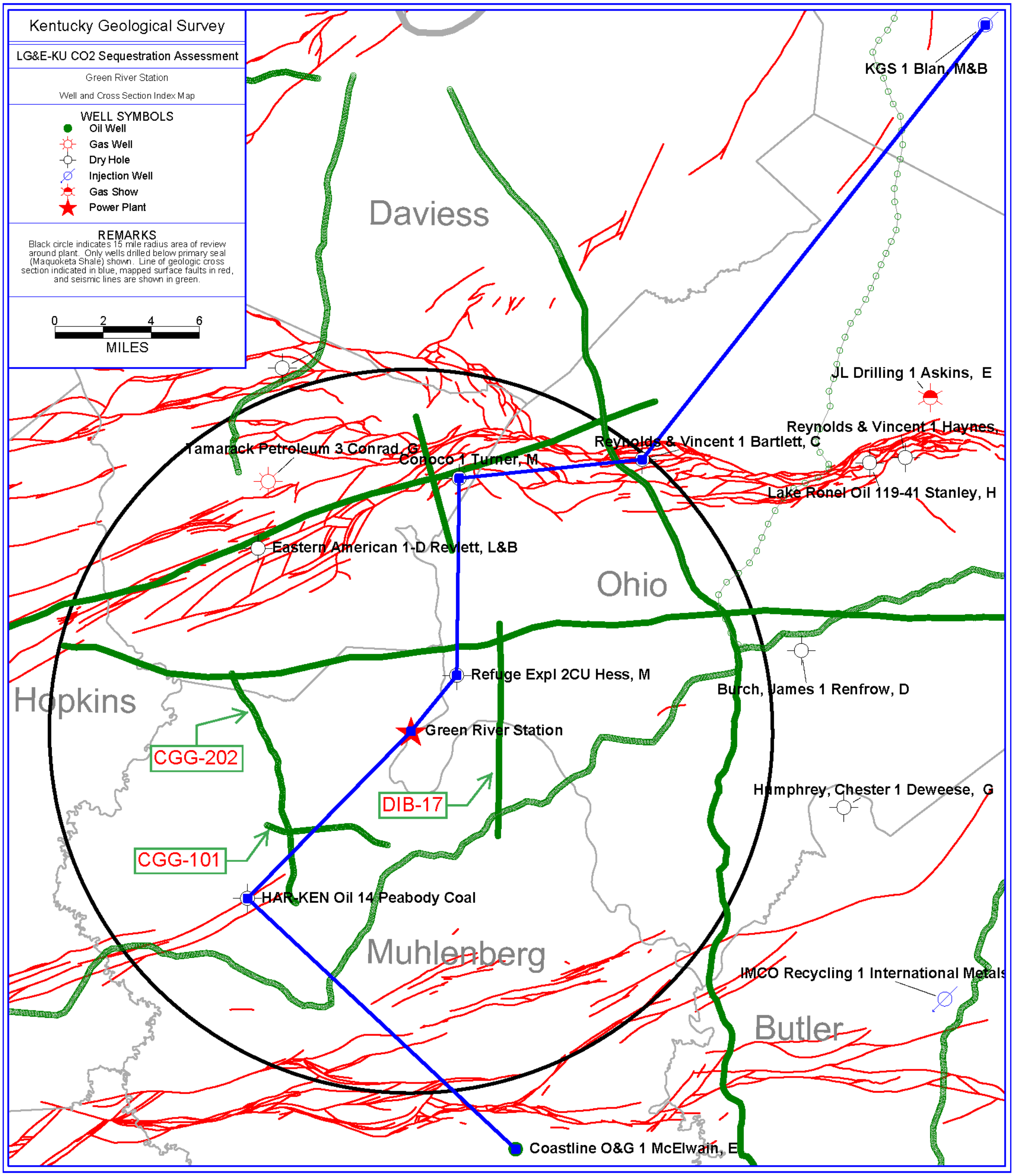

Figure 2-1. Location of the Green River Station in western Kentucky. The study area is enclosed by the black circle. Red lines are faults mapped at the surface and green lines are the locations of seismic profiles used in the study. Wells drilled deeper than the Maquoketa Shale are shown. See Figure 2-2 for surface geology. Blue line is the location of the north-south cross section shown in Figure 2-3.

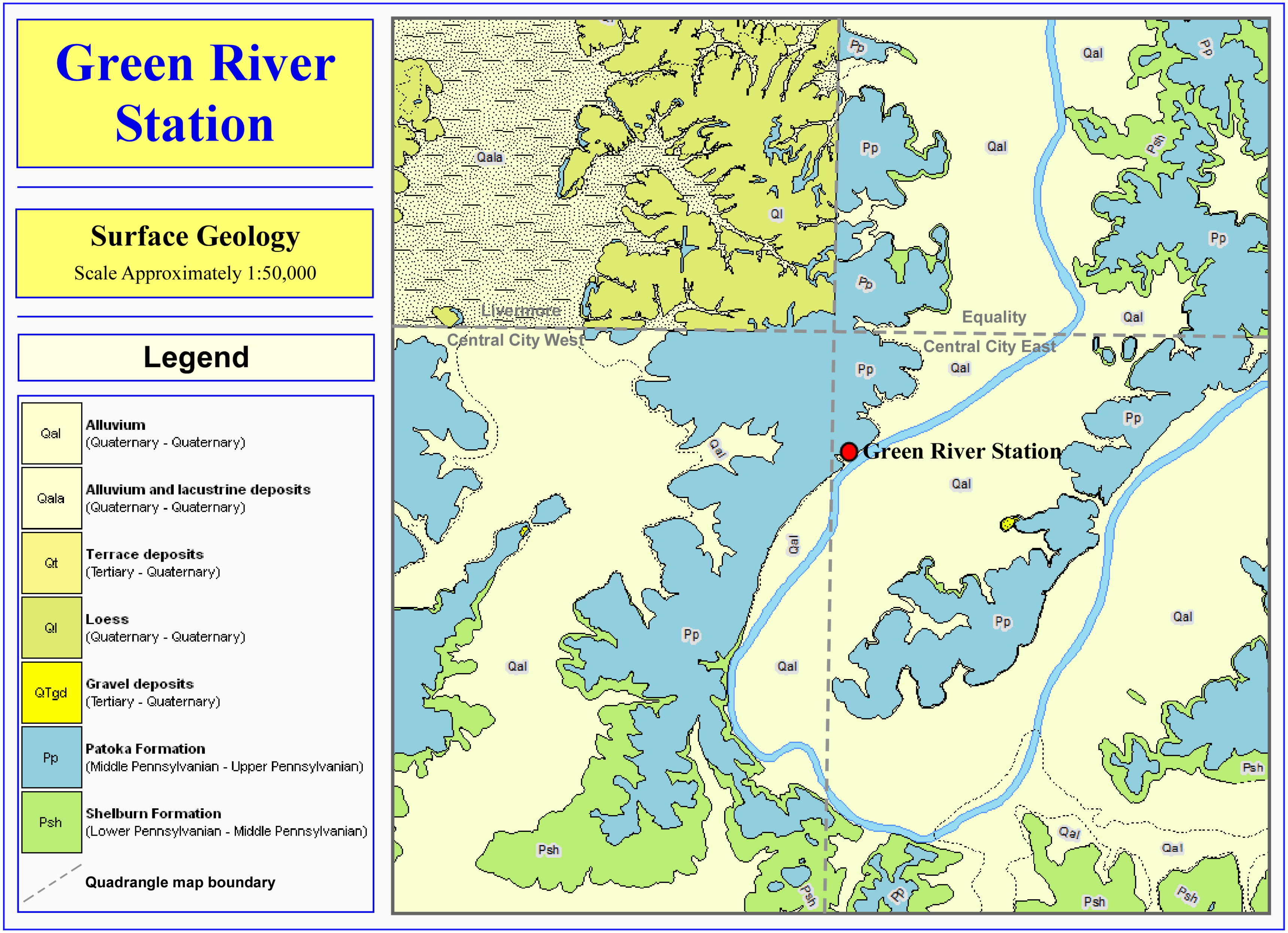

Figure 2-2. Geology of parts of the Central City East (Palmer, 1972), Central City West (Palmer, 1969), Equality (Goudarzi, 1969), and Livermore (Hanson and Smith, 1978) 7.5-minute quadrangles surrounding the Green River Station. Hanson and Smith (1978) used slightly different classifications for unlithified surficial units than the authors of the other geologic quadrangle maps.

overall expense of the construction of monitoring wells. The UIC permit will likely require monitoring down to the base of the underground source of drinking water, defined as having water with less than 10,000 ppm of total dissolved solids, which will require drilling into bedrock.

Stratigraphy and Structure

In areas with normal subsurface temperature and pressure gradients, geologic storage of CO_2 is confined to depths greater than 2,500 ft below the surface so that CO_2 exists in the supercritical, or dense, phase. Supercritical CO_2 has properties of both a liquid and a gas, but much higher density than gaseous CO_2. This results in significant increases in storage capacity within the same storage reservoir. In the Green River Station area, this 2,500-ft depth falls within Upper Mississippian strata (primarily limestones and siltstones). Although these formations can be porous, the lack of an adequate confining unit or stratigraphic seal make these units unsuitable for the storage of CO_2.

The two formations below 2,500 ft that are considered appropriate for use as confining layers in this area are the Upper Devonian New Albany Shale (around 3,500 ft depth) and the Upper Ordovician Maquoketa Shale (at around 5,000 ft). The Silurian Laurel Dolomite is the only porous unit that lies between the New Albany and Maquoketa Shales, but its limited thickness in this area (about 10 ft) makes it unsuitable as a commercial-scale injection target. For these reasons, the Maquoketa Shale will be considered the primary confining unit, with the stratigraphically higher New Albany Shale acting as a secondary confining unit. At shallower locations, the Middle Ordovician Black River Limestone is also considered as a secondary confining unit because of its low porosity and permeability. However, the deeper burial at the Green River site has produced extensive fracturing within this unit, which therefore limits its sealing capacity.

The only unit evaluated for storage capacity at this site is the Upper Cambrian to Lower Ordovician Knox Group. Reservoir zones within the Knox include dolostones with both primary (intergranular) and secondary (vugular) porosity, as well as interbedded porous sandstones.

Unlike at other LG&E-KU study sites, the base of the proposed injection zone at the Green River Station is defined by depth-related porosity loss within the Knox Group, and not by the base of a stratigraphic unit (Fig. 2-3). The depth at which porosity within the Knox is insufficient for storage of CO_2 (less than 7 percent porosity) is around 8,000 ft in the Green River Station area.

Middle Cambrian Eau Claire Formation

The deepest unit evaluated in this study is the Eau Claire Formation. The Eau Claire directly underlies the Knox Group and is predominantly composed of green and gray marine shales, with some interbedded dolomite. The Eau Claire has very low porosity and permeability. Figure 2-4 is a structure map contoured on the top of the Eau Claire. The Eau Claire deepens to the west into the deeper parts of the Rough Creek Graben. The drilling depth to the top of the Eau Claire at the Green River Station is estimated to be 12,300 ft, based on regional seismic interpretation. No units with porosity suitable for CO_2 storage are expected or interpreted below the top of the Eau Claire Formation. Unlike at the Ghent, Trimble, and Mill Creek sites, the Mount Simon Sandstone is not present at this location.

Upper Cambrian–Lower Ordovician Knox Group

Within the Illinois Basin, the Knox Group is divided into two dolomite units: the Beekmantown Dolomite and the Copper Ridge Dolomite, separated by sandstone or a dolomitic sandstone unit of the Gunter Sandstone. Because the Gunter is poorly developed in this area, this study analyzes the Knox Group as a whole without differentiation. The top of the Knox is a regional erosional unconformity that formed when the Knox Group rocks were uplifted above sea level during the Early Ordovician. The Knox Group lies at a subsurface elevation of about 6,010 ft below sea level (Fig. 2-5), and is approximately 5,900 ft thick at the Green River site (Fig. 2-6). The Knox contains scattered porous and permeable intervals separated by impermeable dolomite. It has injection potential in other parts of Kentucky (such as the location of the Kentucky Geological Survey No. 1 Marvin Blan research well in Hancock County) and was used

E.ON US CO2 Sequestration Potential Assessment

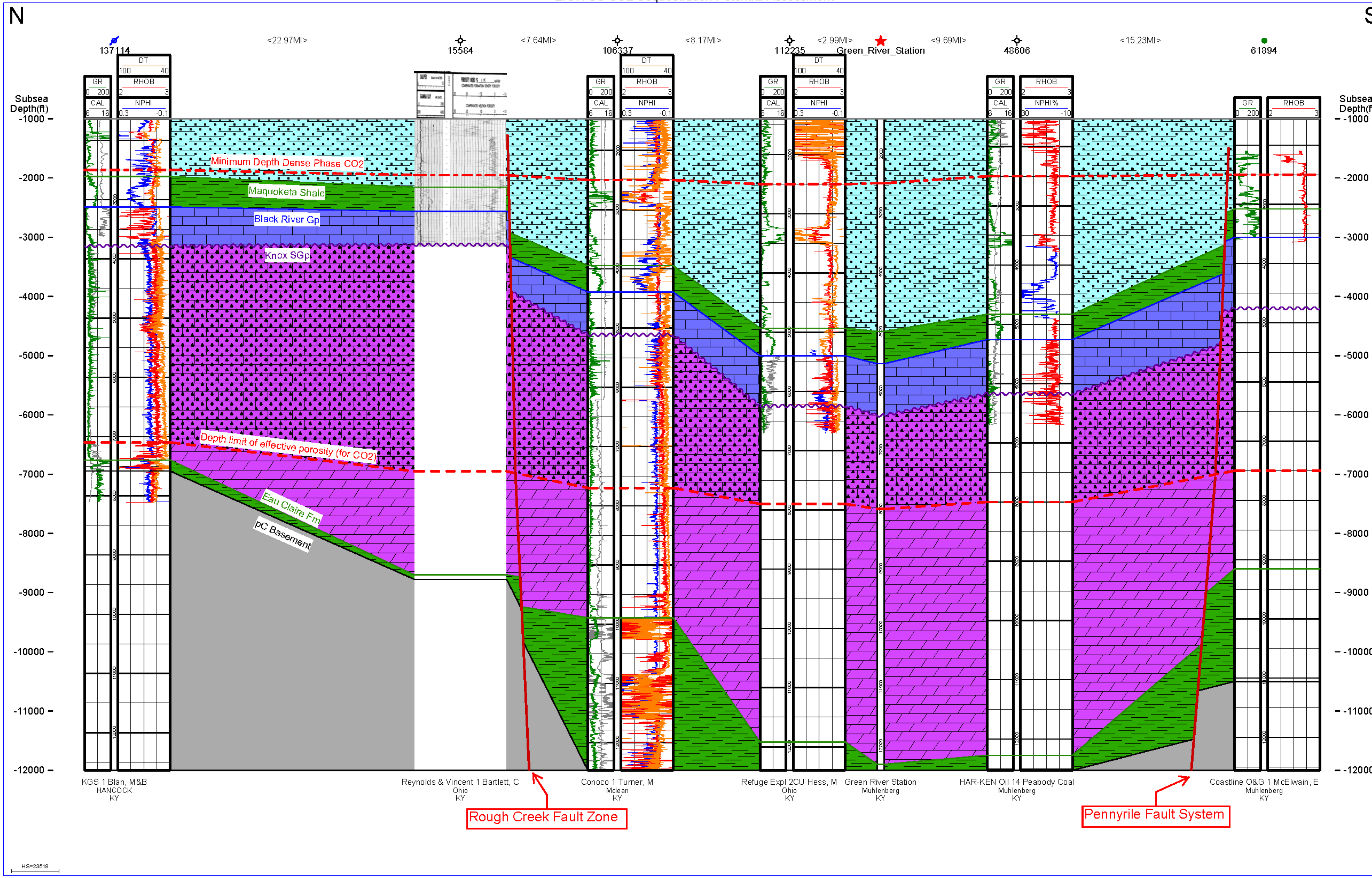

Figure 2-3. North-south regional structural cross section showing well logs for deep wells and the location of the Green River Station. Basement offsets along faults (near the edge of the 15-mi study radius) are not to scale. Well logs are the gamma-ray and caliper in the left track and bulk-density, neutron-porosity, and sonic logs in the right track. Stratigraphic tops below logged intervals (and total depth of wells) were interpreted from regional seismic data. The Maquoketa Shale is the primary seal for the underlying Knox, and extends across the entire area.

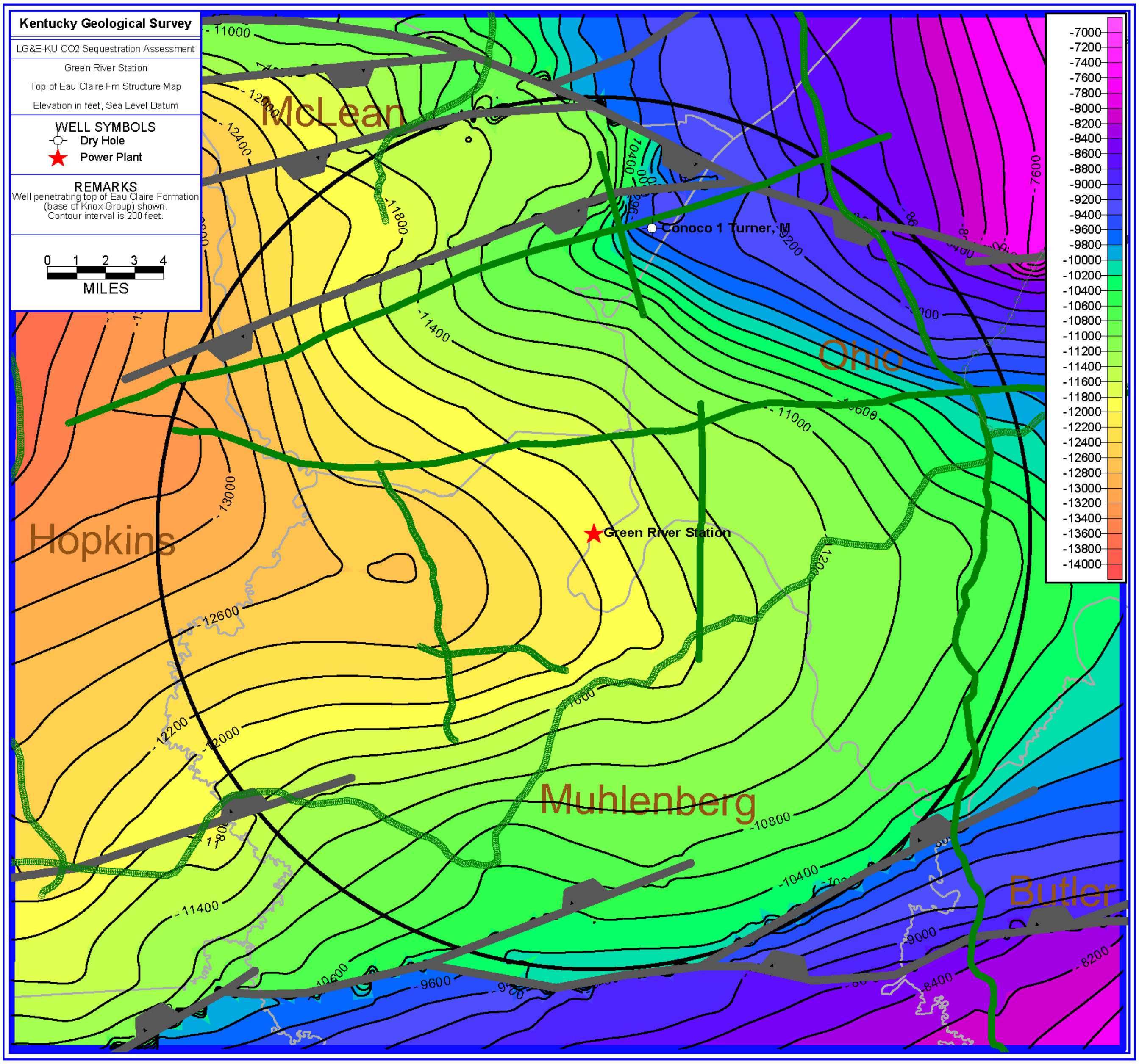

Figure 2-4. Structure on top of the Cambrian Eau Claire Formation. The structure deepens to the west. Regional fault systems are marked in dark gray, seismic profiles in green. The contour interval is 200 ft.

as a hazardous-waste injection zone at the DuPont chemical plant in Louisville. Porous zones in the Knox have also been used for natural gas storage by LG&E in Grant and Oldham Counties (Ballardsville and Eagle Creek storage fields). These storage fields are now abandoned, and the porous zones in them are too shallow for CO_2 storage.

Within the Rough Creek Graben, the Knox Group deepens and thickens to the west. All of the Knox in the study area lies below the 2,500 ft depth limit for CO_2 to be in a supercritical phase. However, the lower part of the Knox (below 7,500–8,000 ft depth) is not an injection target, because the primary porosity (and therefore permeability) has been destroyed by the compaction of burial. Only units with 7 percent or more porosity are suitable for sequestration, so the compaction alters the effective reservoir thickness of the Knox to about 1,575 ft at the Green River Station (Fig. 2-7). This depth limitation reverses the trend shown on the overall

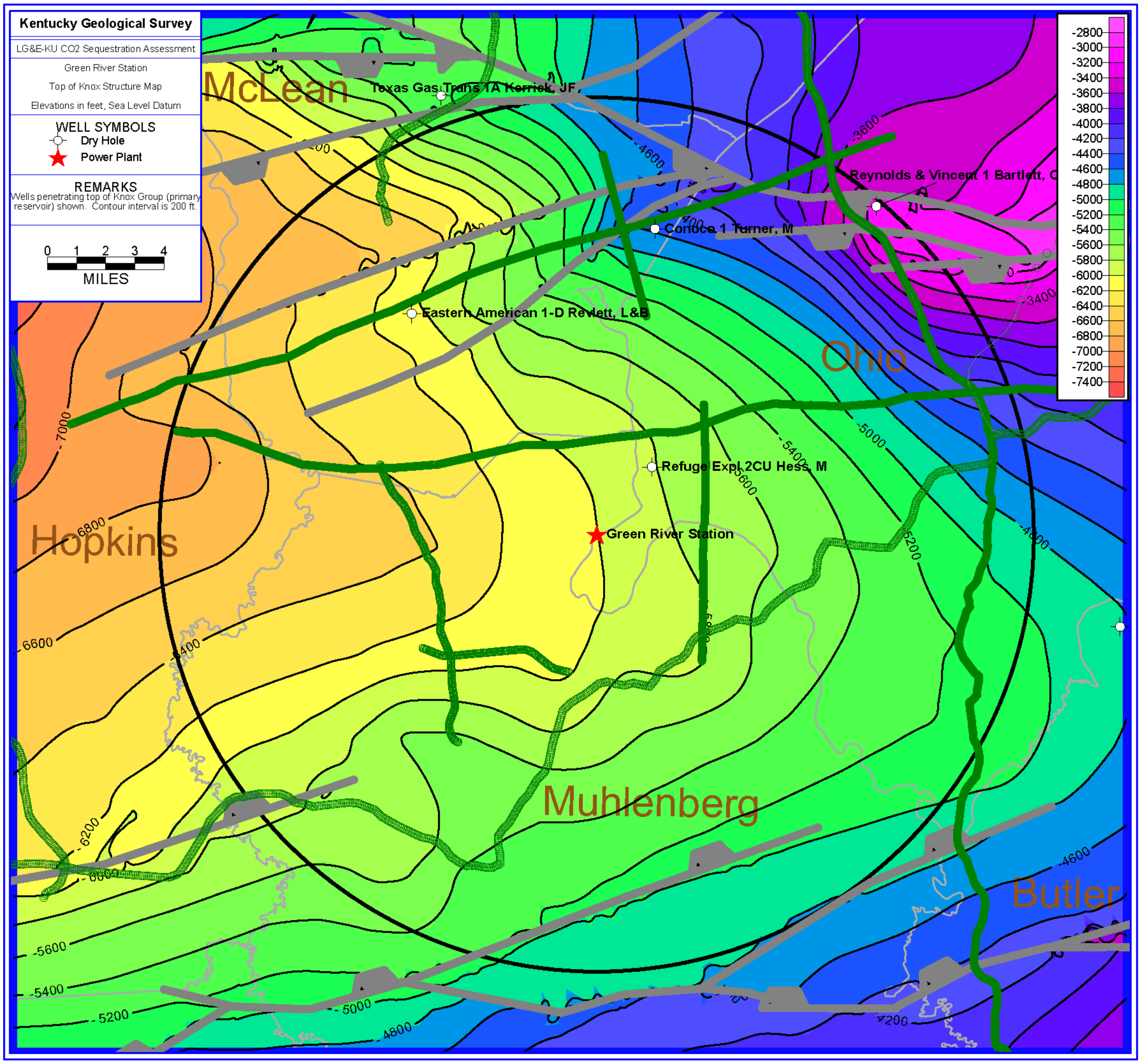

Figure 2-5. Structure on top of the Knox Group. Regional fault systems are marked in dark gray, seismic profile data locations in green. Contour interval is 200 ft. The top of the Knox dips to the west at the site.

thickness map (Fig. 2-6), so that the target interval thickens to the east (Fig. 2-7) and toward the northern and southern boundaries of the Rough Creek Graben (Fig. 2-8). Thus, within the 15-mi radius, the usable thickness of the Knox varies from around 700 ft in eastern Hopkins County to around 4,200 ft in central Ohio County, Ky.

Dutchtown Formation and Joachim Dolomite of the Ordovician Ancell Group

The Dutchtown Formation and Joachim Dolomite are dolomite intervals that contain variable amounts of shale, and immediately overlie the Knox unconformity. They are equivalent to the

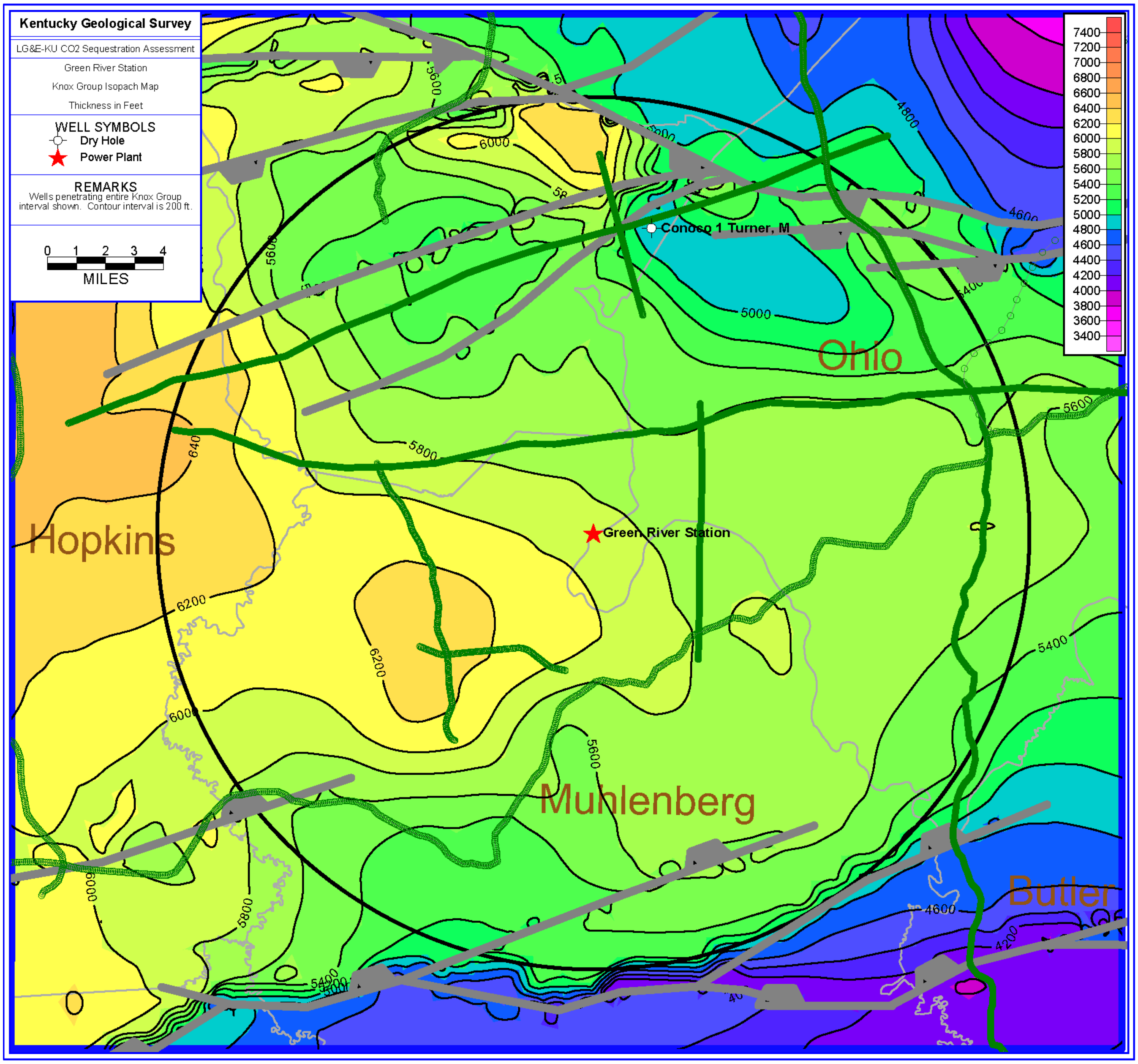

Figure 2-6. Thickness of the entire Knox Group interval.

Wells Creek Dolomite in Ohio and are partly gradational with the St. Peter Sandstone. They generally have low porosity and permeability, and may provide additional confinement for CO_2 injected in deeper zones. The formations were not mapped in detail in this study.

Ordovician Black River Group

In shallower areas, the Black River Group forms a secondary confining zone (seal) for CO_2 injected into the deeper Knox Group. The top of the Black River is at about 5,545 ft depth below the Green River Station (Fig. 2-9), where the interval

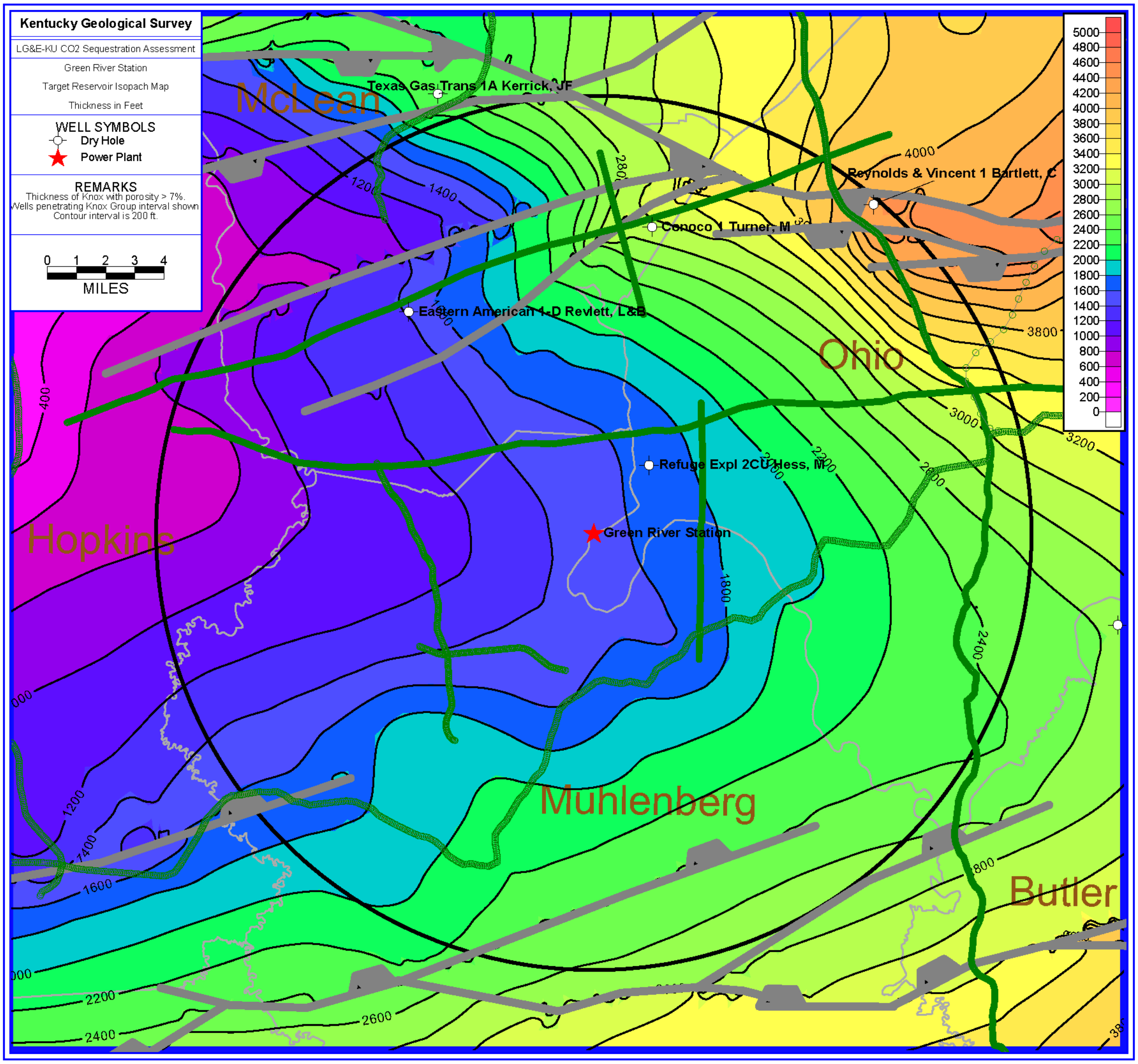

Figure 2-7. Thickness of the upper porous zone of the Knox Group above –7,600 ft in elevation (about 8,000 ft depth).

is about 875 ft thick. These rocks are composed of limestone with minor amounts of dolomite. The interval typically has very low porosity and permeability unless fractured from faulting or burial. Unfortunately, the Black River Group in the area surrounding the Green River Station appears to be extensively fractured, making it unsuitable as a seal.

Upper Ordovician Maquoketa Shale

The Maquoketa Shale is the primary confining unit for the Knox Group at the Green River site. The Maquoketa Shale does not directly overlie the Knox injection target, but instead lies roughly 875 ft above the top of the Knox Group (separated by the rocks of the Ancell and Black River Groups). The Maquoketa Shale is composed of mudstone and

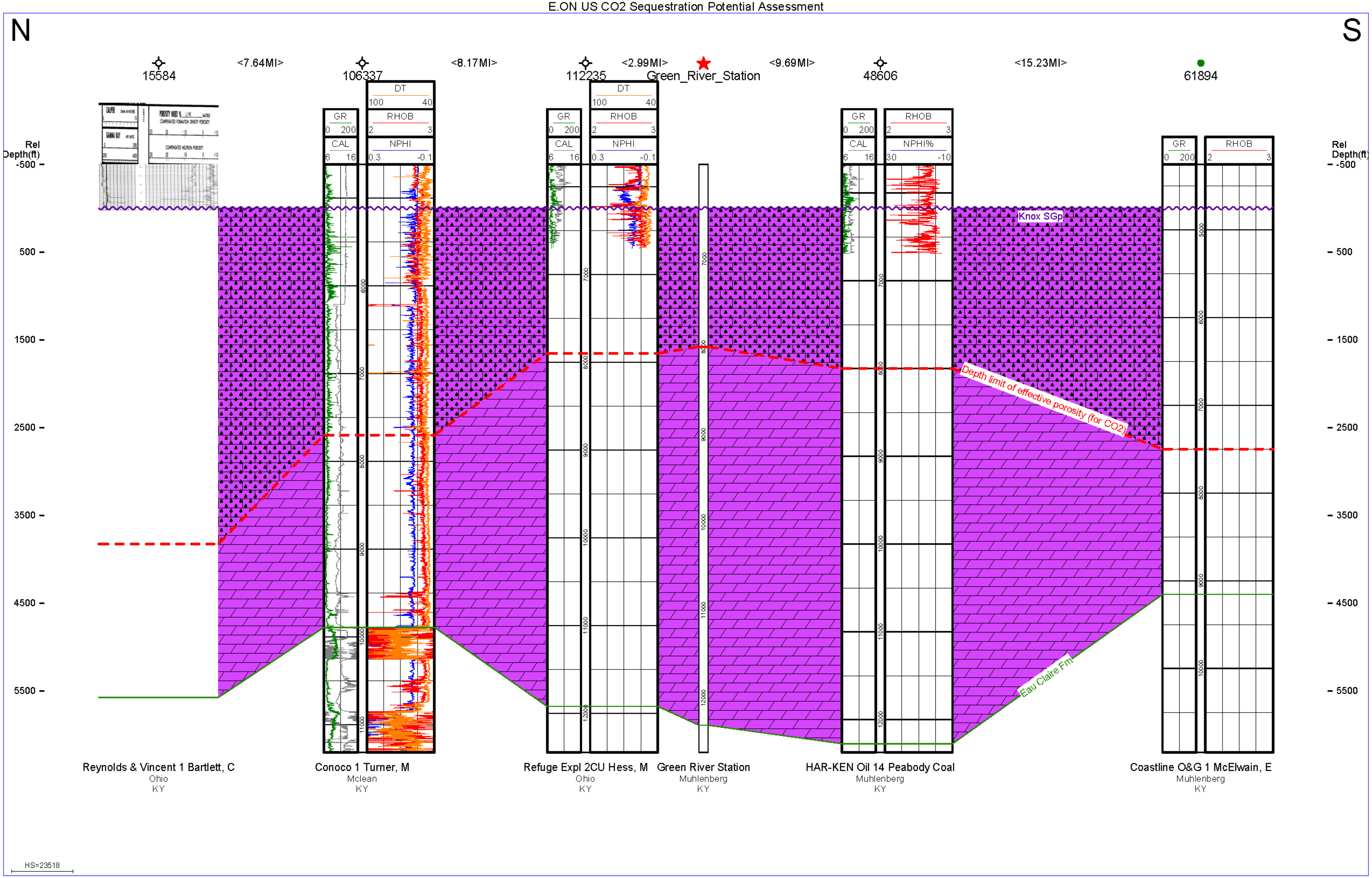

Figure 2-8. Stratigraphic north-south cross-sectional profile across 15-mi radius around the Green River Station. Depth datum is the top of the Knox Group. Stratigraphic tops below logged intervals (and well total depth) interpreted from regional seismic data.

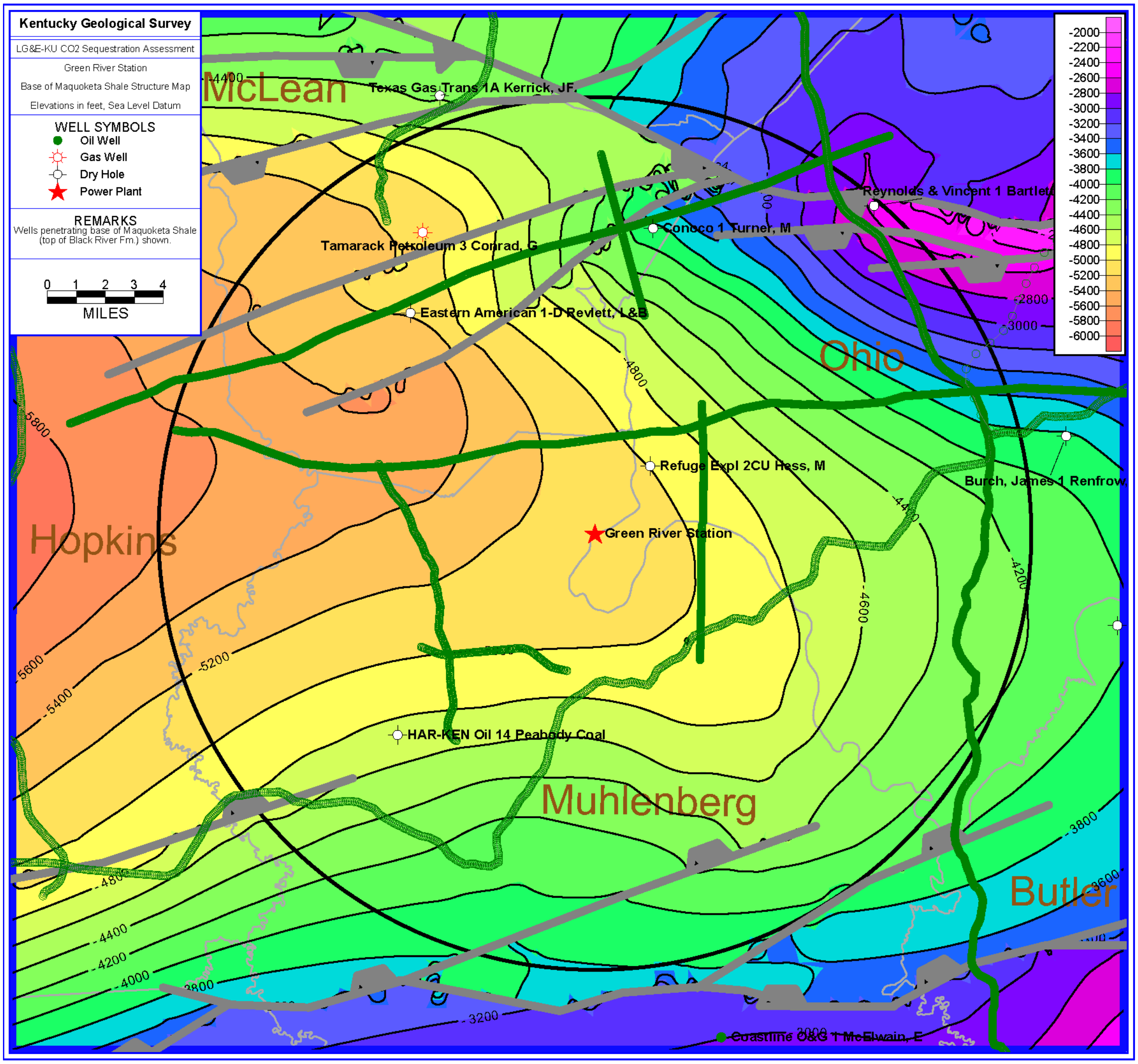

Figure 2-9. Structure on the top of the Middle Ordovician Black River Group (base of the Maquoketa Shale). Contour interval is 200 ft. Regional fault systems are indicated by dark gray lines, and seismic profile locations are marked in green.

siltstones with sufficient clay content to reduce the effective porosity and permeability to almost zero. At the Green River site, the top of the Maquoketa is around 5,000 ft deep (–4,590 ft subsea), and dips gently to the west-northwest (Fig. 2-10). The thickness of the Maquoketa Shale appears to lack the large basinal trends of other units (Fig. 2-11), and is about 545 ft thick at the station.

Seismic Data Interpretation and Deep Faults

Six reflection-seismic profiles on file at KGS were used to interpret the stratigraphy and geologic structure surrounding the Green River Station. In addition, LG&E-KU purchased segments of three different seismic lines from within about 5 mi of the site, in order to help constrain the in-

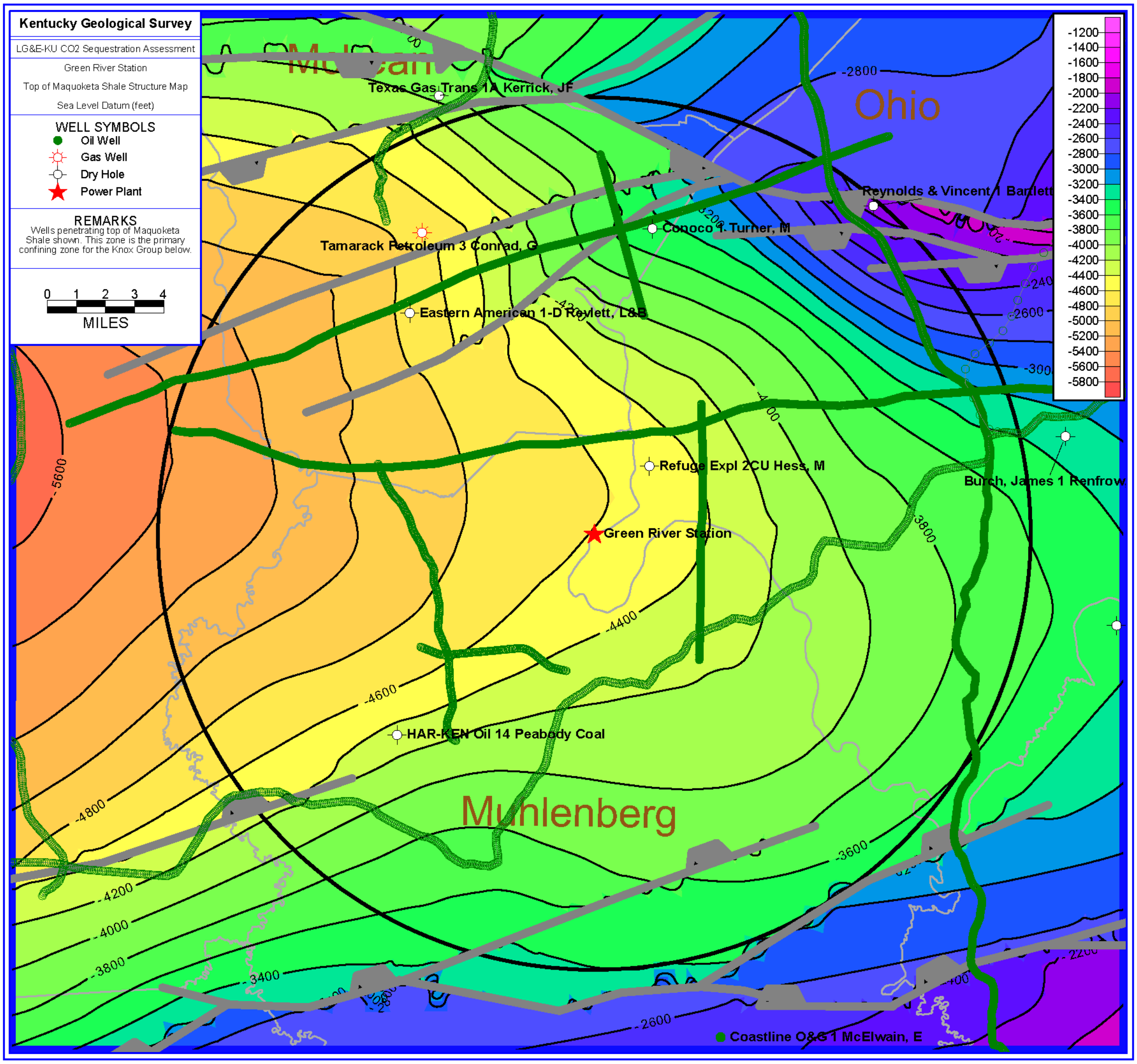

Figure 2-10. Structure on the top of the Upper Ordovician Maquoketa Shale (primary confining unit). Contour interval is 200 ft. Regional fault systems are indicated by dark gray lines, and seismic profile locations are marked in green.

terpretation of reservoir integrity below the station: seismic lines CGG-101, CGG-202, and DIB-17 (Fig. 2-1). With these supplementary data, a nearly complete circumference of seismic data surrounds the station. This raises the confidence level of the structural and stratigraphic interpretations below the Green River Station.

Numerous individual faults have been mapped at the surface within the 15-mi study radius around the Green River Station (Fig. 2-1). At the depth of the primary confining unit (Maquoketa Shale), these faults are interpreted to coalesce into seven fault-system segments, and are represented by bold dark gray lines on the maps. These interpretations were made after an analysis of both well and seismic data (green lines in the previous maps) from the region. However, these fault systems are not evenly distributed, and are primarily along the northern and southern edges of the study area. The fault zone nearest the station is about 7 mi to the

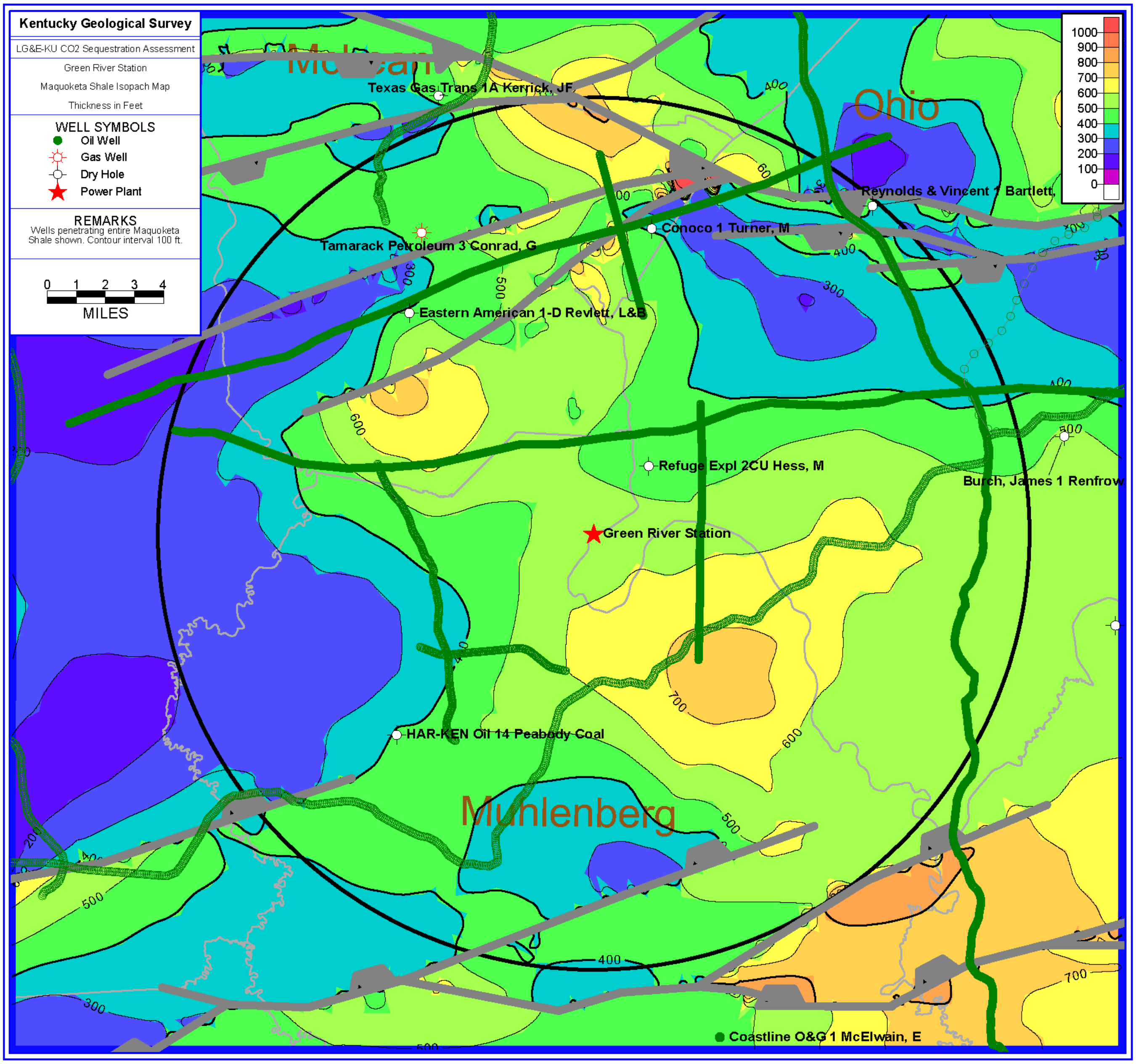

Figure 2-11. Thickness of the Maquoketa Shale (primary confining unit). Contour interval is 100 ft. Regional fault systems are indicated by dark gray lines, and seismic profile locations are marked in green.

northwest. Because of the structure at the top of the Knox Group, updip migration of buoyant CO_2 away from the station will tend to move to the east-northeast, away from the closest faults that are to the northwest and southwest (Fig. 2-5).

One major concern with the sequestration integrity of the Knox Group below the Green River Station was the possible subsurface extensions of the North and South Graham Faults in northwestern Muhlenberg County (Fig. 2-12). These faults are exposed at the surface 7.9 mi southwest of the station (Fig. 2-1). If these faults do extend beyond their surface exposures and along the same strike (compass direction), they would cross the Green River Valley within 1.5 mi of the station. The parts of seismic lines CGG-101 and CGG-202 that were purchased by LG&E-KU were chosen specifically to address this concern. The north-

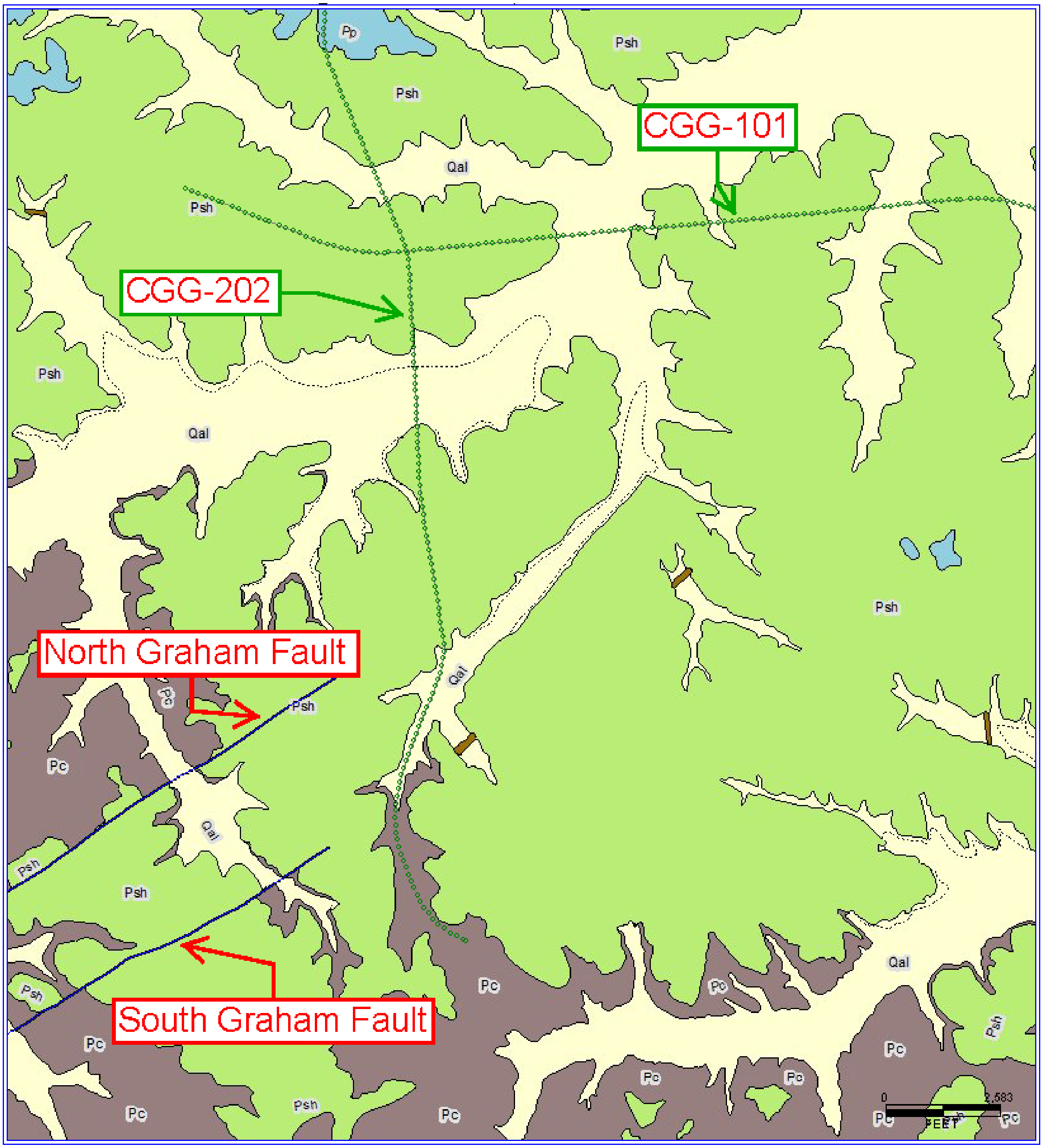

Figure 2-12. Detailed view of the surface geology and seismic line locations (green dotted lines) near the northeastern ends of the North and South Graham Faults. Geologic data from Kehn (1968).

south profile CGG-202 was acquired just east (less than 0.5 mi) of these fault exposures (Fig. 2-1). The near-surface deformation from these faults is visible on the southern end of the line (Fig. 2-13). No structural offset is visible at or below the secondary confining unit, but a linear subvertical zone of reduced amplitudes below this deformed area implies the presence of extensive fracturing near

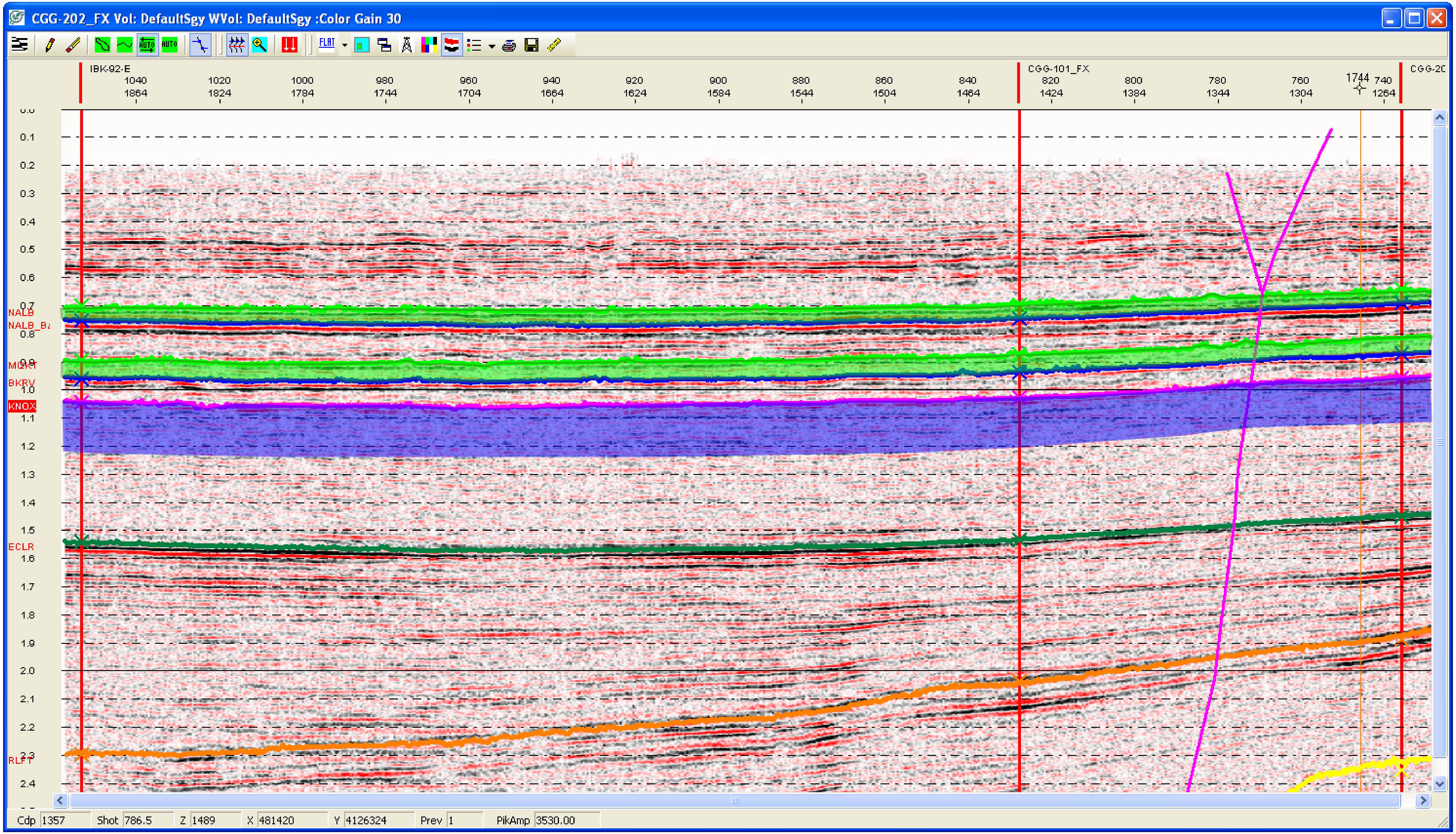

Figure 2-13. Seismic profile CGG-202, Muhlenberg County, Ky. The deeper, primary confining unit (Maquoketa Shale) and shallower, secondary confining unit (New Albany Shale) are highlighted in green. The estimated porous interval of the Knox Group is highlighted in purple. The Knox porosity zone is not resolvable on seismic data. The thin purple line on the right is the interpreted deformation zone of the Graham Faults (Fig. 2-12).

or just beyond the tip of this fault (highlighted in purple in Figure 2-13). If this truly is a fault-related deformation zone, it appears to end before crossing line CGG-101 (Fig. 2-14), 3 mi to the northeast (Fig. 2-12). East of the station, no faults or fracture deformation is visible along the 8.7 mi covered by line DIB-17 (Fig. 2-15). From the data available to this study, no faults were interpreted to breach the Knox Group or its primary or secondary confinement units within 5 mi of the Green River Station.

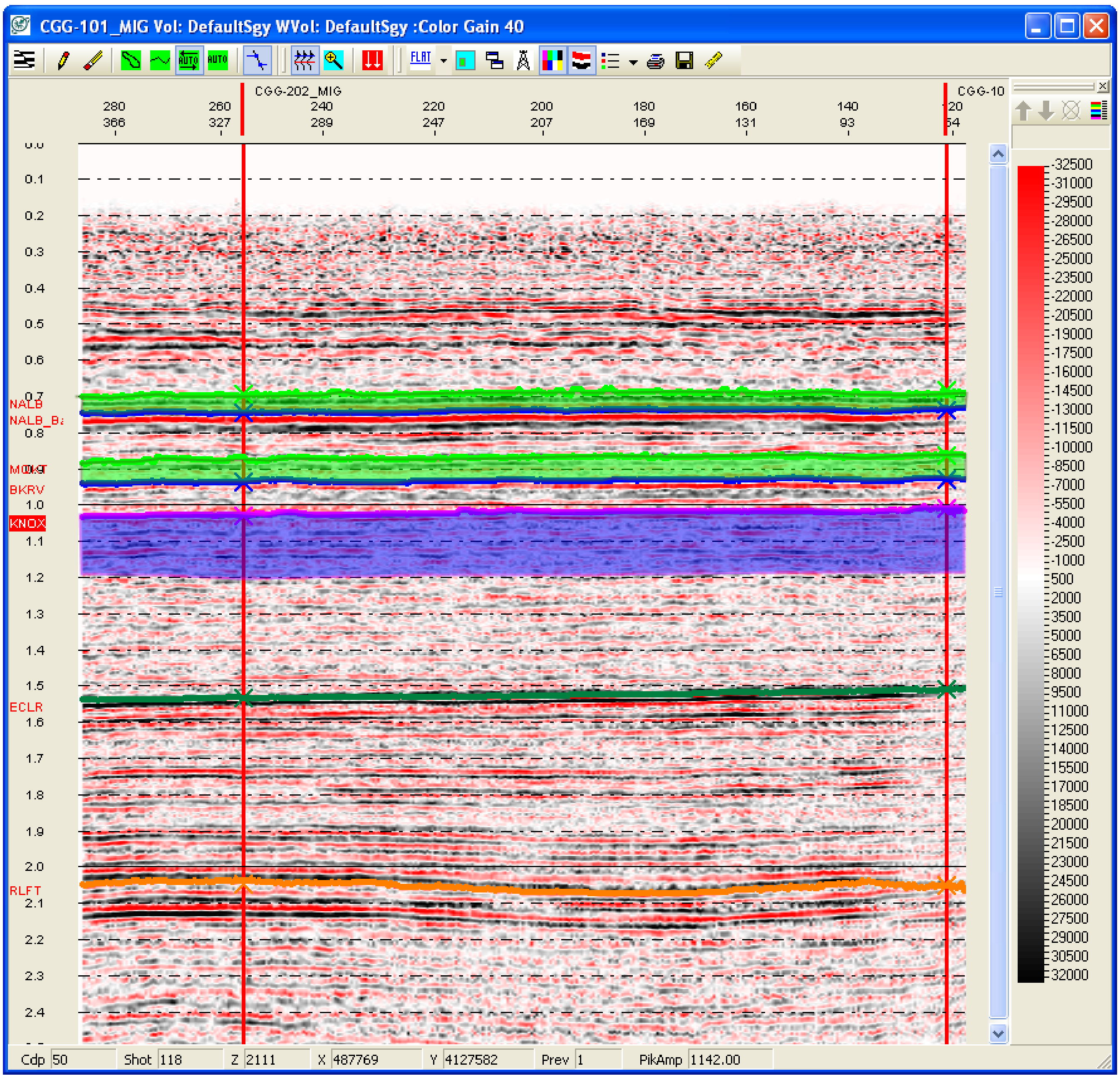

Figure 2-14. East-west seismic profile CGG-101, central Muhlenberg County, Ky. The deeper, primary confining unit (Maquoketa Shale) and shallower, secondary confining unit (New Albany Shale) are highlighted in green. The estimated porous interval of the Knox Group (although not resolvable on seismic data) is highlighted in purple. The base of the Knox Group (Eau Claire Formation) is marked in dark green.

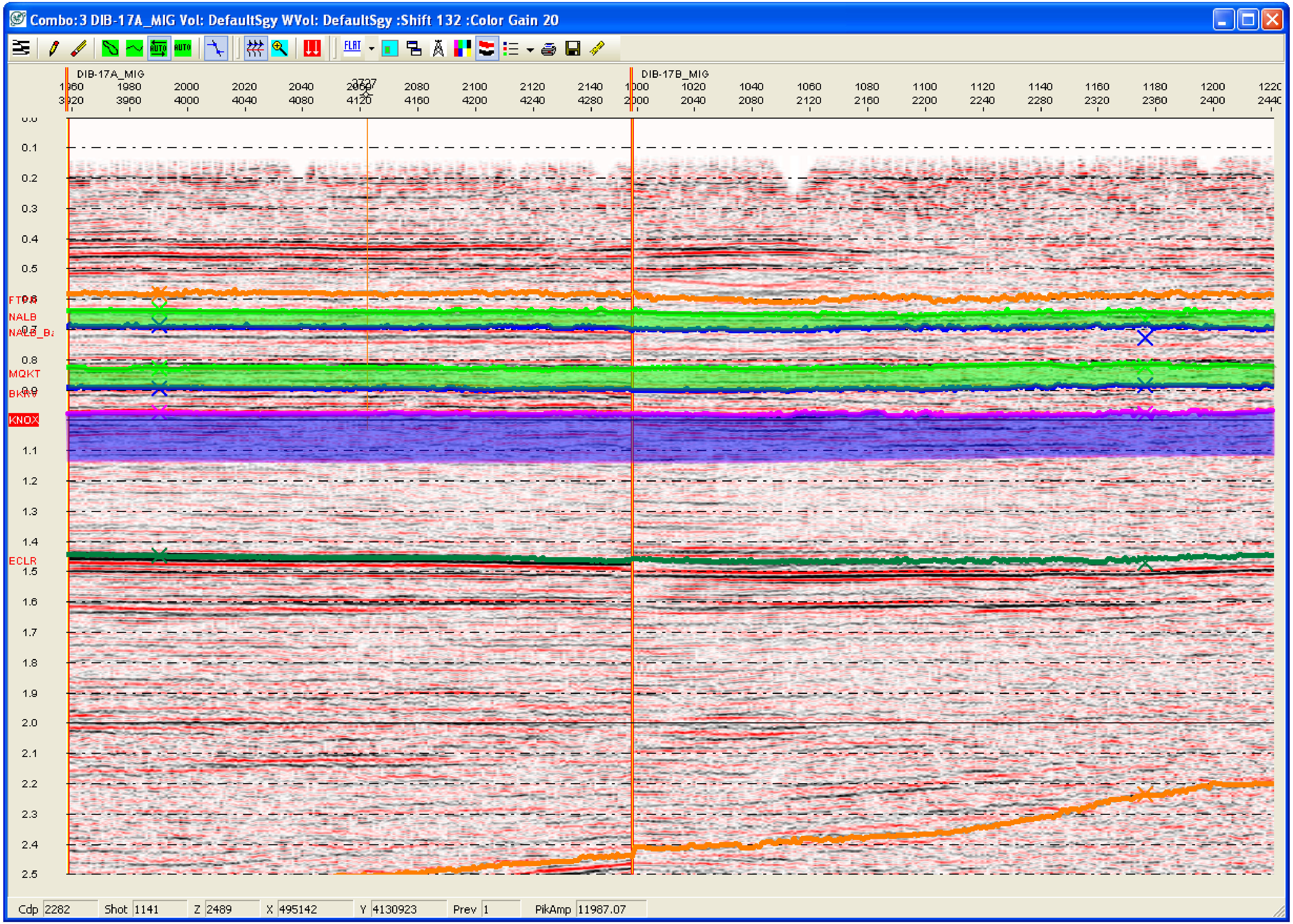

Figure 2-15. Seismic profile DIB-17, Muhlenberg and Ohio Counties, Ky. The deeper, primary confining unit (Maquoketa Shale) and shallower, secondary confining unit (New Albany Shale) are highlighted in green. The estimated porous interval of the Knox Group (although not resolvable on seismic data) is highlighted in purple. The base of the Knox Group (Eau Claire Formation) is marked in dark green.

Reservoir Quality and Injection Zone Thickness

In order to calculate carbon sequestration capacity, the average porosity and thickness of the storage reservoir are required. Since there are no wells currently drilled to the base of the Knox Group at the Green River Station plant site, exact porosity data are not available. For this reason, estimates for porosity and net injection zone thickness were calculated from data from nearby wells. Data from the Kentucky Geological Survey No. 1 Marvin Blan CO_2 injection test well were especially helpful, since high-quality well logs and core data are available from this well.

Porosity and Permeability

The most direct and accurate method of determining porosity and permeability is through the analysis of rock samples. Because of the cost associated with drilling well cores, far fewer well samples than well logs of the Knox Group are available. Porosity (but not permeability) data are also derived from downhole well logs, especially the bulk-density log. Logs provide a continuous data set for the entire formation, but are not as accurate as core data. A total of four wells with density logs were used to estimate dolostone porosity at the plant site: Refuge Exploration No. 2 CU Hess, Conoco No. 1 Turner, Texas Gas Transmission No. 1A Kerrick, and Kentucky Geological Survey No. 1 Marvin Blan.

Plotting porosity versus permeability illustrates the positive correlation between the two. Because porosity can be measured with downhole logs and permeability cannot, this cutoff allows the thickness of rock with suitable porosity and permeability for injection to be summed from porosity-log data alone. An empirical analysis of the relationship of porosity versus permeability within the Knox Group was performed by Bowersox (2010), using 54 rock samples (from sidewall and whole cores) obtained from the Kentucky Geological Survey No. 1 Marvin Blan well in Hancock County, Ky. Although this well lies outside of the Rough Creek Graben and is 38 mi from the station, the lithology and depositional environment of the Knox Group does not vary significantly over this area. Therefore, we believe that those characteristics are applicable to the Knox Group below the Green River Station. Although there is some variability in the data, the best-fit curve of the data can be described as:

$$k = 8.4 \times 10^{-4}\, e^{0.75\Phi}$$

where k = permeability in millidarcys and Φ = porosity in percent. Using this methodology, the average permeability in the Knox Group is calculated as 1.24 md at an average porosity of 9.7 percent. The floor of the injection zone within the Knox Group is calculated to have a permeability of 0.16 md at 7.0 percent porosity.

Porosity in the Knox Group decreases with increasing burial depth. This is primarily because of cementation and compaction, and is a result of increased temperature, pressure, and the amount of time the rocks have been buried. Cross-plots of porosity versus depth establish a general correlation between porosity and depth within the Knox (approximately 1.8 percent loss of porosity per 1,000 ft of depth). This rate of porosity loss correlates well with regional Knox porosities calculated from available well-log data. At depths below about 8,000 ft in the Knox, porosity values drop below 7 percent, and therefore the Knox is unsuitable for CO_2 storage. For this reason, 8,000 ft is considered the floor of the potential sequestration zone within the Knox Group. It should be noted that these conclusions are based on average porosity values, and the data vary significantly.

Calculation of Net Porous Dolostone

Once a porosity cutoff was chosen, the amount of net porous dolostone and average porosity of dolostones above the cutoff were determined for each well in the study area from bulk-density logs. Results of the net dolostone calculations are shown in Table 2-1. Average porosity calculated from bulk-density logs and total porosity-feet (thickness of void space) were also calculated. Gross thickness is the thickness of the Knox Group shallower than 8,000 ft depth. A net-to-gross ratio was calculated for each well to allow a similar thickness to be calculated at the Green River site using the total mapped thickness. The net-to-gross ratio ranges from 0.35 in the Refuge Exploration No. 2 CU Hess well to 0.017 in both the Conoco No. 1 Turner and Texas Gas Transmission No. 1A Kerrick wells. Average log-derived porosity of the net dolostone

Table 2-1. Knox Group reservoir data.

Knox Group Well-Log Data	*Average Depth (below surface, ft)*	*Gross Thickness (ft)*	*Net Porous Dolostone > 7% Porosity (ft)*	*Net-to-Gross Ratio*	*Average Log Porosity of Net Porous Dolostone (%)*	*Porosity-Feet*
Refuge Exploration 2CU Hess	7,054	1,693	59	0.03	10.6	15.0
Conoco 1 Turner	6,368	2,665	45	0.02	10.3	29.5
KGS 1 Blan	5,441	3,318	1,020	0.31	9.6	97.7
TGT 1A Kerrick	6,665	2,068	36	0.02	8.4	16.4
Calculated data						
Green River Station	7,211	1,579	149	0.09	9.7	14.5

interval ranges from 10.6 percent in the Refuge Exploration No. 2 CU Hess to 8.4 percent in the Texas Gas Transmission No. 1A Kerrick well. The Kentucky Geological Survey No. 1 Marvin Blan well is outside of the Rough Creek Graben and the Knox there is at a much shallower depth than it is below the Green River Station. This led to a much higher proportion of porous dolomite and dolomitic sandstone within the Knox Group in the No. 1 Blan well than would be expected at the study site. For this reason, the net/gross ratio from the Kentucky Geological Survey No. 1 Marvin Blan well (0.307) was not used to calculate storage volumes at Green River Station.

Table 2-1 lists calculated data for the Green River site. The gross thickness was taken from the thickness map of the Knox Group shallower than 8,000 ft depth (Fig. 2-7). Then a net dolostone footage was calculated using the net-to-gross ratios determined from the four analog wells. This yields a net dolostone estimate for the Green River Station of 149 ft.

CO_2 Capacity Calculations

Storage capacity is based on the porosity, thickness, and area of the injection zone and density of the injected CO_2. The density of CO_2 is a function of reservoir pressure and temperature. The Knox Group is deep enough for supercritical-phase CO_2 injection (reservoir temperature and pressure greater than 1,072 psi and 88°F) at the Green River Station. The CO_2 density calculations were made using the CO_2 properties calculator at the MIDCARB project Web site: www.midcarb.org/calculators.shtml. The Midcontinent Interactive Digital Carbon Atlas and Relational dataBase was produced by a research consortium composed of the state geological surveys of Illinois, Indiana, Kansas, Kentucky, and Ohio, funded by the U.S. Department of Energy. Calculated CO_2 densities are shown in Table 2-2.

These parameters are required to calculate CO_2 storage capacity:

Reservoir pressure: assumed hydrostatic conditions (with a salinity of 100,000 ppm) and calculated at 0.465 psi/ft for the reservoir depth

Temperature: assumed continental thermal gradient of 1°F/100 ft depth

Reservoir thickness: the net porous dolostone thickness as calculated above

Reservoir area: standard area of 100 acres

Reservoir porosity: the average porosity for the net reservoir footage

The equation for CO_2 storage capacity, modified from Medina and others (2011), is:

$$SC = A_n * h_n * \Phi_n * \rho_{CO2} * \dot{\varepsilon} / 1{,}000$$

where SC is the storage capacity in metric tons, A_n is the area in square meters, h_n is the net reservoir thickness, Φ_n is the average porosity of the net res-

Table 2-2. Calculated CO_2 density at reservoir conditions.

Site	*Reservoir Pressure (psi)*	*Reservoir Temperature (°F)*	*CO_2 Density (lb/ft^3)*	*CO_1 Density (kg/m^3)*
Green River	3,300	130	49.41	791.47

ervoir, ρ_{CO2} is the density of CO_2 at reservoir conditions, and $\dot{\varepsilon}$ is the storage efficiency factor (discussed below).

The reservoir parameters used and CO_2 capacities calculated are shown in Table 2-3.

Efficiency of CO_2 Storage

The storage capacity equation above includes an efficiency factor, which reduces the CO_2 storage capacity. This factor is applied because 100 percent of the available pore volume is never completely saturated with CO_2 because of fluid characteristics and geologic variability within the reservoir.

Litynski and others (2010) calculated efficiency factors for carbon storage in various reservoir types that account for factors that reduce the volume of CO_2 that can be stored. These factors include:

Geologic Factors

- Net-to-total area ratio of a basin suitable for sequestration
- Net-to-gross thickness ratio of a reservoir that meets minimum porosity and permeability requirements
- Ratio of effective to total porosity (fraction of connected pores)

Displacement Factors

- Areal displacement efficiency: area around a well that can be contacted by CO_2
- Vertical displacement efficiency: fraction of vertical thickness that will be contacted by CO_2
- Gravity: fraction of reservoir not contacted by CO_2 due to buoyancy effects
- Displacement efficiency: portion of pore volume that can be filled by CO_2 due to irreducible water saturation

Combining all of these factors using a Monte Carlo simulation results in a probable range of total efficiency factors of 0.64 to 5.5 percent (Litynski and others, 2010). For the purposes of this assessment, we can assume the *geologic* factors are equal to 1. In our 100-acre unit, the net to total area is the same, the net to gross thickness has already been calculated and used in the calculation, and for dolomite reservoirs (dolostones) we can assume that the porosity is well connected with a ratio of effective (connected) porosity to total porosity is equal to 1. Litynski and others (2010) calculated efficiency factors for just the *displacement* factors separately, and for dolostone reservoirs they range from 16 to 26 percent, with a P_{50} (most likely) efficiency factor of 21 percent. This means the most likely case is that 21 percent of the pore space can be filled with CO_2. The range of storage volumes using the probabilistic efficiency factors for Green River Station is shown in Table 2-4.

Summary

The Green River Station has potential for geologic storage of CO_2 beneath the site property. The strata of the Knox Group are the only formations with suitable porosity and permeability at the depths required for supercritical-phase sequestration. Excellent confinement for injected CO_2 is provided by the Maquoketa Shale, which is more than 500 ft thick.

Table 2-3. Reservoir parameters and calculated CO_2 storage capacities for a 100-acre area at theoretical limits (100 percent) and probable (21 percent) storage efficiencies. The 21 percent efficiency rate for porous dolostone reservoirs taken from DOE's 2010 Carbon Sequestration Atlas of the United States and Canada (Litynski and others, 2010).

Site	*Net Reservoir Thickness (ft)*	*Net Reservoir Thickness (m)*	*Average Porosity (%)*	*CO_2 Density (kg/m^3)*	*CO_2 Capacity per 100 acres at 100% Efficiency (metric tons)*	*Storage Efficiency Factor*	*CO_2 Capacity per 100 acres at 21% Efficiency (metric tons)*
Green River	36	11.1	9.7	791.47	345,515	0.21	72,558

Table 2-4. Range of probabilistic storage volumes using DOE's displacement efficiency factors for clastic reservoirs (Litynski and others, 2010).

Site	*Minimum Volume (metric tons/100 acres) $\dot{\varepsilon}$ = 16%*	*Most Likely Volume (metric tons/100 acres) $\dot{\varepsilon}$ = 21%*	*Maximum Volume (metric tons/100 acres) $\dot{\varepsilon}$ = 26%*
Green River	55,282	72,558	89,834

Geologic data control for the Green River Station is moderate, with only four wells drilled to the reservoir within a 15-mi radius, and only one (Conoco No. 1 Turner) that penetrated the entire section of the Knox. The proximity of the Kentucky Geological Survey No. 1 Marvin Blan well to Green River Station lowers the risk of finding a suitable reservoir, and excellent core, log, and engineering data are available from this research project. The three seismic lines surrounding the station purchased for this project were useful, not only for subsurface mapping, but also for analyzing the extent and locations of fault systems within and above the target injection zone. Using these data, we interpreted no faults below the confining units within a 5-mi radius of Green River Station. Interpretation of the Knox Group structure map (Fig. 2-5) suggests that injected CO_2 would migrate slowly updip (approximately 1°) to the east-northeast.

Reservoir quality is probably adequate for injection at the Green River Station. The additional cost (compared to the other LG&E-KU stations in this project) of drilling a well more than 7,000 ft deep to the Knox would be offset somewhat by the increased volume of CO_2 that can be stored at that greater depth and pressure.

The most likely volume of CO_2 that could be stored at the Green River Station, using property owned by LG&E-KU, is shown in Table 2-5.

Table 2-5. Total storage volume onsite assuming 100 percent use of LG&E-KU property.

Site	*CO_2 Storage Volume (metric tons per acre)*	*Total Property Size (acres)*	*Total Site Storage Volume (metric tons)*
Green River	726	415.8	301,697

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Chapter 3: Geologic CO_2 Sequestration Potential of the LG&E-KU E.W. Brown Station, Central Kentucky

LG&E-KU CO_2 Sequestration Geologic Summary Sheet

Power Plant: E.W. Brown **County:** Mercer **Geologic Basin:** Cincinnati Arch

Data Quality:	
Distance to nearest well control in reservoir:	6.8 mi
Wells to primary injection zone within 15-mi radius:	8
Distance to nearest core in injection zone:	10.8 mi
Distance to nearest good-quality seismic control:	N/A (all poor quality)
Reservoirs:	
Primary injection zone:	Cambrian Rome Formation and basal sandstone
Rock type:	sandstone (quartzarenite and arkose)
Drilling depth at plant site:	N/A (4,600 ft offsite)
Trapping mechanism:	closed fault trap
Maximum reservoir pressure:	2,400 psi (hydrostatic)
Reservoir temperature:	110°F
Salinity of reservoir fluid:	200,000 ppm
Reservoir thickness (gross/net):	1,561/312 ft
Average porosity:	10 percent
Average permeability:	56 md
Secondary injection zone:	none at this site
Confinement and Integrity:	
Primary confining zone:	Cambrian Conasauga Group
Rock type:	shale and limestone
Thickness of primary confining zone:	1,000 ft
Height above primary injection zone:	0 (overlies injection zone)
Well penetrations of primary seal within 15-mi radius:	13
Secondary confining zone:	Ordovician Black River Limestone (High Bridge)
Rock type:	limestone
Thickness of secondary confining zone:	600 ft
Height above primary injection zone:	4,000 ft
Well penetrations of secondary seal within 15-mi radius:	
Number of faults cutting primary seal within 15-mi radius:	numerous
Distance to nearest mapped fault:	0.3 mi
Storage Capacity:	
Calculated CO_2 storage capacity, primary injection zone:	2,918,344 metric tons/100 acres (assuming 100 percent efficiency); 408,568 metric tons/100 acres (at 14 percent efficiency)

Data compiled and interpreted from well records maintained by the Kentucky Geological Survey.

Introduction

Geologic CO_2 sequestration potential was evaluated for an area surrounding the LG&E-KU E.W. Brown Station in Mercer County, Ky. A circular area with a 15-mi radius around the plant was defined as the primary focus of the evaluation, but data from beyond 15 mi were also used because of limited data from the primary area. The 15-mi-radius circle around the E.W. Brown Station is shown in Figure 3-1.

The following data were compiled for the evaluation:

1. The 7.5-minute topographic and geologic quadrangle maps for the Wilmore and Little Hickman quadrangles
2. Locations of all mineral- and petroleum-exploration wells and boreholes
3. Formation tops for geologic units from the top of the Ordovician to the Precambrian
4. Available digital geophysical logs for Knox and deeper wells
5. Core analyses (porosity and permeability) for the Rome Formation in one well
6. Reflection-seismic data available at KGS (four lines)

Within the 15-mi radius around the E.W. Brown Station, three wells have been drilled that penetrate the entire Paleozoic sequence, ending in Precambrian rocks. These wells provide the key geologic data used in this assessment. Two additional Precambrian wells are located just outside the 15-mi radius, and were also used in the evaluation. Numerous other shallower wells have been drilled in the area around the Brown station, and were used for mapping shallower formations.

Our evaluation of the Brown site indicates that carbon sequestration is not feasible directly below the power-plant site. The geologic formations are either too shallow (Knox Supergroup) or not present (Mount Simon Sandstone) at depths below 2,500 ft (the minimum depth required for supercritical-phase CO_2 storage). There is potential for sequestration approximately 6 mi to the east in a geologic feature known as the Rome Trough: a deeper, fault-bounded basin that contains thick sandstones at depths greater than 2,500 ft. The western end of the Rome Trough lies within the 15-mi radius around the E.W. Brown Station, and this evaluation proposes that this area be used for CO_2 storage. This would require a pipeline to transport CO_2 a minimum of 6 mi east of the Brown station. Access would also have to be obtained to surface property and subsurface pore space.

Geologic Setting and Surface Geology

The E.W. Brown Station is near the crest of the Cincinnati Arch, a broad anticline that separates the deeper sedimentary basins in western Kentucky (Illinois Basin) and eastern Kentucky (Appalachian Basin). The arch developed in Middle Ordovician time, and rock units deposited prior to this time have been tilted to the west toward the Illinois Basin. Rocks deposited from the Middle Ordovician and later were influenced to some extent by the growing arch, but for the interval of interest in this study, the arch had no effect on thickness or lithology. The geologic formations at the Brown site are shallower than the equivalent formations in northern Kentucky at the Ghent and Trimble County Stations.

The Brown station is located in the Wilmore 7.5-minute quadrangle, and the geology of this quadrangle was mapped by Cressman and Hrabar (1970). The geologic map indicates the plant is located on bedrock consisting of the Ordovician Lexington Limestone (Fig. 3-2). This formation is primarily limestone with interbedded shale. Since the plant site itself is not feasible for CO_2 sequestration, Figure 3-2 includes the area to the east where sequestration is possible, which is in the Little Hickman quadrangle; the geology of this quadrangle was mapped by Wolcott (1969). A prominent feature in the Little Hickman quadrangle is the Kentucky River Fault Zone (Fig. 3-2). It extends from the surface to Precambrian basement rocks. The fault zone forms the western boundary of the Rome Trough. At the basement level, there is more than 2,700 ft of throw (offset) between the upthrown (west) and downthrown (east) sides of the fault. East of the fault zone, surface rocks are of Ordovician age and consist of the Clays Ferry Formation, Garrard Siltstone, and Calloway Creek Limestone. The Clays Ferry Formation is predominantly shale with minor limestone, whereas the Calloway Creek is mostly limestone with less abundant shale. In lower elevations on both sides

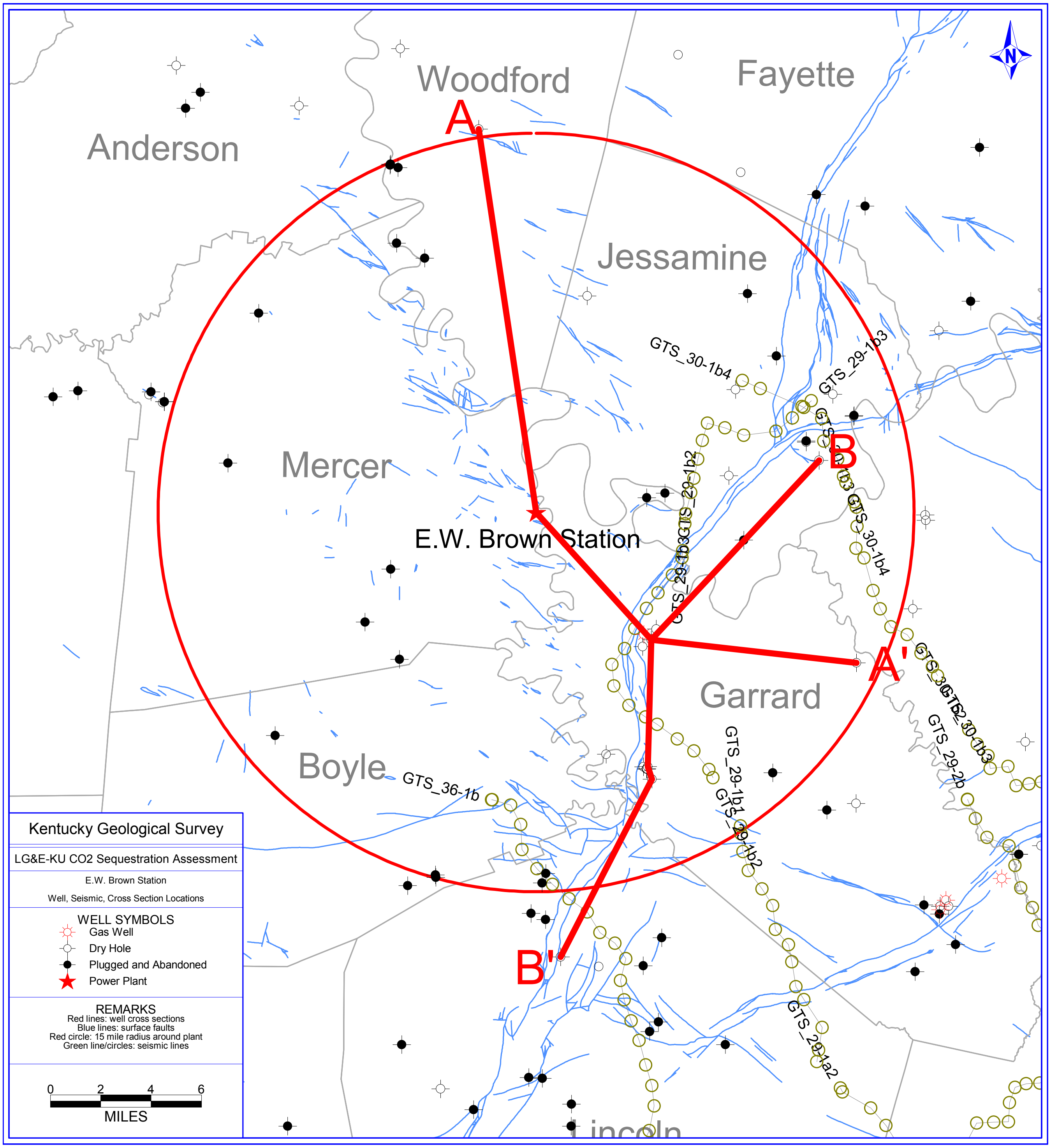

Figure 3-1. Location of the E.W. Brown Station in central Kentucky. Red circle is the 15-mi radius of the site. Locations of all known wells are shown. Blue lines are mapped surface faults. The locations of the two geologic cross sections, A–A' and B–B', are shown by the red lines. Reflection-seismic lines are indicated by small green circles (shotpoint locations).

of the fault zone, the deeper Tyrone Limestone of the High Bridge Group is exposed. This formation consists of thickly bedded, dense limestone.

Surface geology does not have a direct impact on carbon sequestration potential, since CO_2 injection will occur much deeper. However, surface ge-

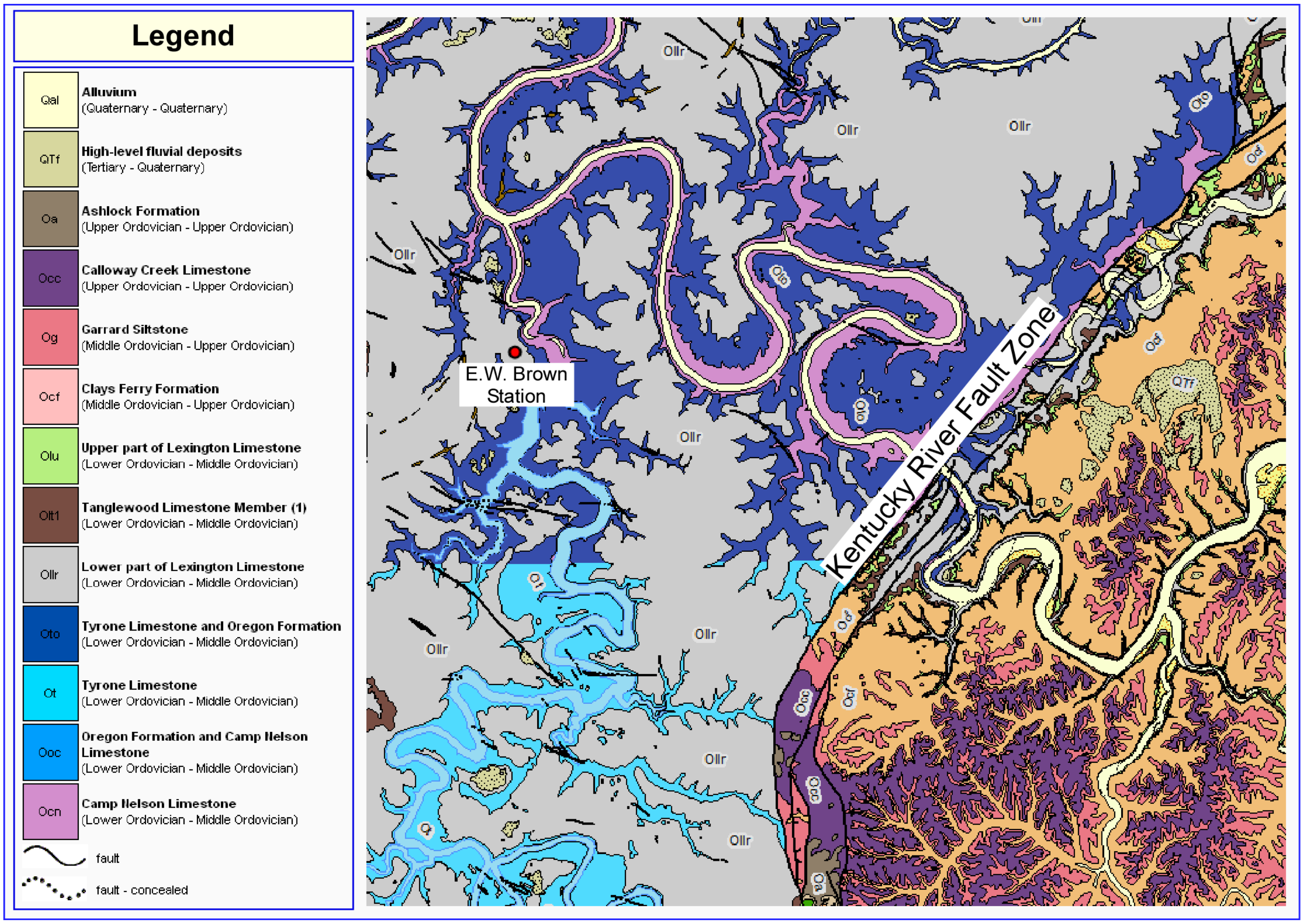

Figure 3-2. Geology of part of the Wilmore and Little Hickman 7.5-minute quadrangles (Cressman and Hrabar, 1970; Wolcott, 1969, respectively). The geology changes abruptly along the Kentucky River Fault Zone, the prominent line of faults that run northeast-southwest across the area. This fault zone is downthrown to the east, and forms the western boundary of the Rome Trough, a geologic basin that is deeper here than at the E.W. Brown site, in which CO_2 from the Brown station could be sequestered. The surface geology east of the fault zone consists of the Ordovician Clays Ferry Formation (Ocf), primarily shale with minor interbedded limestones. The Kentucky River runs northwest-southeast across the map area, leaving Quaternary alluvium (Qal) deposits along the valley bottom.

ology will have an impact on the design and implementation of shallow groundwater monitoring wells that will be required by the U.S. Environmental Protection Agency for an underground injection permit. The UIC permit will likely require monitoring down to the base of the underground source of drinking water, which may require drilling into bedrock. However, the Upper and Middle Ordovician rocks at the surface east of the Kentucky River Fault Zone may not be suitable for groundwater monitoring because of their low porosity and permeability. Wolcott (1969) reported the occurrence of springs along faults, fractures, and above a widespread bentonite (altered volcanic ash) bed in the Tyrone Limestone that forms an impermeable layer. The presence of this relatively shallow impermeable layer should be considered when planning a monitoring program, because it could prevent upward movement of CO_2 if leakage were to occur. Monitoring wells may need to be drilled deeper than this layer for effective monitoring.

Stratigraphy and Structure

The subsurface geology of the area around the E.W. Brown Station varies dramatically on opposite sides of the Kentucky River Fault Zone. Discussion will focus on the east (downthrown) side of the fault, where sequestration is favored. We do not believe carbon sequestration is feasible west of the fault zone, such as at the Brown site, for two reasons. First, the Cambrian Mount Simon Sandstone is not present in this area, as indicated by the Texaco No. 1 Sherrer well in Jessamine County (within the 15-mi radius). This well drilled through the Knox Supergroup and Eau Claire shale section, and then into Precambrian basalt and the Middle Run Formation. No Mount Simon Sandstone was encountered. This well confirms that the Mount Simon Sandstone was not deposited in central Kentucky. Other studies have used data from seismic lines outside the Mercer County area to map the extent of the Mount Simon Sandstone across Kentucky. Broader regional data show that the Mount Simon is present in northern Kentucky, pinches out toward the south, and is absent in central Kentucky (Fig. 3-3) (Greb and Solis, 2010).

The second reason we believe sequestration is not feasible at the station is that dolomites in the Cambrian-Ordovician Knox Supergroup are thought to be unsuitable. The basal part of the Knox at the Brown station is deep enough for sequestration, but the overlying seal is not deep enough. Geologic storage of carbon dioxide is limited to depths greater than 2,500 ft below the surface where CO_2 exists in the supercritical, or dense, phase. In the Mercer County area, this 2,500-ft depth is in the lower part of the Knox (the Copper Ridge Dolomite). Despite the depth and possibility for good porosity, CO_2 storage in the Knox at the E.W. Brown site is not feasible because the shale and limestone seals overlying the Knox occur above 2,500 ft (the top of the Knox is interpreted to be at a depth of about 750 ft at the Brown station). With the top of the Knox and overlying seal so shallow, a concern is that if CO_2 were to migrate upward through the Knox interval (along fractures), it could rise well above 2,500-ft depth before being trapped by the overlying seals. Above 2,500 ft, the CO_2 phase would change from supercritical to gas, resulting in a large volume and pressure increase. If the permeability of the formation was not sufficient to dissipate this pressure pulse, it could be sufficient to fracture the rock and breach the reservoir.

Other geologic formations below the 2,500-ft depth in the area west of the fault zone include the Upper-Middle Cambrian Eau Claire Formation and the Precambrian Middle Run Formation. These formations lack suitable porosity for storage of CO_2 and thus have no sequestration potential.

East of the Kentucky River Fault Zone, the deep geology is very different. Movement on this

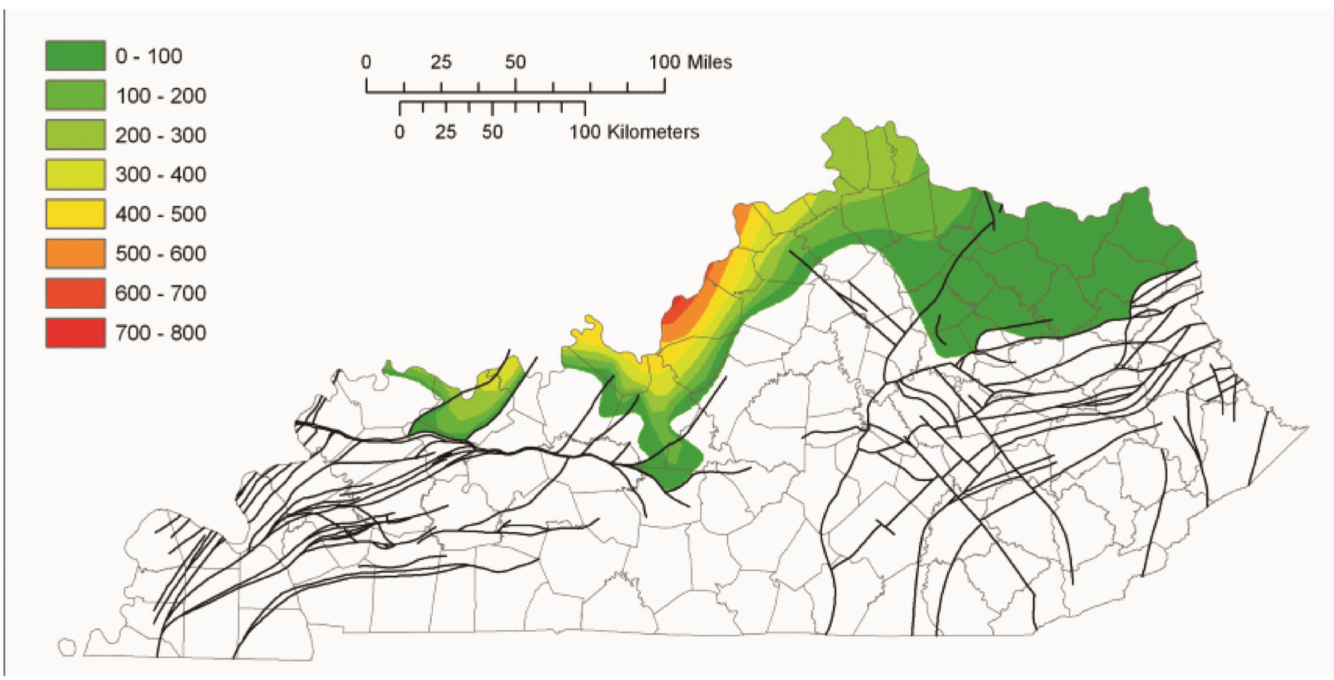

Figure 3-3. Regional thickness of the Mount Simon Sandstone in Kentucky. This map indicates that the Mount Simon is present in northern Kentucky (under the Ghent and Trimble County Stations), but is absent at the E.W. Brown Station in central Kentucky. Interpretation based on seismic and well data. Contours in feet. From Greb and Solis (2010).

fault in the Early to Middle Cambrian created a deeper basin to the east (the Rome Trough), which was filled with a thick package of sandstone and shale that does not extend outside of the basin (Rome Formation). These sandstones have good porosity and are at depths of 4,500 to 5,500 ft. Although in the same stratigraphic position as the Mount Simon Sandstone in other parts of Kentucky, the Rome Formation is older and not laterally connected to the Mount Simon sandstones. Figure 3-4 is a type geophysical log for the western end of the Rome Trough, showing the stratigraphic units in this area. Above the Rome Formation is the Conasauga Group, roughly equivalent to the Eau Claire Formation on the west side of the fault. The Conasauga contains mostly shale with minor limestone, and forms a seal above the Rome. These units are discussed in more detail below.

Precambrian Rocks

The Precambrian basement rocks in the study area are different on opposite sides of the Kentucky River Fault Zone. On the west, outside of the Rome Trough, Precambrian rocks include basalt (a volcanic rock) and red sandstones assigned to the Middle Run Formation. Both basalt and Middle Run sandstones were drilled in the Texaco No. 1 Sherrer well in Jessamine County, 8 mi from the E.W. Brown site. In this well, 600 ft of basalt overlies 2,000 ft of Middle Run sandstones. The Middle Run consists of fine-grained, red lithic sandstones and minor siltstone and shale. It was deposited in nonmarine fluvial environments in a fault-bounded rift basin (Drahovzal and others, 1992). The sandstone is well cemented and lacks porosity and permeability in this area. It has no potential for carbon sequestration in the study area.

East of the Kentucky River Fault Zone, in the Rome Trough, Precambrian basement rocks consist of metamorphic rocks of the Grenville Province. Grenville rocks were encountered in three wells in the Jessamine-Garrard-Madison County area. These metamorphic rocks have no porosity and no potential for carbon sequestration.

A structure map on the top of Precambrian rocks is shown in Figure 3-5. This map is based on the few wells that penetrate the Precambrian surface in the area and the older seismic-reflection data indicated. As such, it should be considered a general representation of the structure of the area. This map indicates that the depth to basement is about 3,788 ft (–2,875 ft below sea level) at the E.W. Brown Station. To the east, and across the Kentucky River Fault Zone, Precambrian rocks are much deeper because of displacement on the fault. Basement rocks range from about –4,600 ft to about –6,000 ft below sea level. The downthrown side of the fault was filled with the Rome Formation and Conasauga Group rocks. The Precambrian surface in the trough deepens to the east, and is shallowest against the fault.

Cambrian Mount Simon Sandstone

The Mount Simon Sandstone, the proposed injection zone at Trimble County and Ghent Stations, is absent in the area around the E.W. Brown Station. The main injection zone in the area is the Rome Formation, confined to the east side of the Kentucky River Fault Zone.

Cambrian Basal Sandstone and Rome Formation

East of the Kentucky River Fault Zone, a graben developed because of movement on the fault. Sediment deposition was limited to this deeper area, named the Rome Trough, with limited deposition outside the trough. Initial deposition in the trough was a sandstone informally referred to as the basal sandstone. This sandstone is overlain by the thicker Rome Formation. These two formations differ somewhat in lithology, but for the purposes of this study the two units are combined. Both contain porous sandstones that could store CO_2. The basal sandstone directly overlies Precambrian metamorphic rocks and is 200 to 300 ft thick in the study area. It contains variable amounts of feldspar grains, which can cause a high gamma-ray response, similar to shale. No core or core data are available from the basal sandstone zone in the study area.

Above the basal sandstone is the Rome Formation, a complex interval of sandstone, shale, and thin limestones. Many of the sandstones in the Rome are porous in the study area, and form the proposed primary injection zone for CO_2. The Rome is commonly thinly bedded, with numerous

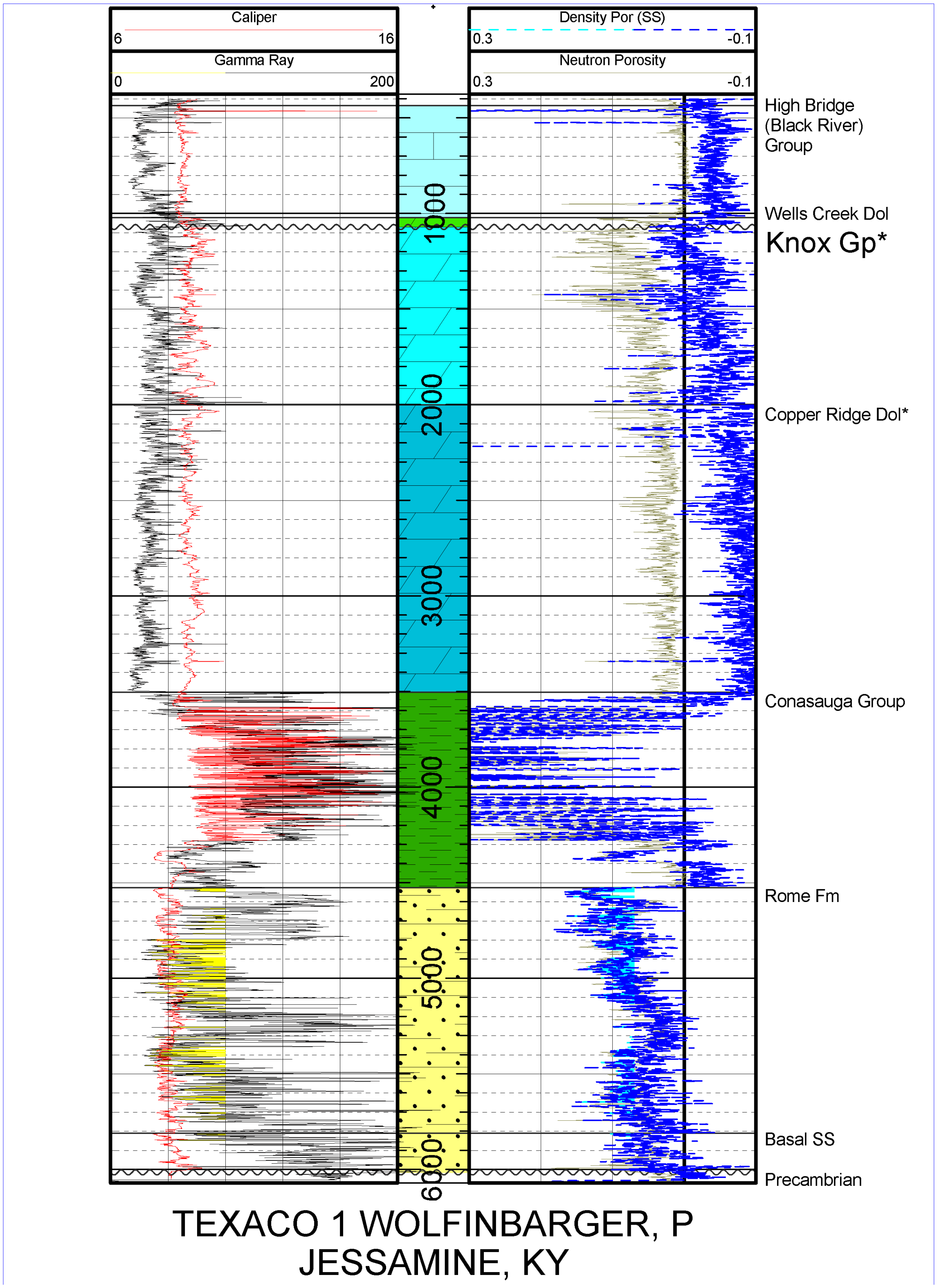

Figure 3-4. Geophysical log for the Texaco No. 1 Wolfinbarger well drilled in Jessamine County, Ky. This well is located east of the Kentucky River Fault Zone, in the Rome Trough. The potential CO_2 injection zone is in the Cambrian Rome Formation and basal sandstone. The density-porosity log is shaded light blue in the Rome and basal sandstone intervals where porosity is greater than 7 percent. The gamma-ray log on the left is shaded yellow where less than 80 API units (clean sandstone). Red line in the left track is the caliper log (hole size), which is erratic in the Conasauga zone because of shale washout.

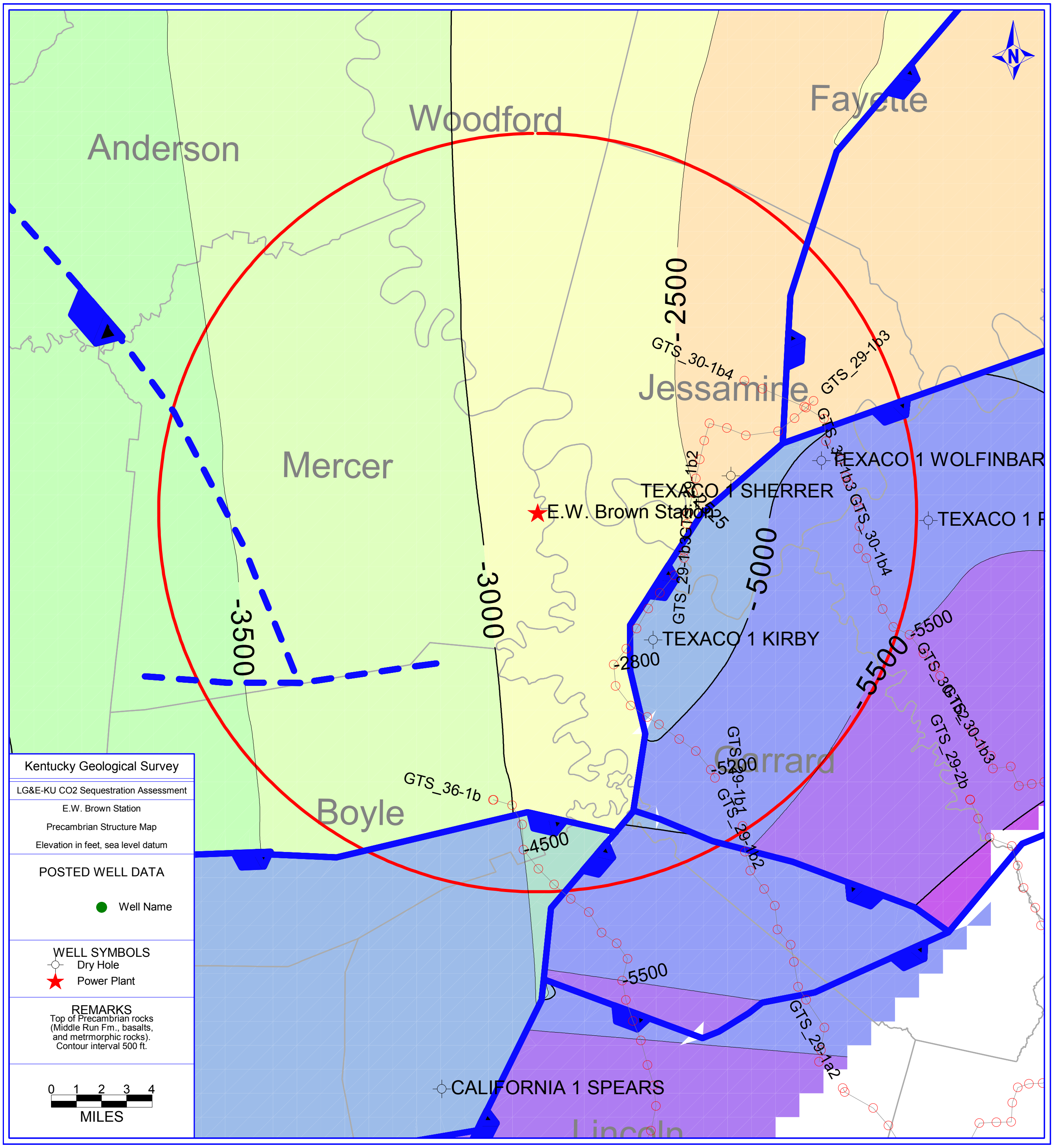

Figure 3-5. Structure on top of the Precambrian basement surface. Solid blue lines are simplified traces of mapped basement faults, and dashed blue lines are faults inferred from shallow geology, but offset is uncertain. Precambrian rocks are much shallower on the west (upthrown) side of the Kentucky River Fault compared to the east, in the Rome Trough.

shale interbeds, as indicated on the gamma-ray log (Fig. 3-4). Porous sandstones occur as multiple stacked beds, separated by shale, rather than a thick uniform reservoir.

A structure-contour map on the top of the Rome Formation is shown in Figure 3-6. Like the Precambrian map, this map shows the formation deepens away from the Kentucky River Fault Zone to the east. With the sandstones dipping away from the fault, a potential trapping mechanism is

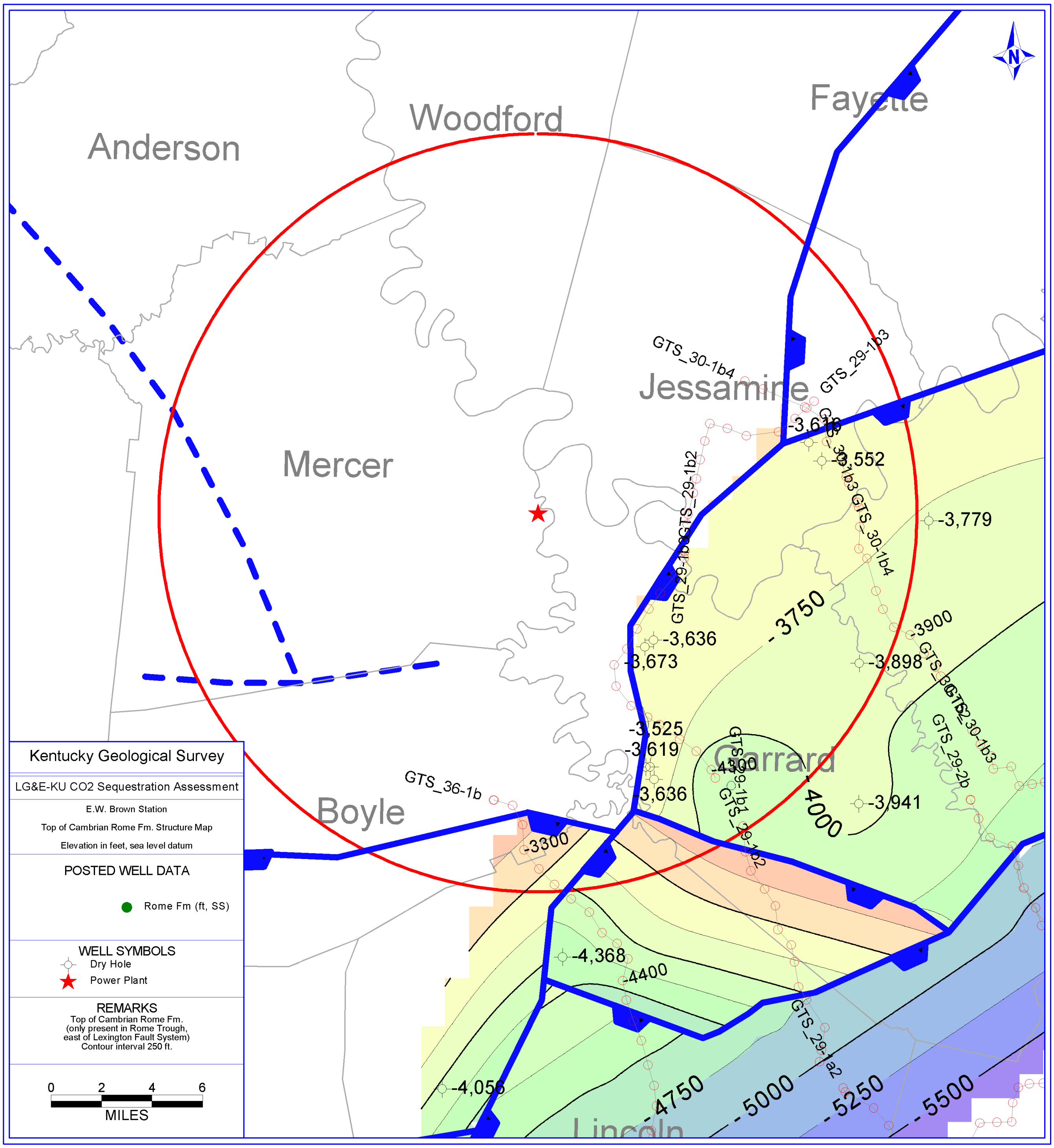

Figure 3-6. Structure on top of the Cambrian Rome Formation. Contour interval is 250 ft. These rocks deepen to the southeast, away from the Kentucky River Fault Zone. The structure indicates that injected CO_2 would migrate toward the fault zone and likely be trapped by the fault zone.

present, where buoyant fluids such as CO_2 would migrate up toward the fault, and be trapped there. Near the fault, where sequestration would likely occur, the top of the Rome is at –3,600 to –3,700 ft below sea level (4,600 to 4,700 ft below the surface).

The isopach map (Fig. 3-7) shows thinning of the combined basal sand/Rome interval toward the southwest. The gross thickness ranges from about 1,500 to 1,000 ft away from the fault. The thickness of sandstone in this interval will be significantly less because of abundant interbedded shale. This map is based on limited data because so few wells have penetrated the entire sequence.

Cambrian Conasauga Group and Eau Claire Formation

The Cambrian Conasauga Group directly overlies the Rome Formation in the Rome Trough, and is partly equivalent to the Eau Claire Formation outside of the trough. The Conasauga is predominantly composed of green and gray marine shale, with some interbedded limestones. The Conasauga Group consists of several formations defined by their lithology. In this area, three of these formations are present, two are limestone-dominated, and one is a thick shale. This shale (the Nolichucky Shale) and the limestones form the primary confining zone above the Rome Formation. Figure 3-4 shows the thickness of the Conasauga interval. The erratic log response in the Conasauga (particularly on the red caliper curve) is due to enlarged borehole conditions caused by sloughing of the shale during drilling.

Figure 3-8 is a structure map on the top of the Conasauga and the equivalent Eau Claire Formation west of the Kentucky River Fault Zone. In the Rome Trough it shows a general deepening to the south and east. It is important to note the Conasauga is below the 2,500 ft depth required to store supercritical-phase CO_2. This ensures that CO_2 will remain in the dense phase at the level of the primary seal. Figure 3-9 is an isopach (thickness) map of the Conasauga for only the Rome Trough area east of the Kentucky River Fault Zone. The Conasauga ranges from 800 to more than 1,100 ft thick, indicating a large amount of impermeable rocks immediately above the Rome/basal sandstone injection zone.

Cambrian-Ordovician Knox Supergroup

The Knox Supergroup is divided into an upper dolomite unit, the Beekmantown Dolomite, and the lower Copper Ridge Dolomite, separated by sandstone or a sandy dolomite unit (Rose Run Sandstone) that is poorly developed in this area. The Knox is 2,200 to 3,000 ft thick in the study area. As discussed previously, the Knox is too shallow at the E.W. Brown site for CO_2 sequestration. Much of the Knox lies above the 2,500-ft depth limit for CO_2 to be in a supercritical phase. The lower part of the Knox (below 2,500 ft depth) is also not a potential injection target, since the primary seal above the Knox is above the phase change boundary for CO_2. Movement of CO_2 upward within the Knox would result in a rapid phase change to gas, increasing pressure significantly. This pressure pulse could fracture the seal above the Knox, allowing CO_2 to leak upward.

The Knox is the shallowest interval mapped in this evaluation. Figure 3-10 is a structure map of the top of the Knox. Because of its shallow depth, more wells have been drilled to the top of the Knox than to the deeper formations, and thus more data are available for the Knox structure map. The Knox deepens to the west and to the east, with the shallowest area at the crest of the Cincinnati Arch (center of the map, near the E.W. Brown Station).

The Knox contains scattered porous and permeable intervals separated by impermeable intervals. It has injection potential in deeper parts of Kentucky (such as at the KGS No. 1 Blan research well in Hancock County), and was used as a hazardous-waste injection zone at the DuPont chemical plant in Louisville. The top of the Knox is a regional erosional unconformity that formed when the Knox was uplifted above sea level during the Early Ordovician. In this area, impermeable intervals in the Knox would provide an additional confining zone for CO_2 injected in deeper reservoirs such as the Rome sandstones.

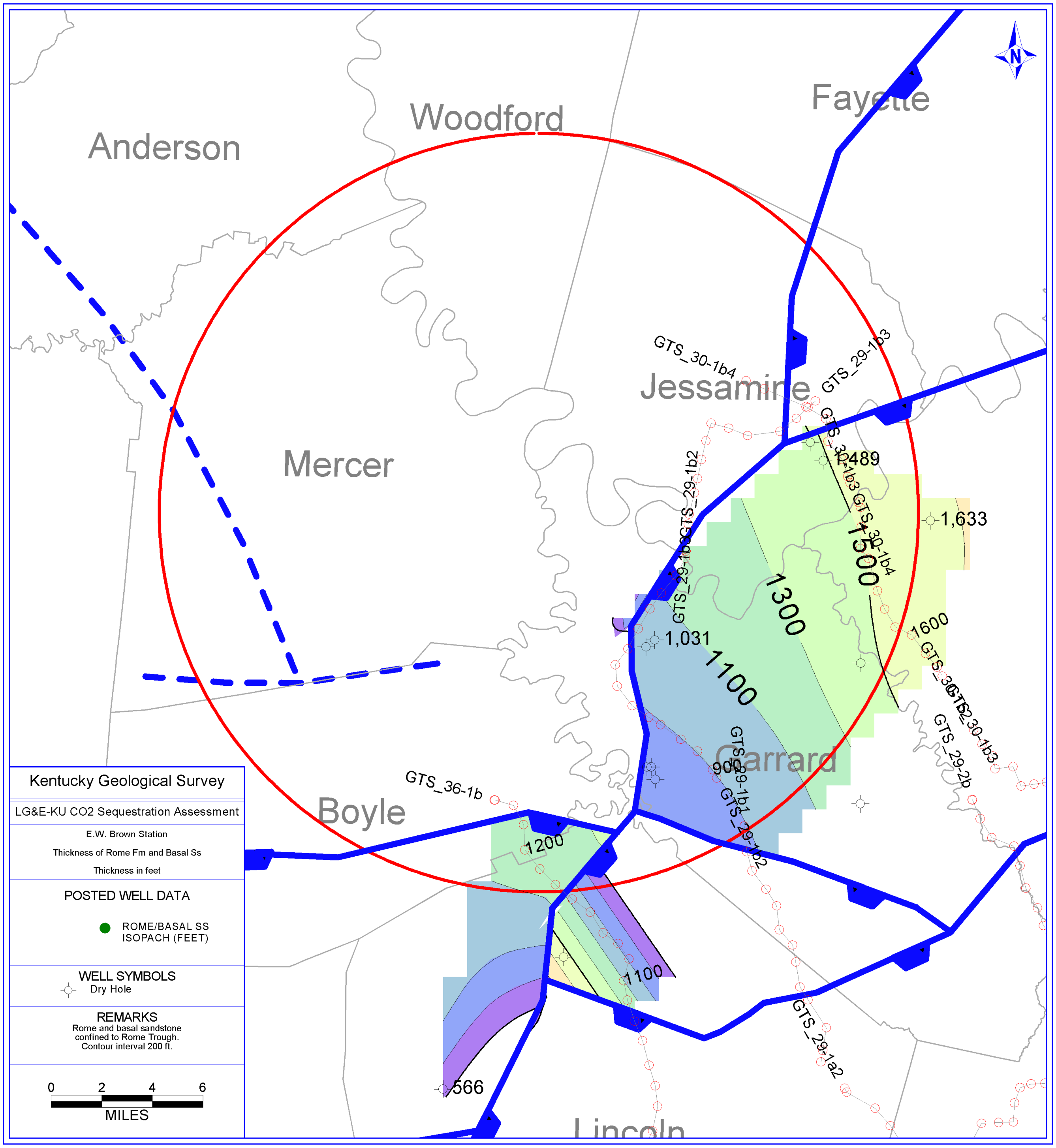

Figure 3-7. Thickness of the Cambrian basal sandstone and Rome Formation. The Rome/basal sandstone interval thins to the south, but this map is based on limited data (four wells and poor seismic data), so it should be considered very general. The formations extend farther than the color-shaded areas because the map is limited to data in the Brown station area. Contour interval is 200 ft.

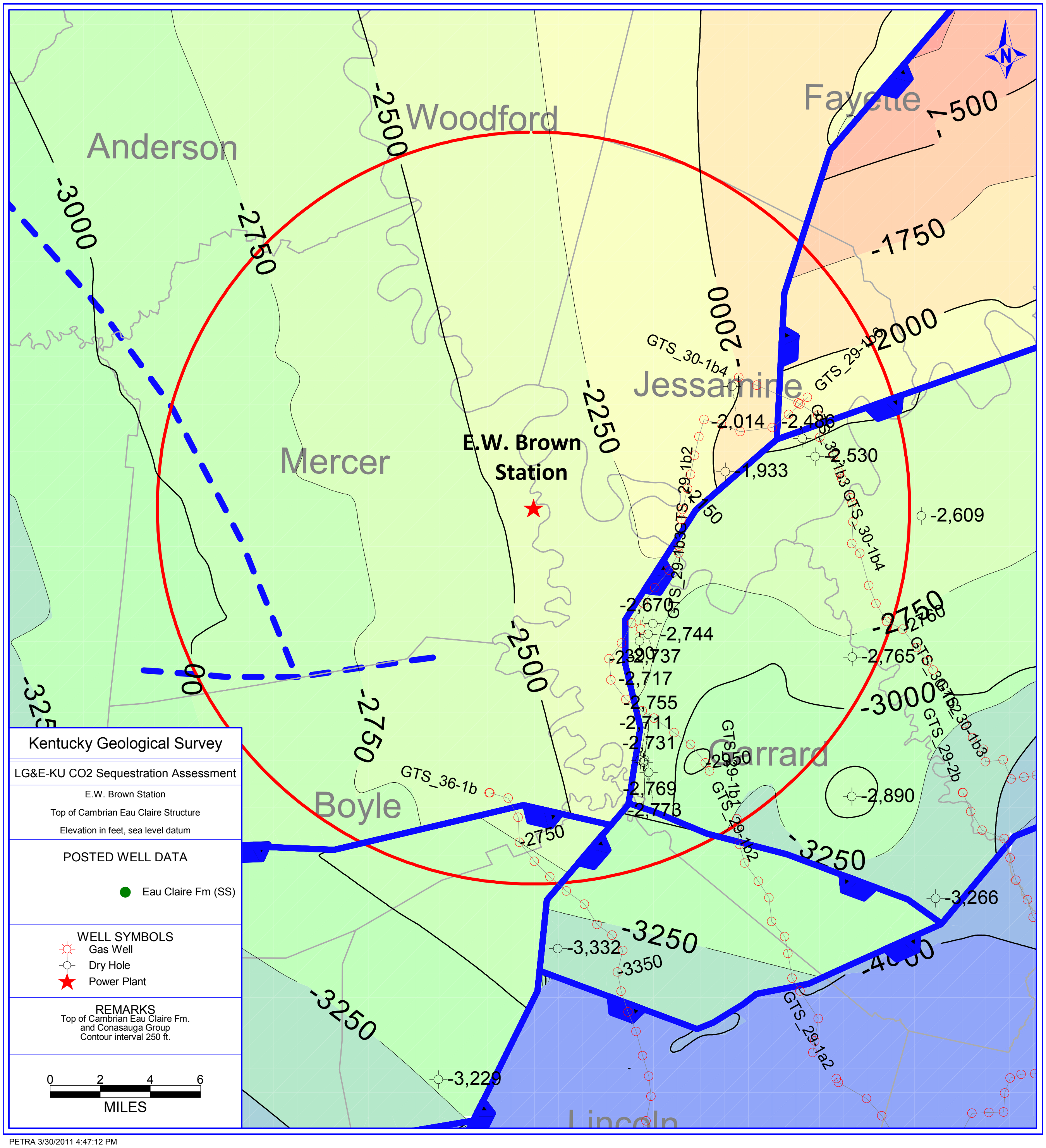

Figure 3-8. Structure on top of the Cambrian Conasauga Group and equivalent Eau Claire Formation. Contour interval is 250 ft. The map indicates that this confining interval is deeper than 2,500 ft below the surface throughout most of the area (depth required to store supercritical-phase CO_2).

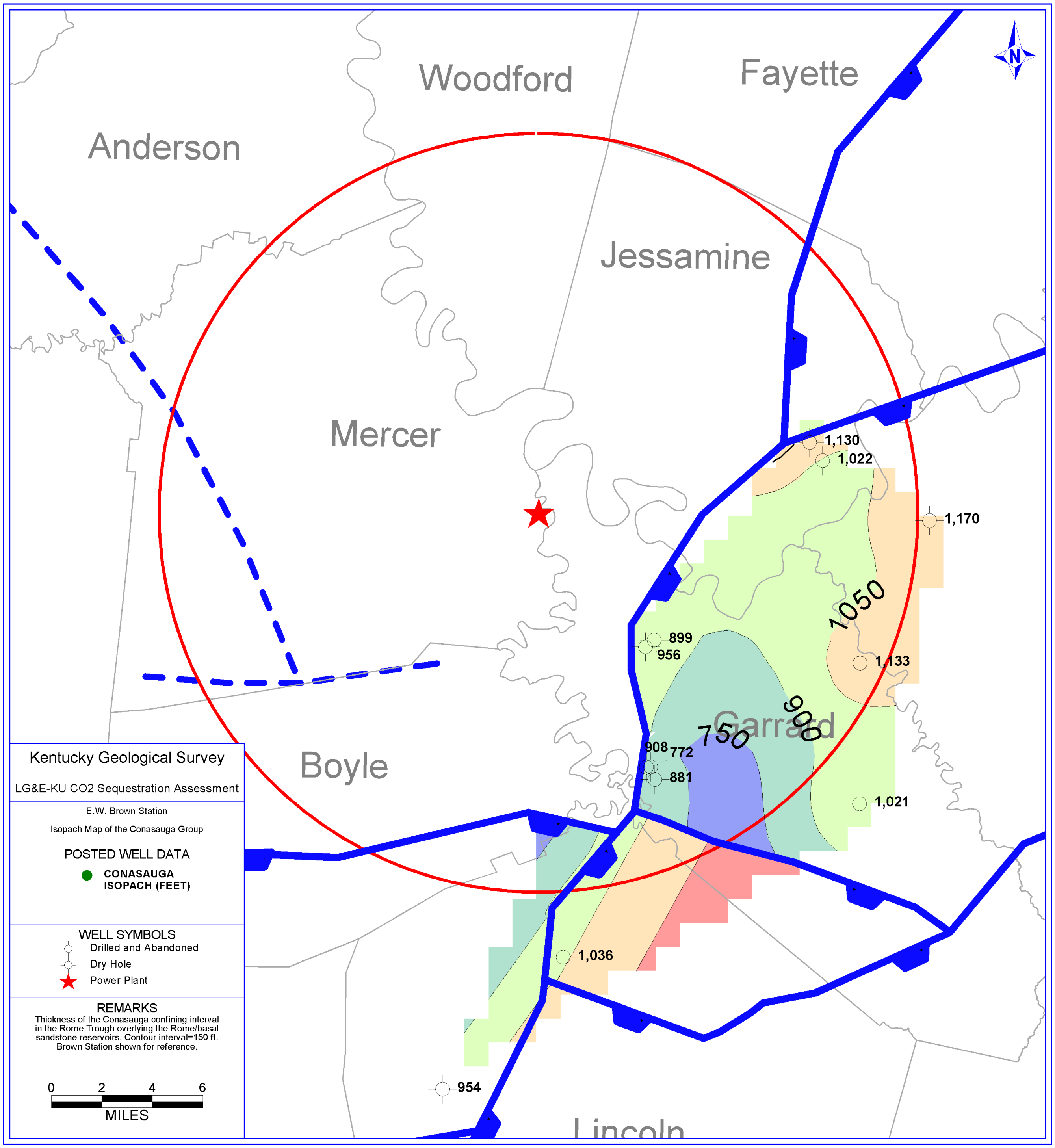

Figure 3-9. Thickness of the Conasauga Group in the Rome Trough portion of the study area. Equivalent Eau Claire Formation to the west is not included. Shale and limestones in this interval range from about 800 to more than 1,100 ft thick, providing a seal for CO_2 injected into the Mount Simon Sandstone below.

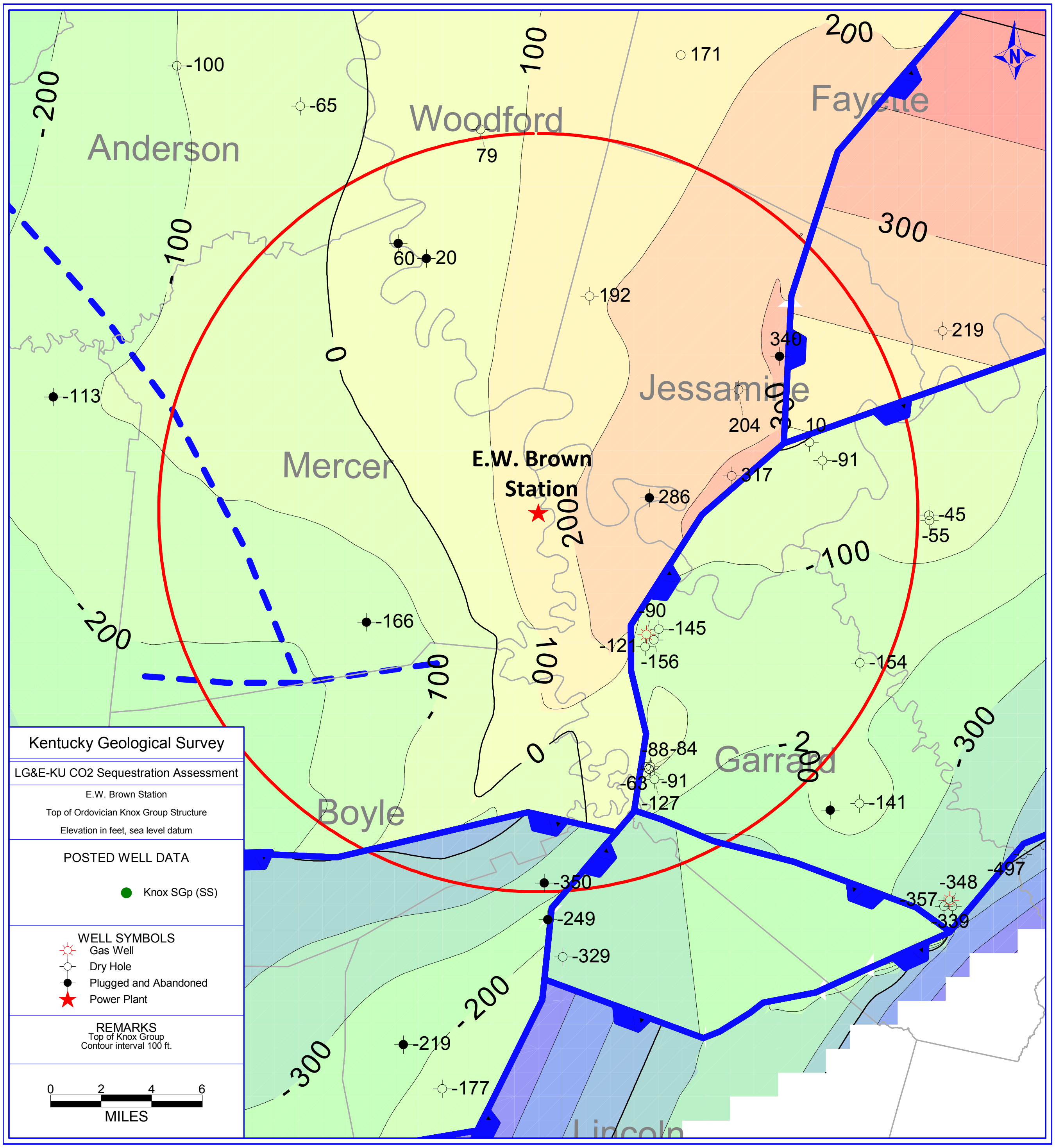

Figure 3-10. Structure on top of the Knox Supergroup. The top of the Knox is shallowest near the E.W. Brown Station (more than 300 ft above sea level) and deepens to the west away from the Cincinnati Arch and to the east across the Kentucky River Fault Zone. The Knox is too shallow for CO_2 storage in this area. Contour interval is 100 ft.

Wells Creek Dolomite, Black River Group, and Trenton Limestone

Overlying the Knox in this area are limestones and dolomites in the Wells Creek Dolomite, Trenton Limestone, and High Bridge (Black River) Group, which together form a shallow secondary confining seal for CO_2 injected into the deeper Rome and basal sandstone zones. These rocks are composed of limestone, minor dolomite, and interbedded shale. The interval typically has very low porosity and permeability unless fractured. In the Rome Trough area, these formations have a combined thickness of 700 to 850 ft.

Deep Faults and Available Seismic Data

Older 1970's-vintage seismic data are available for the eastern part of the study area, east of the Kentucky River Fault Zone. Locations of these lines are shown on the various maps for which the data were used. Selected depth and thickness estimates from these lines were incorporated into structure and isopach maps.

The E.W. Brown area has numerous faults mapped at the surface. These are shown in blue on Figure 3-1. The complex surface faults were simplified for use in making the structure maps. West of the Kentucky River Fault Zone, numerous short en echelon faults trend southeast-northwest through the E.W. Brown site. These faults likely extend to basement, but do not have an impact on potential sequestration since this area is too shallow for CO_2 injection. The main fault zone of interest is the Kentucky River Fault Zone, which runs east of the E.W. Brown site, and forms the western boundary of the Rome Trough. Structure maps indicate reservoir strata dip away from these faults and will form a lateral seal for CO_2 injected into the Rome sandstones. Fortunately, there is good evidence that these faults are sealed and will not transmit CO_2. Several wells drilled adjacent to the fault zone found natural gas in the Rome sandstone reservoirs. This gas was of low quality (not commercial) but has unusually high levels of helium. It appears to be trapped by the Kentucky River Fault Zone, indicating the fault has good sealing capability. Thus, the Kentucky River Fault Zone is interpreted to have a low risk of leakage of injected CO_2, and provides a structural trap to contain CO_2 in the area east of the faults. The helium found in the Rome sandstone reservoirs is a potential economic resource, and its future development could create legal problems for CO_2 sequestration in the area. Any sequestration project would need to be designed to protect existing gas resources from contamination by carbon dioxide.

Structural Cross Sections

Two subsurface correlation cross sections were constructed from well logs to illustrate the geology and structure around the E.W. Brown Station. Locations of these sections are shown on Figure 3-1. Section A–A' (Fig. 3-11) is oriented northwest-southeast and crosses the Kentucky River Fault Zone. The location of the Brown station is shown for reference. This section shows the basal sandstone and Rome Formation confined to the east side of the Kentucky River Fault Zone, on the downthrown side. This section also shows the absence of deep sandstones west of the fault, and how near Precambrian basement is to the 2,500-ft supercritical CO_2 storage boundary.

Section B–B' (Fig. 3-12) is oriented northeast-southwest, parallel to the Kentucky River Fault Zone, but on the downthrown side. It includes data from two wells that were drilled to Precambrian basement and two wells that only penetrated the upper part of the Rome Formation. This section illustrates the depth, continuity, and porosity of the reservoir sandstones and the thickness of the overlying Conasauga, Knox, and High Bridge Group/Lexington Limestone confining zones.

Reservoir Quality and Injection Zone Thickness

In order to calculate carbon sequestration capacity, the average porosity and thickness of the storage zone are required. Since the geology is not suitable for sequestration at the E.W. Brown Station, we are proposing using sandstones in the Rome Formation and basal sandstone east of the Kentucky River Fault Zone, approximately 7 to 10 mi from the E.W. Brown Station. Figure 3-13 shows the area that was evaluated.

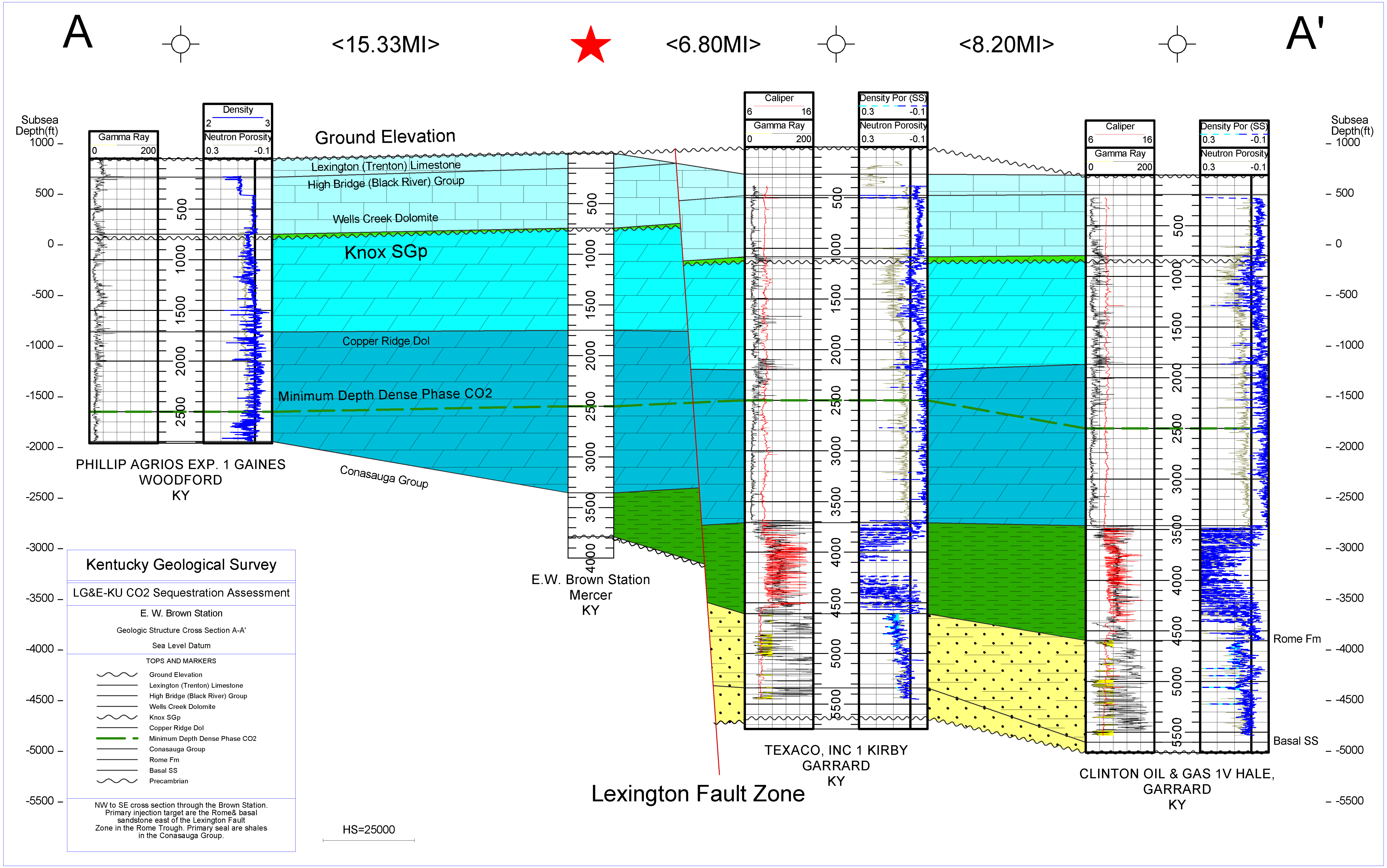

Figure 3-11. Northwest-southeast regional structural cross section showing well logs for deep wells and the location of the E.W. Brown Station for reference. The proposed injection zone in the Rome Formation and basal sandstone is restricted to areas east of the Kentucky River Fault Zone. Well logs include the gamma-ray and caliper in the left track, and density and neutron-porosity logs in the right track. The density-porosity log is shaded blue where porosity is greater than 7 percent in the Rome Formation and basal sandstone. The Conasauga Group (and equivalent Eau Claire Formation) is the primary seal for the underlying Rome Formation and basal sandstone.

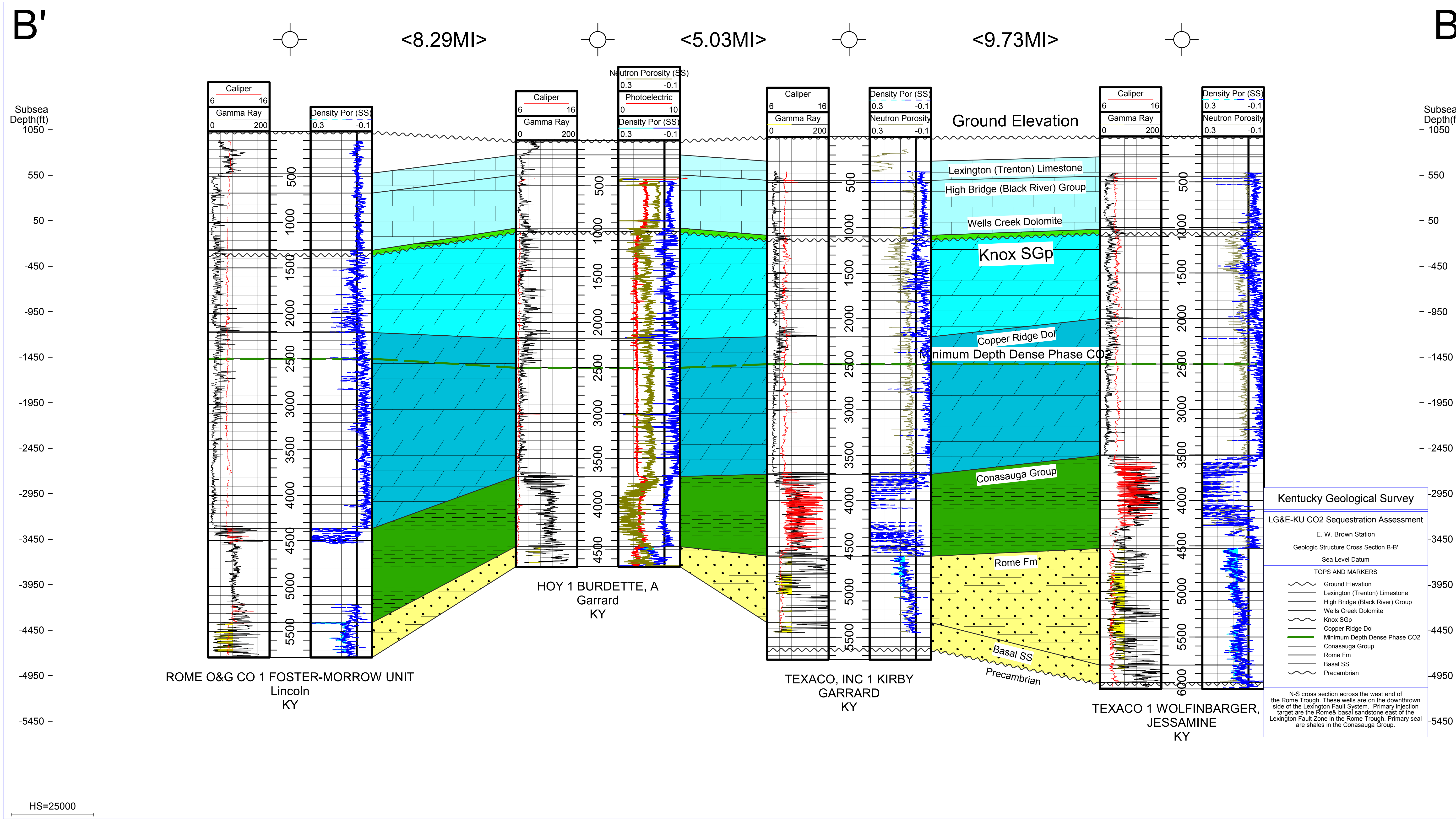

Figure 3-12. Northeast-southwest regional cross section showing well logs for deep wells drilled in the Rome Trough east of the Kentucky River Fault Zone. The proposed injection zone is the Rome Formation and basal sandstone, shaded yellow. The two wells on the left only penetrated the top of the Rome Formation. Well logs include the gamma-ray and caliper in the left track, and density and neutron-porosity in the right track. The density-porosity log is shaded blue where porosity is greater than 7 percent in the Rome Formation and basal sandstone. The Conasauga Group (and equivalent Eau Claire Formation) is the primary seal for the underlying Rome Formation and basal sandstone.

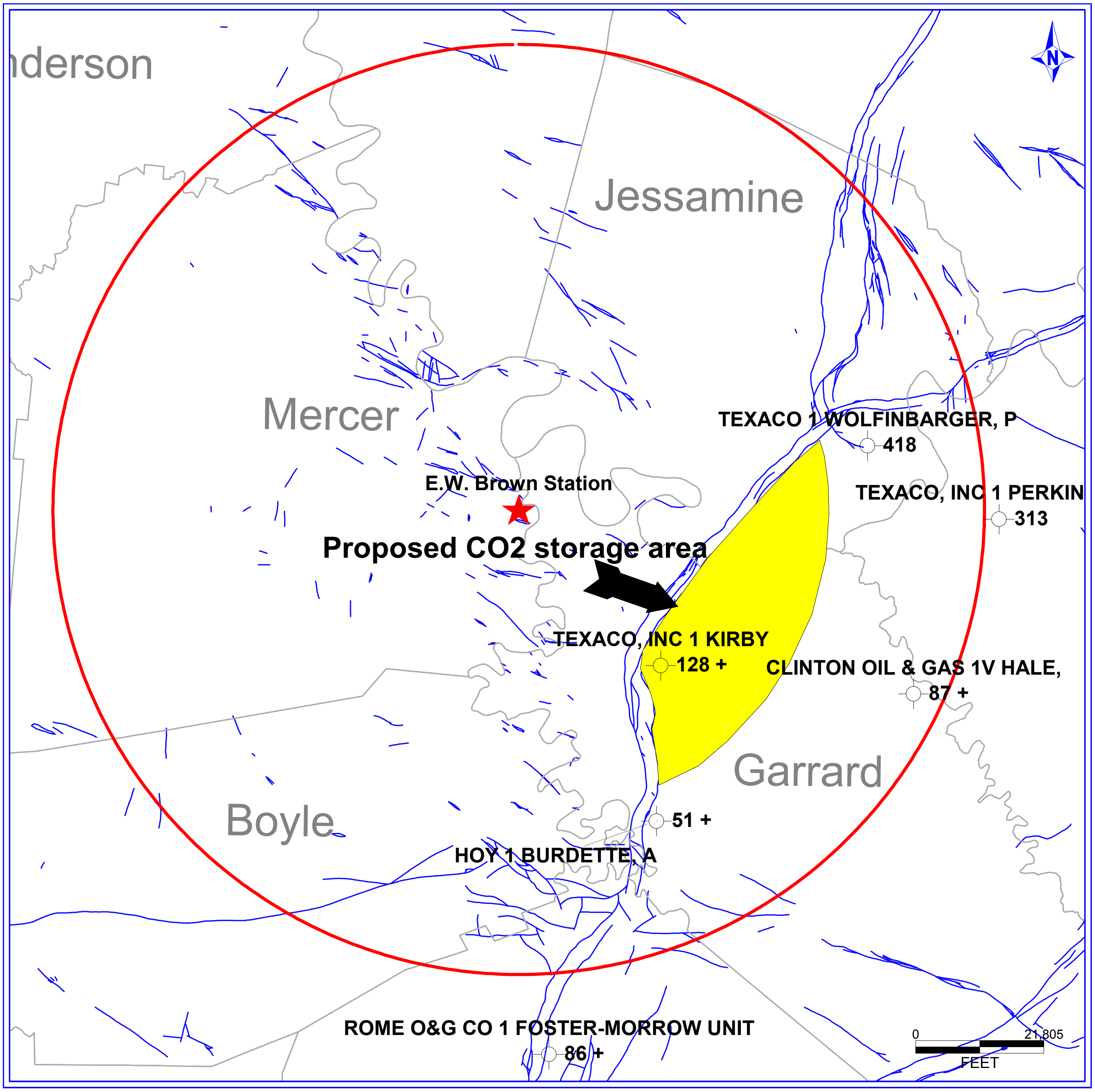

Figure 3-13. Proposed sequestration target area within 10 mi of E.W. Brown Station. Yellow area has suitable reservoir and seals less than 10 mi from Brown. The locations and thickness of net porous sandstone (ft) are shown for the six wells used in the reservoir calculations. A plus symbol (+) indicates the well only partly penetrated the reservoir interval.

A limit of 10 mi from E.W. Brown was used to define the potential sequestration area, which is highlighted in yellow on the map. Reasonable estimates for porosity and net injection-zone thickness were calculated from six wells, and locations are shown in Figure 3-13. Only one of these wells lies within 10 mi of E.W. Brown, but four are located within 15 mi.

Reservoir Porosity Estimates

Both geophysical well logs and porosity measured from core samples were used to estimate porosity. Cores provide the most accurate porosity and permeability data because they are analyzed directly in a laboratory. Porosity from well logs is an indirect measurement, based on the density or other rock properties measured with radioactive devices. Core-measured porosity and permeability data for the Rome Formation are available from a single well (the Texas West Bay No. 1 Burdette in Garrard County). Core data from this well are presented in Figures 3-14 and 3-15. The porosity and permeability versus depth plots (Figs. 3-14a, b) also include data from the Mount Simon Sandstone for comparison (the reservoir at the Trimble County, Ghent, and Mill Creek Stations). The Rome sandstone porosity and permeability data indicate good reservoir quality. Average porosity is higher (13.1 percent) than for the Mount Simon reservoir (Fig. 3-14a), whereas permeabilities are similar (Figs. 3-14b, 3-15).

Plotting porosity versus permeability illustrates the apparently positive correlation between the two measurements (Fig. 3-15). This plot allows a minimum porosity to be interpreted for sandstone with acceptable permeability for injection. Because porosity can be measured with downhole logs and permeability cannot, a porosity cutoff allows the net thickness of rock with suitable porosity and permeability for injection to be summed from porosity geophysical-log data alone.

A minimum porosity of 7 percent was chosen as the cutoff for the Rome interval in this area. This was done for consistency with published Mount Simon reservoir calculations (Medina and others, 2011), and because the core porosities are higher than the log-derived porosities (discussed below). The reason for this difference is not clear, and will require additional study.

Core data were available for a 38-ft interval in one well. Porosity (but not permeability) data are also derived from geophysical well logs, especially the bulk-density log. Logs provide a continuous data set for the entire formation, but are not as accurate as core data. A total of six wells with formation bulk-density geophysical logs were used to estimate sandstone porosity.

Calculation of Net Porous Sandstone

Once a porosity cutoff was chosen, the net thickness of porous sandstone and average porosity of sandstones above the cutoff were determined for use in CO_2-capacity calculations. Because the Rome and basal sandstones contain abundant thin shales and some clay-rich sandstones with poor reservoir quality, only clean, shale-free sandstone was included in the net-sandstone calculation. The natural gamma-ray geophysical log is the best discriminator of clay and shale, and a cutoff of 80 API gamma-ray units was used to identify clean sandstone. Intervals with 80 API units or less were classified as sandstone.

A log analysis program (Petra) was used to calculate the net feet of sandstone in each well with a gamma-ray reading of less than 80 API units, and sandstone density porosity greater than or equal to 7 percent. The results of the net-sandstone calculation are shown in Table 3-1. Average log porosity and total porosity-feet (thickness of void space) were also calculated. Gross thickness is the total thickness of the Rome and basal sandstone, or the feet penetrated in the well if a partial penetration. Only two wells penetrated the entire Rome/basal sandstone interval in the area. A net-to-gross sandstone ratio was also calculated for each well. The net-to-gross sandstone ratio ranges from 0.09 to 0.28. Average log-derived porosity of the net sandstone interval ranges from 8.6 to 11.5 percent.

Table 3-1 also includes data estimated from averages of the six wells for use in the capacity calculation. The gross thickness is the average of the two wells that fully penetrated the interval. The net-to-gross sandstone ratio is the average of the six wells. This ratio (0.2) gives an estimated net porous sandstone thickness of 312 ft. The average porosity of 9.6 percent was rounded up to 10 percent for the capacity calculation.

CO_2 Capacity Calculations

Using the compiled and calculated data, CO_2 storage-volume calculations were made. CO_2 storage capacity is based on the porosity, thickness, and area of the injection zone and density of the injected CO_2. CO_2 density is a function of reservoir pressure and temperature. The Rome interval is deep enough for supercritical-phase CO_2 injection in the area east of the E.W. Brown Station. CO_2-density calculations were made using the CO_2 properties calculator at the MIDCARB project Web site: www.midcarb.org/calculators.shtml. The Midcontinent Interactive Digital Carbon Atlas and Relational

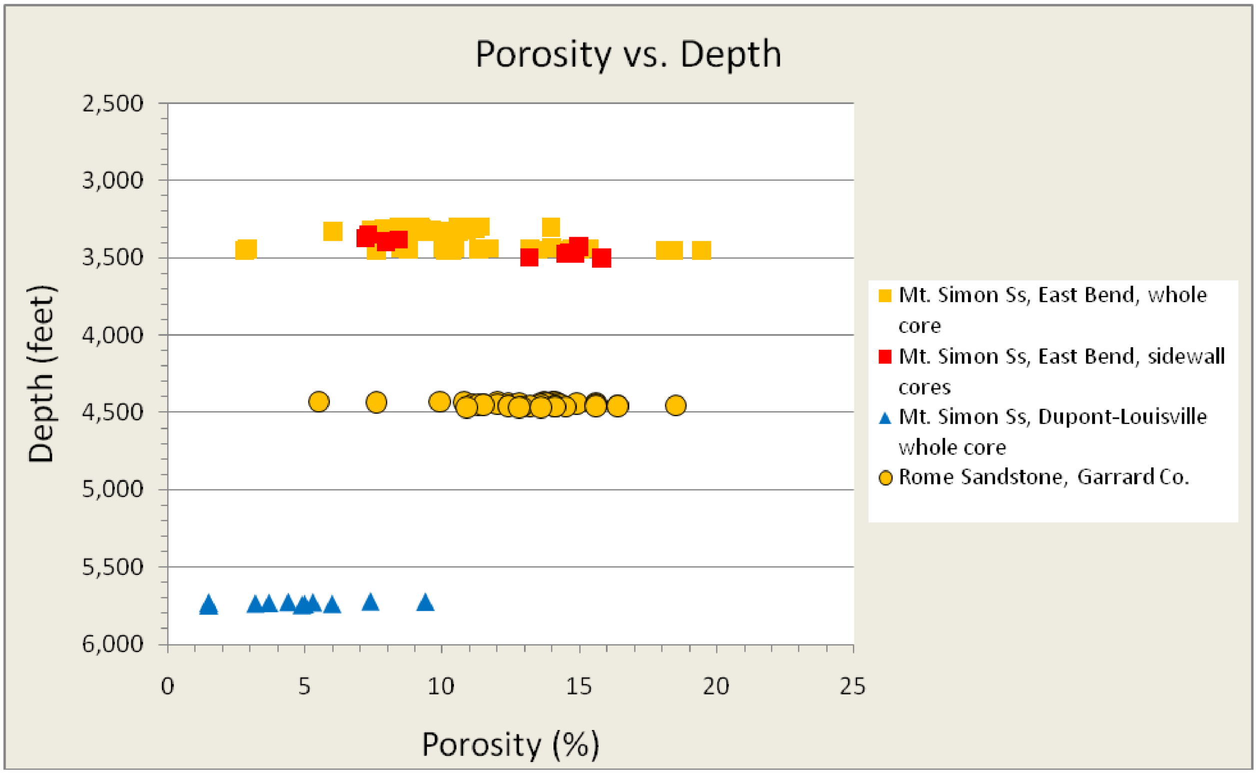

Figure 3-14a. Core porosity versus depth below the surface for Rome sandstones (circles). Data from the Mount Simon Sandstone in northern Kentucky and Louisville are included for comparison. Average core porosity for the Rome sandstones is 13.1 percent, and is higher than for the Mount Simon Sandstone cores.

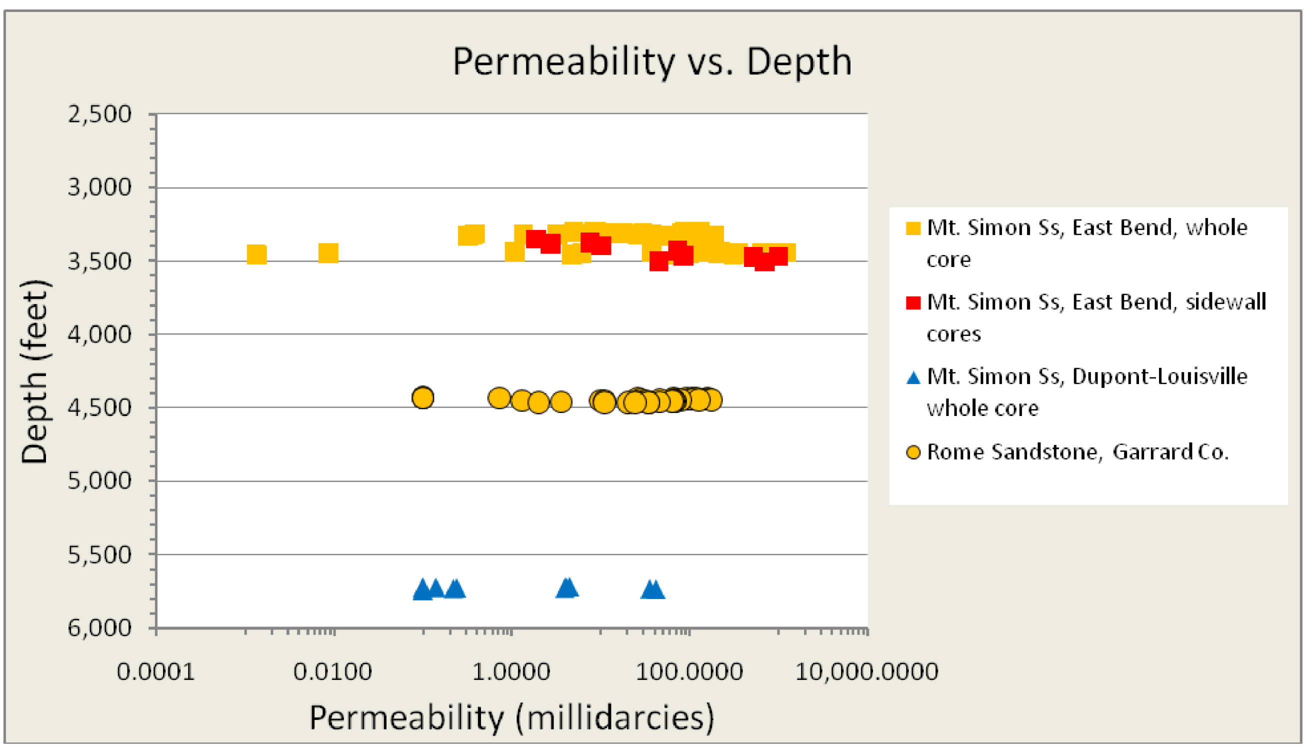

Figure 3-14b. Core permeability versus depth below surface for Rome Formation sandstones (circles). Data from the Mount Simon Sandstone in northern Kentucky and Louisville are included for comparison. Permeability in the Rome is variable, but is comparable with that of the Mount Simon in northern Kentucky. Average permeability for the Rome sandstone core is 56 md.

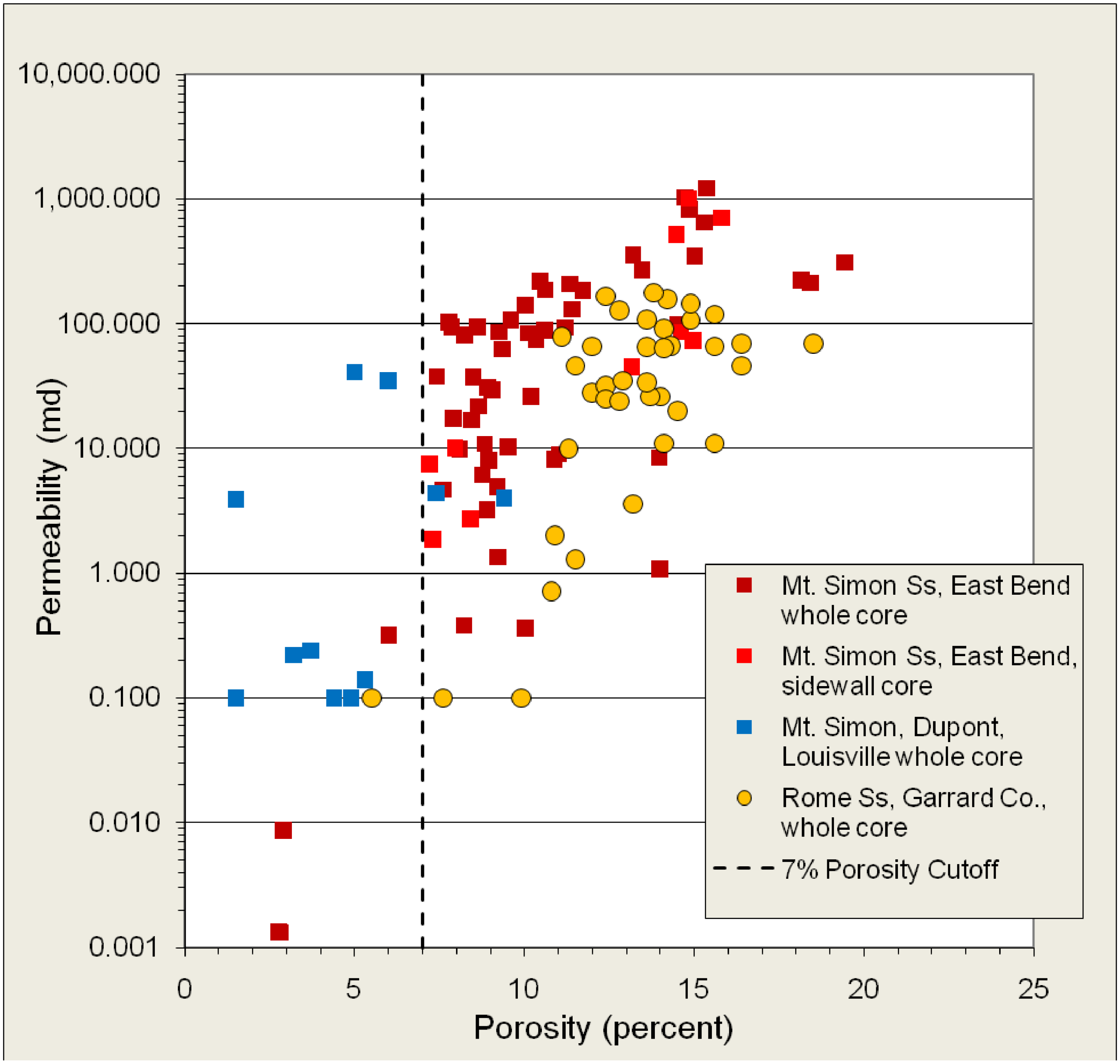

Figure 3-15. Porosity versus permeability for the Rome sandstone core in Garrard County (circles). Data from the Mount Simon Sandstone in northern Kentucky and Louisville are included for comparison. Porosity in the Rome is higher than in the Mount Simon in northern Kentucky, whereas permeability is similar.

dataBase was a research consortium composed of the state geological surveys of Illinois, Indiana, Kansas, Kentucky, and Ohio, funded by the U.S. Department of Energy.

Calculated CO_2 density is shown in Table 3-2.

These parameters are required to calculate CO_2 storage capacity:

Reservoir pressure: assumed hydrostatic and calculated at 0.433 psi/ft for the reservoir depth

Temperature: taken from well-log data in Garrard and Jessamine Counties

Table 3-1. Rome and basal sandstone reservoir data.							
Well Data	*Average Depth (ft)*	*Gross Thickness (ft)*	*Full or Partial Interval*	*Net Porous Sandstone (ft)*	*Net-to-Gross Ratio*	*Average Porosity (%)*	*Porosity-Feet*
Texaco Perkins	5,500	1,633	full	312.5	0.19	9.40	29.3
Texaco Wolfinbarger	5,100	1,489	full	418.0	0.28	9.50	39.5
Clinton Oil Hale	5,100	937	partial	87.0	0.09	9.20	7.9
Texaco Kirby	5,000	842	partial	128.0	0.15	8.60	11.0
Hoy Burdette	4,800	184	partial	50.5	0.27	11.50	5.8
Rome Oil Foster-Morrow	5,600	380	partial	85.5	0.23	9.40	8.0
Average	5,183	–	–	–	0.20	9.60	–
Calculated Data							
Estimate for Capacity Calculation	5,200	1,561		312.0	0.20	10.0	31.2

Table 3-2. Calculated CO_2 density at reservoir conditions.				
Site	*Reservoir Pressure (psi)*	*Reservoir Temperature (°F)*	*CO_2 Density (lb/ft³)*	*CO_2 Density (kg/m³)*
E.W. Brown	2,200	110	47.3	758.3

Reservoir thickness: the net porous sandstone thickness as calculated above
Reservoir area: standard area of 100 acres
Reservoir porosity: the average porosity for the net reservoir footage

The equation for CO_2 storage capacity was modified from Medina and others (2011):

$$SC = A_n * h_n * \Phi_n * \rho_{CO2} * \dot{\varepsilon} / 1{,}000$$

where SC is the storage capacity in metric tons, A_n is the area in square meters, h_n is the net reservoir thickness, Φ_n is the average porosity of the net reservoir, ρ_{CO2} is the density of CO_2 at reservoir conditions, and $\dot{\varepsilon}$ is the storage efficiency factor (discussed below).

The reservoir parameters used and CO_2 capacities calculated are shown in Table 3-3.

Efficiency of CO_2 Storage

The storage-capacity equation used above includes an efficiency factor, which reduces the CO_2 storage capacity. This factor is applied because 100 percent of the available pore volume is never completely saturated with CO_2 because of the fluid characteristics and geologic variability within the reservoir.

Litynski and others (2010) calculated efficiency factors for carbon storage in various reservoir types that account for factors that reduce the volume of CO_2 that can be stored. These factors include:

Geologic Factors

- Net-to-total area ratio of a basin suitable for sequestration

Table 3-3. Reservoir parameters and calculated CO_2 storage capacity for a 100-acre area at 100 percent and 14 percent storage efficiency.								
Site	*100-Acre Area (m²)*	*Net Reservoir Thickness (ft)*	*Net Reservoir Thickness (m)*	*Porosity (%)*	*CO_2 Density (kg/m³)*	*CO_2 Capacity at 100% Efficiency (metric tons)*	*Storage Efficiency Factor*	*CO_2 Capacity at 14% Efficiency (metric tons)*
E.W. Brown	404,686	312	95.1	10	758.31	2,918,344	0.14	408,568

- Net-to-gross thickness ratio of a reservoir that meets minimum porosity and permeability requirements
- Ratio of effective to total porosity (fraction of connected pores)

Displacement Factors

- Areal displacement efficiency: area around a well that can be contacted by CO_2
- Vertical displacement efficiency: fraction of vertical thickness that will be contacted by CO_2
- Gravity: fraction of reservoir not contacted by CO_2 due to buoyancy effects
- Displacement efficiency: portion of pore volume that can be filled by CO_2 due to irreducible water saturation

Combining all of these factors, using a Monte Carlo simulation, results in a probability range of total efficiency factors of 0.51 to 5.4 percent (P_{10} to P_{90} range) (Litynski and others, 2010). For the purposes of this assessment, the *geologic* factors are known and thus equal to 1. In our 100-acre evaluation unit, the net-to-total area is the same, the net-to-gross thickness has already been calculated, and for clastic reservoirs (sandstones) we can assume that the porosity is well connected with a ratio of effective (connected) porosity to total porosity equal to 1. Litynski and others (2010) calculated efficiency factors for the *displacement* factors separately, and for sandstone reservoirs they range from 7.4 to 24 percent, with a P_{50} (most likely) efficiency factor of 14 percent. This means the most likely case is that 14 percent of the pore space can be filled with CO_2. The range of storage volumes using the probabilistic efficiency factors for the E.W. Brown site is shown in Table 3-4.

The application of an efficiency factor significantly reduces the storage capacities, but is necessary to estimate storage volume.

Summary

The E.W. Brown Station is located in an area where geologic sequestration is not feasible directly below the plant site because of the absence of porous reservoirs at depths necessary for supercritical-phase CO_2 storage. However, an area 7 to 10 mi east of the Brown station is suitable for geologic sequestration in deep sandstones of the Rome Formation. Use of this area would require transporting compressed CO_2 from the Brown station by pipeline. This area, east of a major fault zone, has excellent confinement for injected CO_2 provided by the 1,000-ft-thick Conasauga Group. In addition, this area provides a structural trap for injected CO_2 against the Kentucky River Fault Zone. Injected CO_2 would migrate a short distance to the west toward the fault zone, which forms a lateral barrier to further migration. The fault has a low risk of leakage because oil and gas exploration wells have encountered natural gas trapped in the Rome sandstones against the fault.

Geologic data for this area are good, with numerous wells in the reservoir and one core of the reservoir rock. Additional seismic data will be necessary to better define the specific area chosen for a demonstration project. Existing seismic data are of poor quality, and limited in extent.

One problem with using this area for sequestration is a potential conflict with oil and gas mineral owners. Natural gas has been found in wells in the area, but is high in nitrogen and has too little methane for commercial production. However, several wells contain gas with anomalously high levels of helium (up to 2 percent). This potential helium resource has been known since the 1970's, but has not been commercially developed. Rising prices for helium may generate interest in this area to develop the helium resource. Obviously, injection of CO_2 into a reservoir with potentially economic resources would contaminate the helium. These potential issues will have to be resolved before sequestration begins. It may be possible to identify deeper reservoirs for CO_2 sequestration that do not affect potential gas resources.

Because the sequestration target for the E.W. Brown Station is offsite, total site capacity will

Table 3-4. Range of probabilistic storage volumes using DOE's displacement efficiency factors for clastic reservoirs (Litynski and others, 2010).

Site	*Minimum Volume (metric tons/100 acres) $\dot{\varepsilon}$ = 7.4% (P_{10})*	*Most Likely Volume (metric tons/100 acres) $\dot{\varepsilon}$ = 14% (P_{50})*	*Maximum Volume (metric tons/100 acres) $\dot{\varepsilon}$ = 24% (P_{90})*
E.W. Brown Station	215,957	408,568	700,403

depend on the size of the property leased for the storage project. For comparison with the other, larger sites (Ghent and Trimble County), we have assumed that an area of 2,000 acres will be used (Table 3-5). A site of this size near the E.W. Brown Station would allow 8.2 million tons of CO_2 to be stored.

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Table 3-5. Total site storage capacity at E.W. Brown Station assuming a 2,000-acre area.

Site	*CO_2 Storage Volume (metric tons/acre)*	*Total Site Size (acres)*	*Total Site Storage Volume (metric tons)*
E.W. Brown	4,086	2,000	8,171,363

Chapter 4: Geologic CO_2 Sequestration Potential of the LG&E-KU Mill Creek Station, West-Central Kentucky

LG&E-KU CO_2 Sequestration Geologic Summary Sheet

Power Plant: Mill Creek **County:** Jefferson **Geologic Basin:** Cincinnati Arch

Data Quality:

Distance to nearest well control in reservoir:	12 mi
Wells to primary injection zone within 15-mi radius:	1
Distance to nearest core in injection zone:	12 mi
Distance to nearest good-quality seismic control:	11 mi

Reservoirs:

Primary injection zone:	Cambrian Mount Simon Sandstone
Rock type:	sandstone (quartzarenite)
Drilling depth at plant site:	5,600 ft
Trapping mechanism:	regional dip (capillary and solution trapping)
Maximum reservoir pressure:	2,800 psi (hydrostatic)
Reservoir temperature:	116°F
Salinity of reservoir fluid:	200,000 ppm (estimated)
Reservoir thickness (gross/net):	470/70 ft
Average porosity:	8 percent
Average permeability:	8 md
Secondary injection zone:	none at this site

Confinement and Integrity:

Primary confining zone:	Cambrian Eau Claire Shale
Rock type:	shale and dolomite
Thickness of primary confining zone:	900 ft
Height above primary injection zone:	0 (overlies injection zone)
Well penetrations of primary seal within 15-mi radius:	2
Secondary confining zone:	Ordovician Black River/Trenton Limestone
Rock type:	limestone
Thickness of secondary confining zone:	575 ft
Height above primary injection zone:	4,500 ft
Well penetrations of secondary seal within 15-mi radius:	12
Number of faults cutting primary seal within 15-mi radius:	2
Distance to nearest mapped fault:	5 mi

Storage Capacity:

Calculated CO_2 storage capacity, primary injection zone:	563,583 metric tons/100 acres (assuming 100 percent efficiency); 78,902 metric tons/100 acres (at 14 percent efficiency)

Data compiled and interpreted from well records maintained by the Kentucky Geological Survey.

Introduction

Geologic CO_2 sequestration potential was evaluated for an area surrounding the LG&E-KU Mill Creek power-generation station in Jefferson County, Ky. A circular area with a 15-mi radius around the plant was defined as the primary focus of the evaluation, but data from beyond 15 mi were also used because of limited data within the primary area. The 15-mi buffer includes parts of Harrison and Floyd Counties, Ind., as well as Jefferson, Meade, and Bullitt Counties in Kentucky. An index map is included in Figure 4-1, which shows the locations of well data, faulting, and geologic cross sections.

The following data were compiled for the evaluation:

1. The 7.5-minute topographic and geologic quadrangle maps for the Valley Station and Kosmosdale quadrangles
2. Locations of all petroleum-exploration and waste-disposal wells penetrating the Cambrian-Ordovician Knox Group or deeper (Kentucky and Indiana Geological Surveys)
3. Formation tops for geologic units from the top of the Ordovician to the Precambrian (Kentucky and Indiana Geological Surveys)
4. Available digital geophysical logs for Knox and deeper wells (Kentucky and Indiana Geological Surveys)
5. Core analyses (porosity and permeability) for the Mount Simon Sandstone, Knox Group, and Eau Claire Formation
6. Reflection-seismic data

Within the 15-mi radius around the Mill Creek Station, one well has been drilled that penetrates the entire Paleozoic sequence, bottoming in Precambrian rocks. The well was drilled as a Class 1 hazardous-waste disposal well at the E.I. DuPont plant in Louisville, 12 mi northeast of Mill Creek. This well tested the injectivity of the Cambrian Mount Simon Sandstone, but because of low permeability, waste-disposal injection was confined to the Knox Dolomite interval. Two other wells were drilled on the DuPont property; both only went to the Knox—one of these was an injection well, the other an observation well. These wells provide key geologic data used in this assessment. A total of 13 wells have been drilled to 2,500 ft or deeper within the 15-mi area. Most are saltwater-disposal wells associated with the Laconia Gas Field (New Albany Shale reservoir) in Indiana.

There are numerous abandoned shallow wells near the Mill Creek site associated with the Meadow Gas Field (southwestern Jefferson County and adjacent Bullitt County) (Fig. 4-1). This field produced gas for domestic use from the New Albany Shale at around 250 ft, and was drilled in the early 1900's. There is no current production from this field, and records are scarce (Kepferle, 1972).

In Meade County to the west, two shallow gas fields, Doe Run and Muldraugh, have been converted to gas storage fields. These fields produced from several shallow reservoirs, including the Devonian New Albany Shale, Devonian Jeffersonville Limestone, and Silurian Laurel Dolomite. Both of these fields lie within a 15-mi radius of the Mill Creek Station, but are shallow enough that they will have no impact on deeper CO_2 storage operations. In addition, they both occur downdip from Mill Creek, opposite the direction of likely CO_2 migration.

More recently in Meade County, in the southwestern part of the study area, numerous wells have been drilled to the Devonian New Albany Shale and underlying carbonates for natural gas. These wells are typically less than 1,000 ft deep, and are shown as the large gas field in southern Meade County on Figure 4-1. This gas production is too shallow to affect deeper injection of CO_2 at Mill Creek.

Other deep wells are located to the northeast and southwest, but lie outside the 15-mi radius. Wells to the northeast were used in the evaluations of the Trimble County and Ghent Stations (see chapter 1). These include two wells drilled in Switzerland County, Ind., by Ashland Oil. In 2009, a CO_2 injection test well was drilled by Battelle Memorial Institute at the Duke Energy East Bend Station in Boone County, Ky., as part of the U.S. DOE–funded Midwest Regional Carbon Sequestration Partnership (www.mrcsp.org). This well, 82 mi from Mill Creek, was drilled to test the Cambrian Mount Simon Sandstone, the same potential reservoir zone that underlies Mill Creek. Data from this well were available for this evaluation, but the

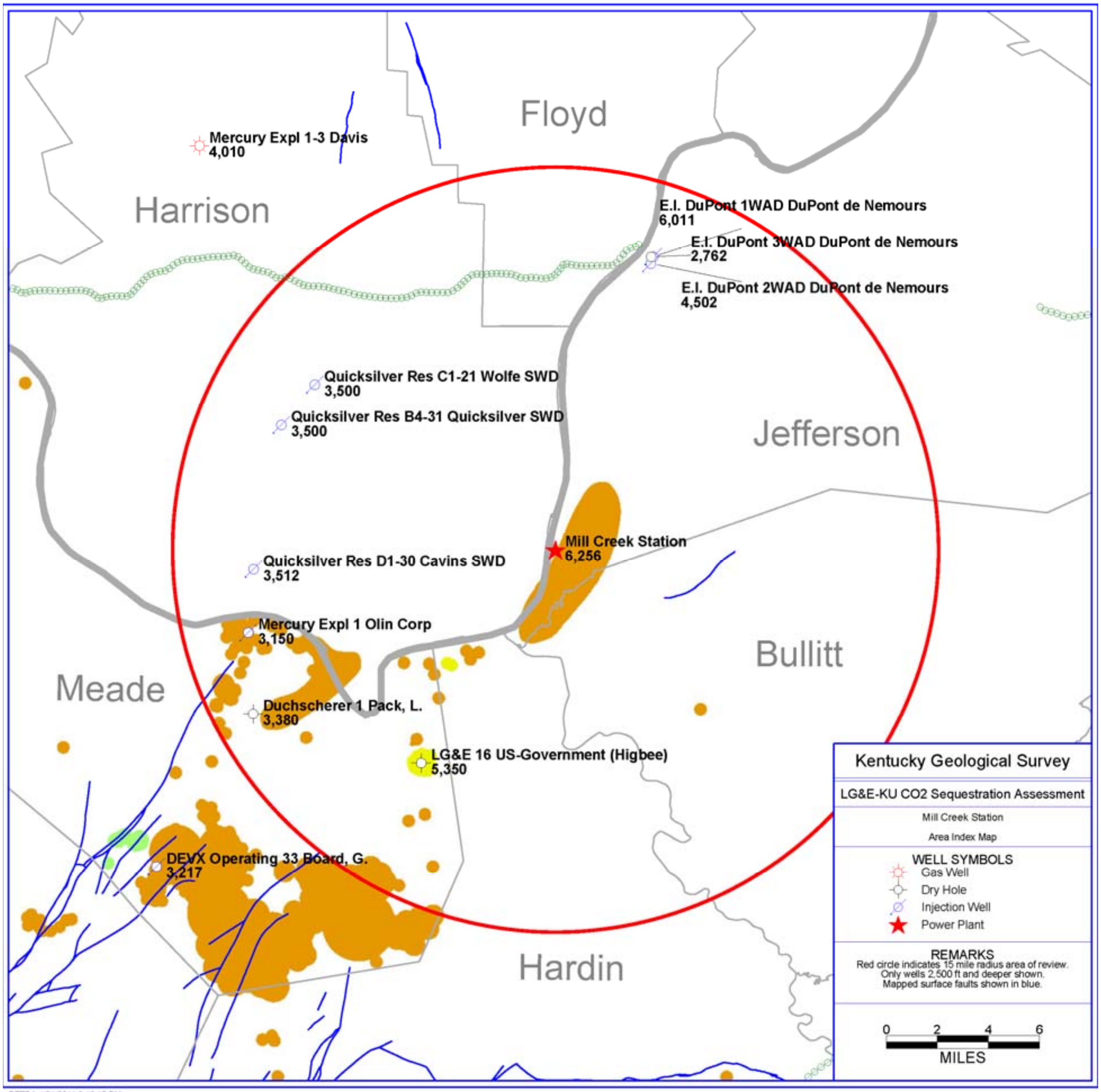

Figure 4-1. Location of Mill Creek Station in Jefferson County, Ky. Heavy gray line is the Ohio River, separating Indiana from Kentucky. Red circle is the 15-mi radius around the station, defining the primary area of study. Wells deeper than 2,500 ft are shown. The location of one seismic line (east-west line of circles in Harrison County, Ind.) is shown. Mapped surface faults are indicated by solid blue lines. Gas (orange) and oil (light green) fields are also shown.

distance from Mill Creek and difference in depth limit their applicability to this evaluation.

To the southwest, two Precambrian wells are located 42 to 46 mi from Mill Creek, in Breckinridge and Hancock Counties. In both of these wells the Cambrian Mount Simon Sandstone is absent, and thus they provide no data for that formation at Mill Creek. The deep well in Hancock County was drilled by the Kentucky Consortium for Carbon Storage (Kentucky Geological Survey and partners). This well was a CO_2 sequestration test of the Knox Group, and numerous cores, seismic data, and logs from it are available. The Precambrian well in Breckinridge County was an unsuccessful oil and gas exploration well, and only logs are available (no core).

Geologic Setting and Surface Geology

Jefferson County lies on the west flank of the Cincinnati Arch, a broad anticline (arch) that separates the deeper sedimentary basins in western Kentucky (Illinois Basin) and eastern Kentucky (Appalachian Basin). The arch developed in Middle Ordovician time, and rock units deposited prior to this time have been tilted to the west toward the Illinois Basin. Rocks deposited from the Middle Ordovician and later were influenced to some extent by the growing arch, but for the interval of interest in this study the arch had no effect on thickness or lithology.

The Mill Creek Station is located in the Kosmosdale 7.5-minute quadrangle, and Kepferle (1972) mapped the geology of this quadrangle. The Mill Creek power plant is located on unconsolidated sediments in a broad alluvial valley along the Ohio River (Fig. 4-2). Sediments underlying the river valley are Quaternary-age (Holocene) alluvium and Pleistocene glacial outwash deposits. Bedrock is exposed in the hills and bluffs to the east. Bedrock consists of Mississippian siltstones and shales of the Borden Group, with hills capped by the Mississippian Harrodsburg and Salem Limestones.

Surface geology does not have a direct impact on carbon sequestration potential, since CO_2 injection will occur much deeper. The New Albany Shale and New Providence Shale are too shallow to form effective seals, and crop out about 10 mi to the east of Mill Creek. Deeper Upper Ordovician shales (500 to 1,000 ft deep) would serve as potential secondary confining layers in the unlikely event CO_2 were to migrate through the deeper primary seals.

The surface geology will impact the design and implementation of shallow groundwater monitoring wells that will be required by the U.S. EPA for an underground injection permit. The presence of unconsolidated alluvial sediments and glacial outwash along the Ohio River at the Mill Creek site allows relatively inexpensive construction of monitoring wells that will yield good water flows. The UIC permit will likely require monitoring down to the base of the underground source of drinking water, which may require drilling into Mississippian bedrock.

Stratigraphy and Structure

Geologic storage of carbon dioxide is confined to depths greater than 2,500 ft below the surface so that CO_2 exists in the supercritical, or dense, phase. Supercritical CO_2 has properties of both a liquid and a gas, but much higher density. In the Jefferson County area, this 2,500-ft depth falls within the Cambrian-Ordovician Knox Group. Geologic formations below 2,500 ft in this area include the basal part of the Knox, the Upper-Middle Cambrian Eau Claire Formation, the Middle Cambrian Mount Simon Sandstone, and Precambrian igneous rocks (see Figure 4-3). These formations are briefly described below, from oldest to youngest.

Precambrian Rocks

The Precambrian basement in the study area consists of igneous rocks. A core of gabbro was recovered from the DuPont No. 1 WAD well in Jefferson County, 12 mi northeast of Mill Creek. Maps by the Cincinnati Arch Consortium show that these igneous rocks continue to the southwest below Mill Creek (Drahovzal and others, 1992). The Louisville area is situated on an uplifted block of igneous rocks, unlike the sedimentary Middle Run Formation found at Trimble County and Ghent Stations. Precambrian rocks dip to the southwest in the study area, consistent with the trend of the Cincinnati Arch (Fig. 4-4). The structure map shown in Figure 4-4 is based on the few wells that penetrate the Precambrian surface in the area, and one seismic line. As such, it should be considered a general representation of the structure of the area. This map indicates that the depth to basement is 6,255 ft (–5,800 ft below sea level) at the Mill Creek Station. This would be the maximum depth required for an injection well in the overlying Mount Simon Sandstone.

Cambrian Mount Simon Sandstone

The Cambrian Mount Simon Sandstone unconformably overlies Precambrian igneous rocks in most of the study area. The Mount Simon is predominantly quartz-rich, and because of its depth

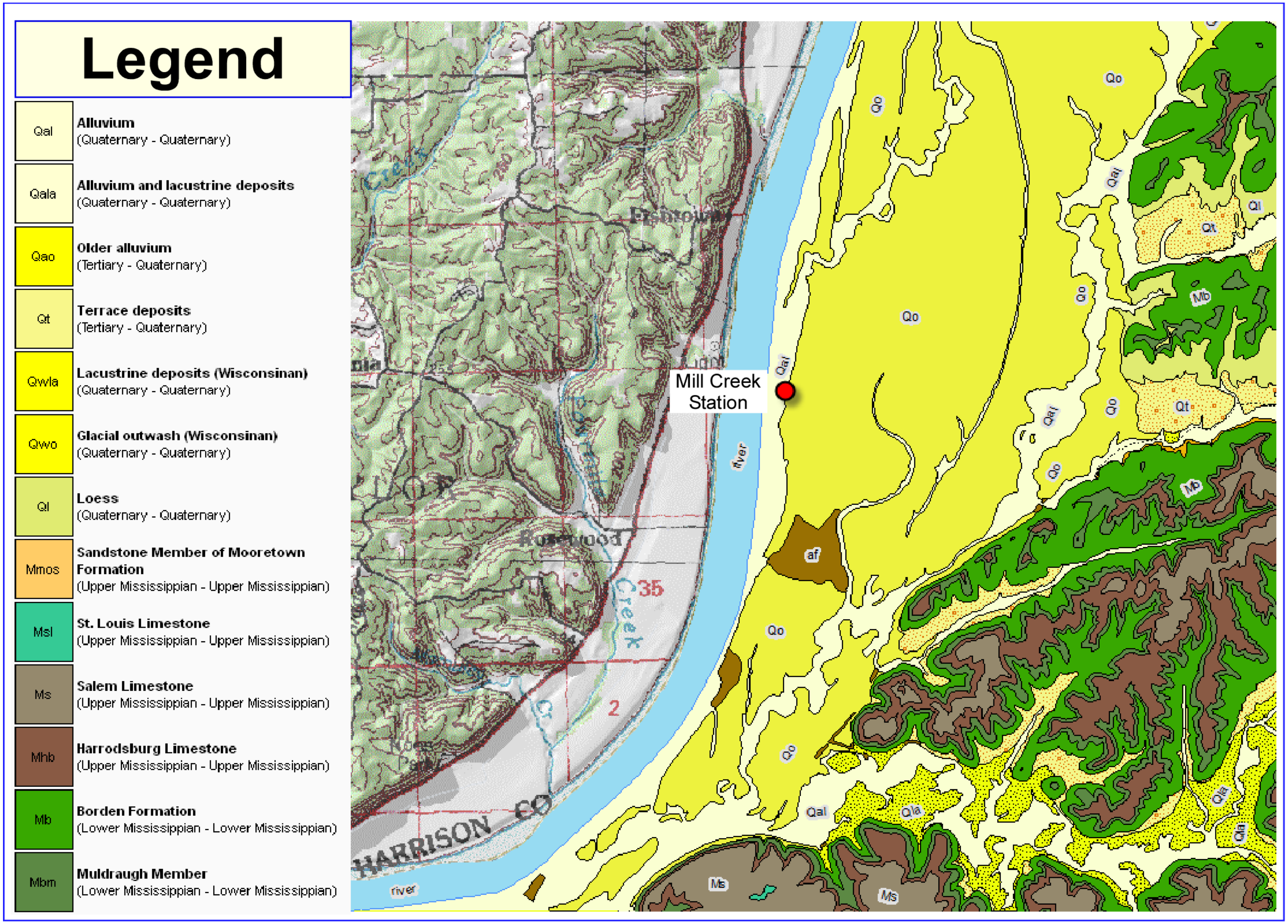

Figure 4-2. Geology of the Kentucky portion of the Kosmosdale 7.5-minute quadrangle (Kepferle, 1972). The Mill Creek Station (red dot) is located on unconsolidated Holocene alluvial deposits (Qal). Hills to the east of the station are underlain by Mississippian siltstones and shales, with hilltops capped by Mississippian limestone.

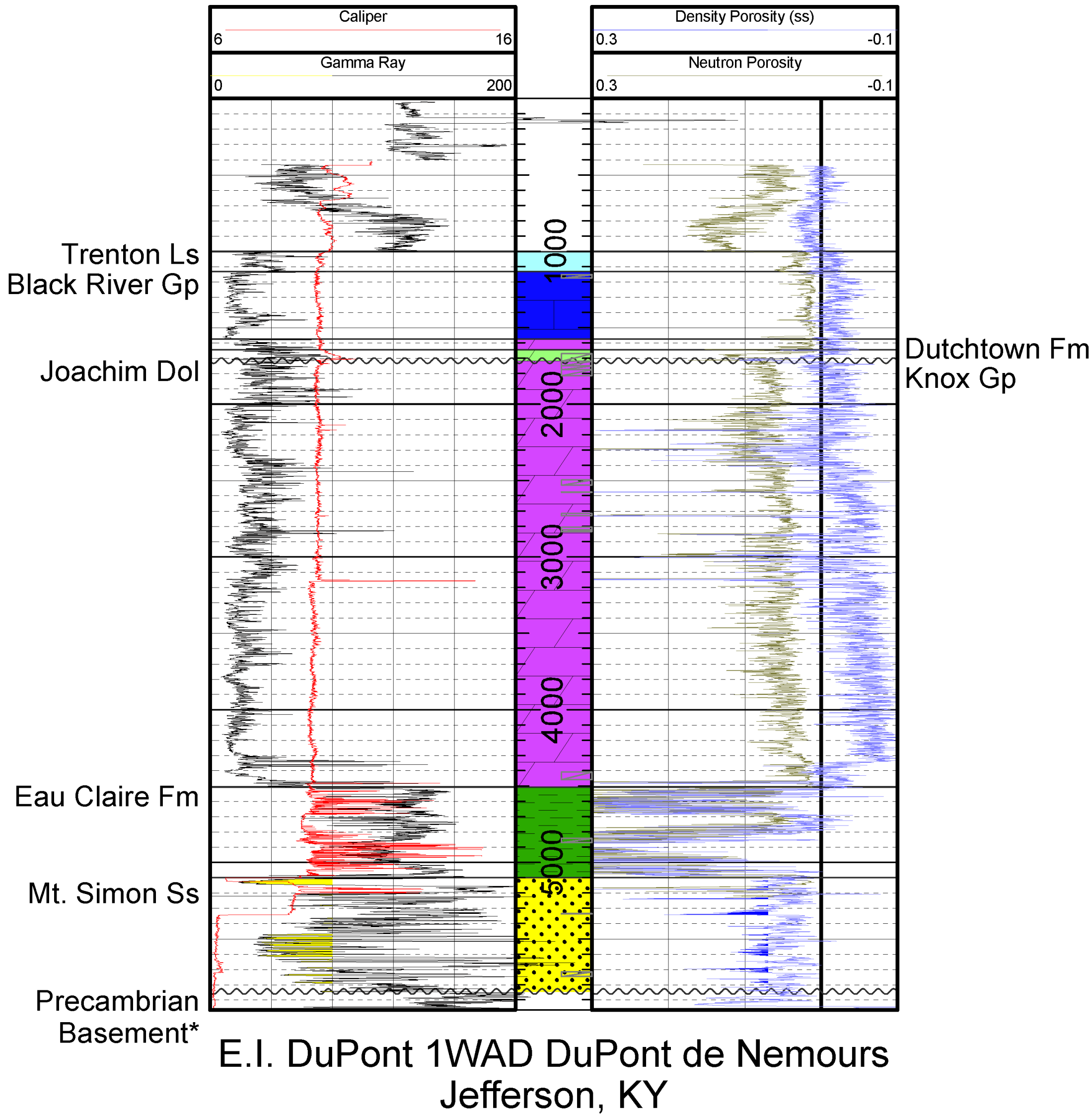

Figure 4-3. Geophysical log for the E.I. DuPont No. 1 WAD well in Jefferson County, Ky. Cored intervals are marked on the right edge of the depth column. The potential CO_2 injection zone is the Mount Simon Sandstone (yellow). The density-porosity log is shaded blue in the Mount Simon interval where porosity is greater than 7 percent, and the gamma-ray log is shaded yellow in the Mount Simon where less than 80 units (clean sandstone). Porosity in the Mount Simon is not well developed in this well.

will be the primary CO_2 injection zone in the Mill Creek area. The Mount Simon has been penetrated in one well in the study area. Cores from the Mount Simon Sandstone are available from this well (the DuPont waste injection well in Louisville). Porosity and permeability data derived from these cores are described further in Reservoir Quality and Injection Zone Thickness.

Other studies have used data from seismic lines outside this study area to map the extent of the Mount Simon Sandstone across Kentucky. The broader regional data show that the Mount Simon thickens to the north and northwest, and pinches out toward the south (Fig. 4-5) (Greb and Solis, 2010). The Mount Simon Sandstone is not present in much of southern Kentucky. This regional data, and the more detailed maps made for this study, show that the Mount Simon Sandstone is thinner at the Mill Creek site than at the DuPont well, 12 mi to the northeast.

The Mount Simon Sandstone is 748 ft thick in the DuPont well in Louisville, and the formation

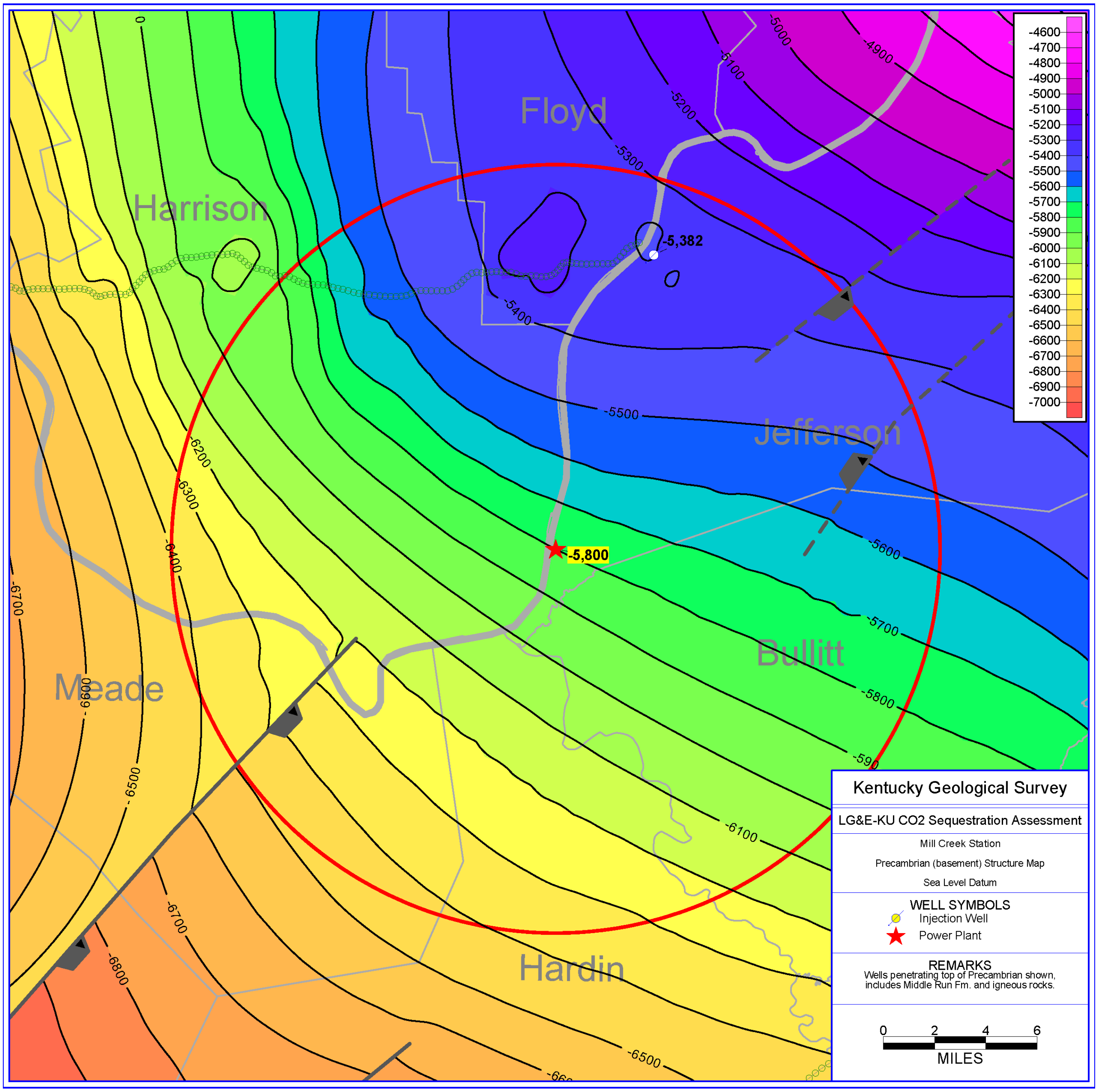

Figure 4-4. Structure on the top of Precambrian basement. The Precambrian surface deepens to the southwest, and is estimated to be at –5,800 ft below sea level at Mill Creek. Inferred deep faults trend northeast-southwest to the northeast and southwest of Mill Creek.

top is at 5,098 ft below the surface (–4,633 ft below sea level). Using available well data and reflection-seismic lines from the area, structure and thickness maps for the Mount Simon were constructed. Figure 4-6 is a structure-contour map on the top of the Mount Simon Sandstone. It shows depth increasing to the south and southwest. The top of the Mount Simon is estimated to be 5,785 ft (–5,330 ft below sea level) at Mill Creek.

The isopach (thickness) map (Fig. 4-7) shows thinning of the Mount Simon Sandstone toward the south. Its thickness is estimated to be 470 ft at

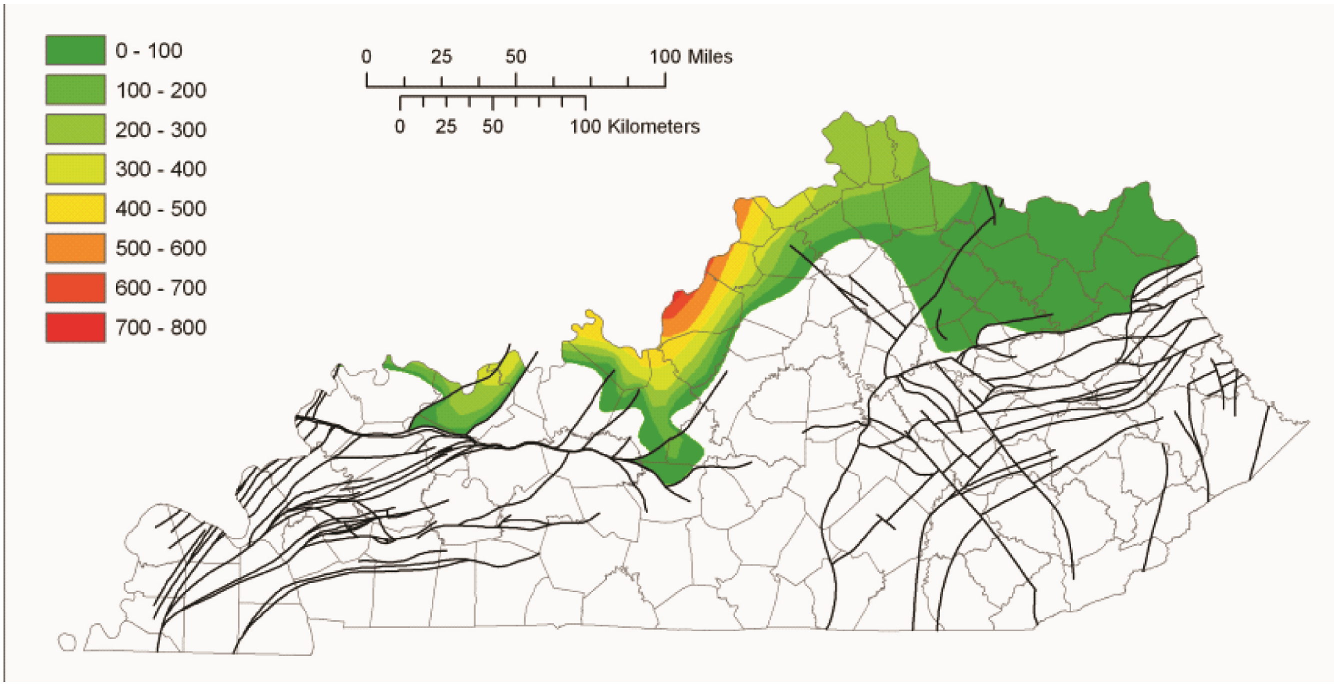

Figure 4-5. Regional thickness of the Mount Simon Sandstone in Kentucky. The formation is present along the Ohio River Valley in northern Kentucky and thins to the south. It is absent in much of western and southern Kentucky. Interpretation based on seismic and well data. Contours in feet. From Greb and Solis (2010).

Mill Creek. The isopach map was interpreted from nearby well data and using the zero thickness line on the regional map.

Cambrian Eau Claire Formation

The Eau Claire Formation directly overlies the Mount Simon Sandstone and is predominantly composed of green and gray marine shale with some interbedded dolomite. The Eau Claire was cored in the DuPont No. 1 WAD well in Louisville, from 4,409 to 4,459 and 4,842 to 4,871 ft. The Eau Claire has very low porosity and permeability and is the primary confining layer (seal) for CO_2 injected into the Mount Simon below.

Figure 4-8 is a structure-contour map on the top of the Eau Claire Formation. The Eau Claire deepens to the southwest into the deeper parts of the Illinois Basin. The top is projected to be at 4,880 ft (–4,425 ft subsea) at the Mill Creek site. The top of this confining layer is well below the minimum depth for supercritical CO_2.

Figure 4-9 is an isopach (thickness) map of the Eau Claire. The Eau Claire Formation thickens to the south, and is projected to be 905 ft thick at Mill Creek. This is about 300 ft thicker than at the DuPont No. 1 WAD well. As the Mount Simon Sandstone thins to the south, the Eau Claire thickens—the combined interval is relatively consistent. This map indicates there is an adequate thickness of impermeable rocks immediately above the Mount Simon injection zone to serve as a seal.

Cambrian-Ordovician Knox Group

The Knox Group is divided into an upper dolomite unit, the Beekmantown Dolomite, and the lower Copper Ridge Dolomite, separated by sandstone or a sandy dolomite unit (Rose Run Sandstone) that is poorly developed in this area. The Knox is approximately 2,800 ft thick in the study area. The Knox contains scattered porous and permeable intervals separated by impermeable dolomite. It has injection potential in deeper parts of Kentucky (such as at the KGS No. 1 Blan research well in Hancock County), and was used as a hazardous-waste injection zone at the DuPont chemical plant in Louisville. Porous zones in the Knox have also been used for natural gas storage by LG&E northeast of the study area, in Grant and Oldham Counties (Ballardsville and Eagle Creek storage fields). The top of the Knox is a regional erosional unconformity that formed when the

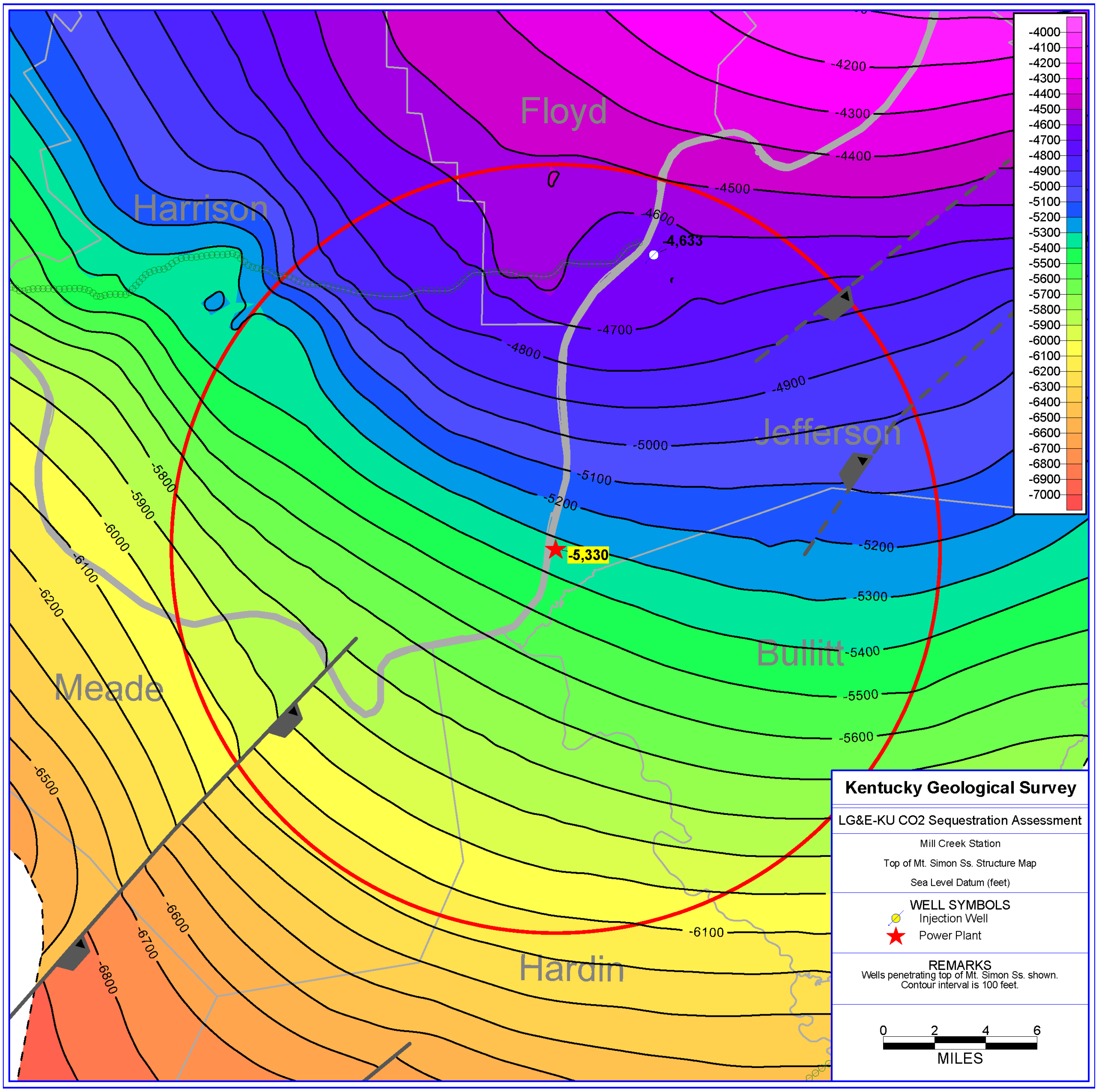

Figure 4-6. Structure on top of the Cambrian Mount Simon Sandstone around the Mill Creek Station. This unit deepens to the southwest. Contour interval is 100 ft. The dashed line in the southwest corner of the map is the pinchout of the Mount Simon interval from the regional thickness map (Fig. 4-5).

Knox was uplifted above sea level during the Early Ordovician.

In the study area, the upper third of the Knox lies above the 2,500-ft depth limit for CO_2 to exist in the supercritical phase. The lower part of the Knox (below 2,500 ft depth) is not a potential injection target, since the primary seal (containment zone) above the top of the Knox is well above the 2,500-ft depth required to keep CO_2 in a supercritical phase.

The Knox is the shallowest interval mapped in this evaluation. Figure 4-10 is a structure map on the top of the Knox. Many more wells have been drilled to the top of the Knox than to the deeper formations, and thus more well data are available

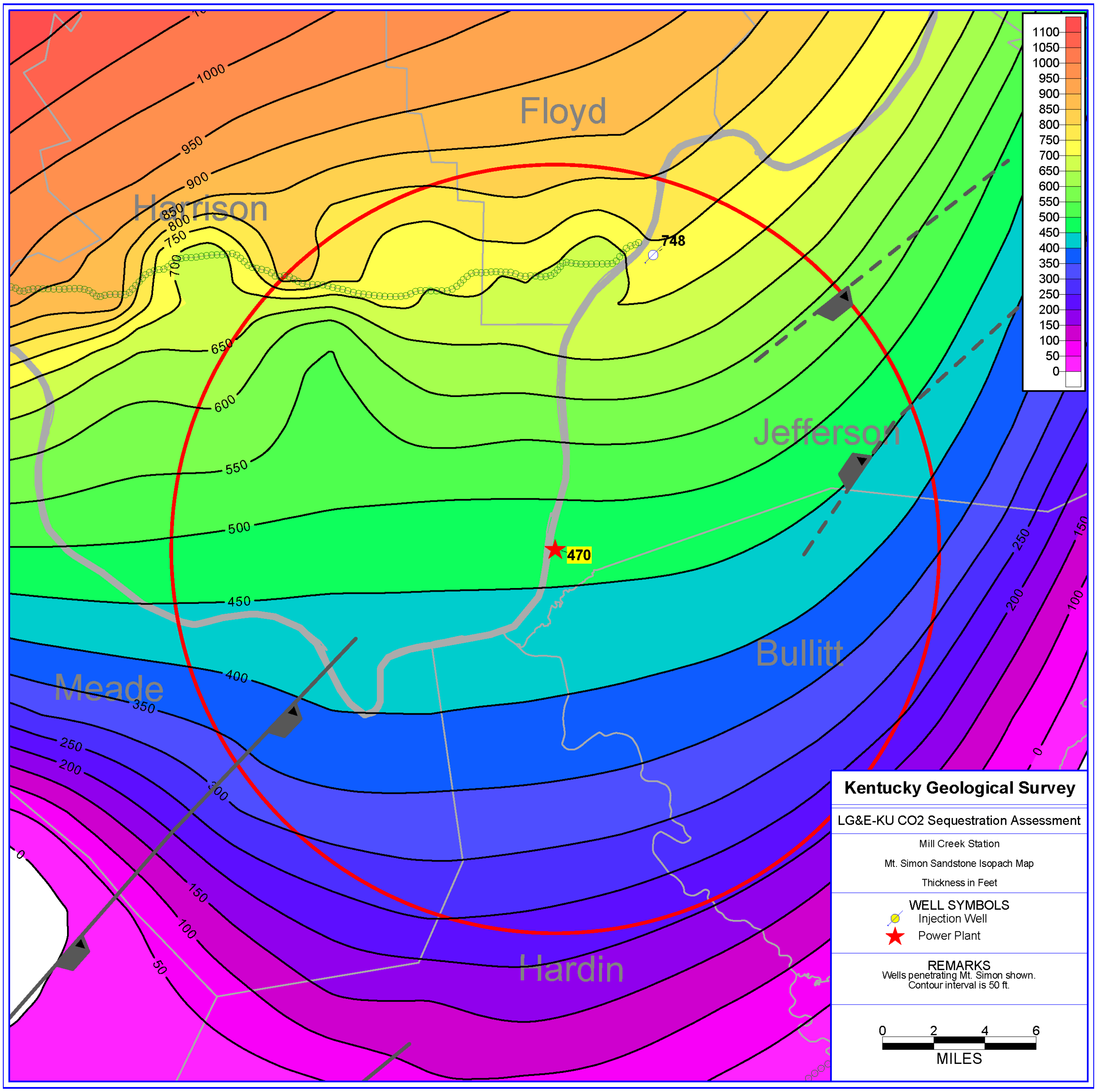

Figure 4-7. Thickness of the Cambrian Mount Simon Sandstone near Mill Creek Station. Contour interval is 50 ft. The Mount Simon thins to the south. The Mount Simon is interpreted to pinch out at the zero contour line (southwestern corner). This interpretation is based on data from several older seismic lines, and should be regarded as approximate.

for the Knox structure map than for other maps. The Knox deepens to the west, with the projected top of the Knox at about 1,915 ft below surface (–1,460 ft subsea) at Mill Creek.

Ordovician Dutchtown Formation and Joachim Dolomite

The Dutchtown Formation and Joachim Dolomite are dolomite intervals that contain variable amounts of shale and overlie the Knox unconformity. They are equivalent to the Wells Creek Do-

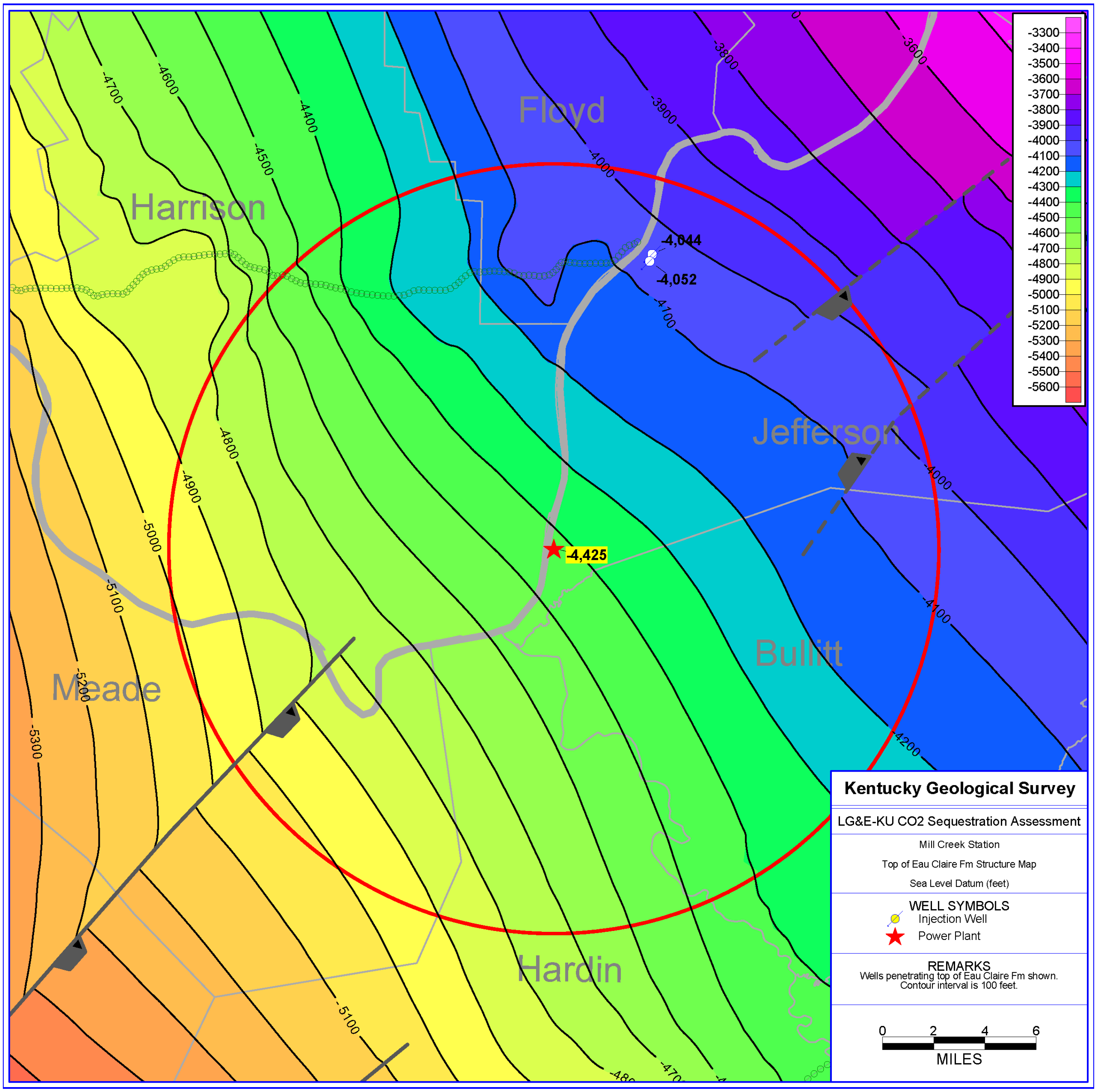

Figure 4-8. Structure on top of the Cambrian Eau Claire Formation. Contour interval is 100 ft. The structure deepens to the southwest, and the top of the Eau Claire is 4,880 ft below surface (–4,425 ft below sea level) at Mill Creek.

lomite in Ohio, and are partly gradational with the St. Peter Sandstone. They generally have low porosity and permeability. They would provide additional confinement for CO_2 injected in deeper zones. These formations were not mapped in detail.

Ordovician Black River Group and Trenton Limestone

The Trenton Limestone and Black River Group together form a shallow secondary confining zone (seal) for CO_2 injected into the deeper Mount Simon Sandstone. These rocks are com-

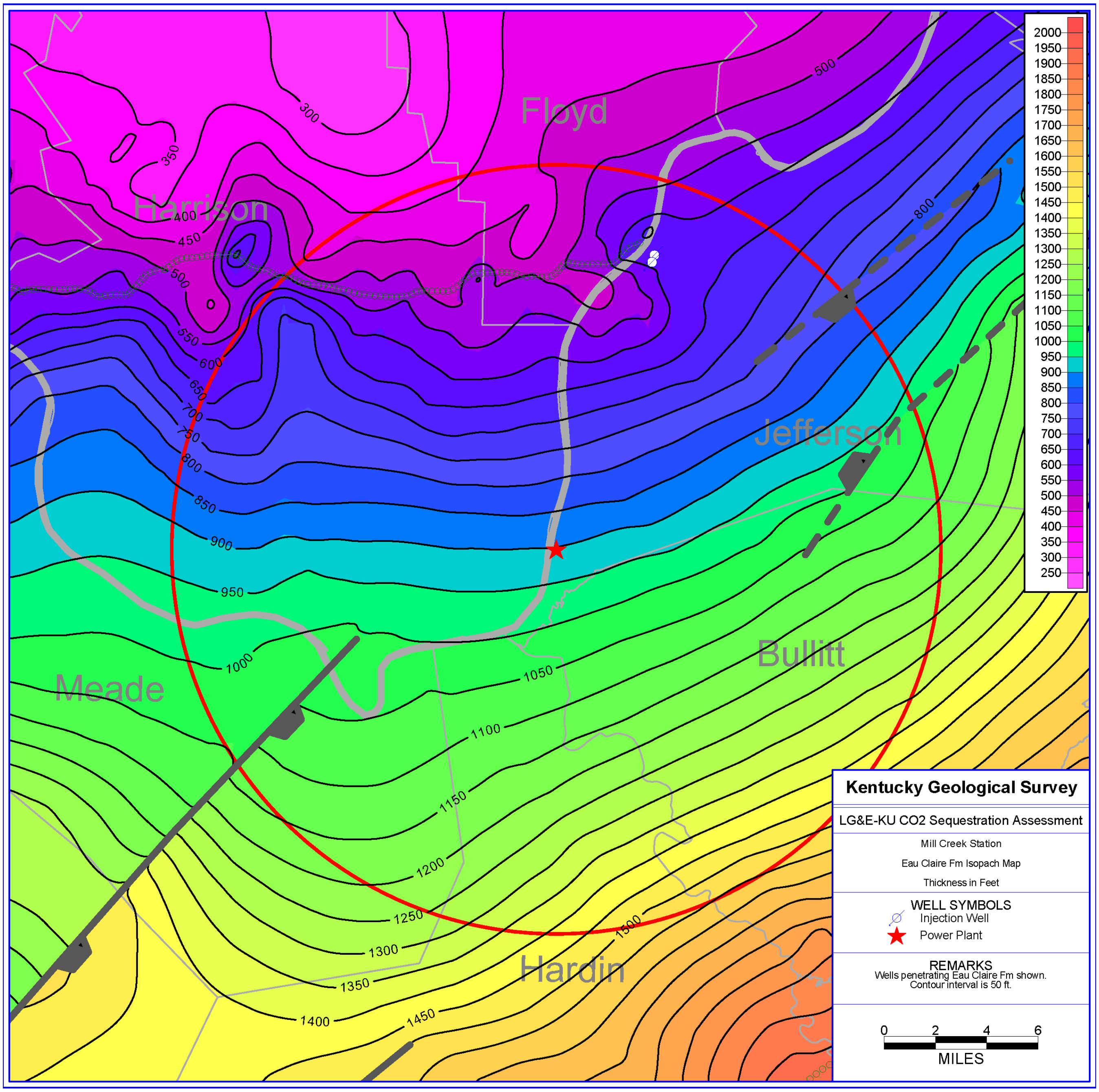

Figure 4-9. Thickness of the Eau Claire Formation. Contour interval is 50 ft. Shale and minor dolomite in this formation are more than 900 ft thick at Mill Creek, providing a good seal for CO_2 injected into the Mount Simon Sandstone below.

posed of limestone, minor dolomite, and interbedded shale. The interval typically has very low porosity and permeability unless fractured. In the DuPont No. 1 WAD well, these formations have a combined thickness of 572 ft. At Mill Creek, the top of the Trenton Limestone is at 1,200 ft below the surface (–745 subsea).

Ordovician Maquoketa Shale

The shallowest interval mapped in the Mill Creek area is the Upper Ordovician Maquoketa Shale. This interval was not mapped in the Trimble County and Ghent areas (chapter 1) because it was very close to the surface. In the Mill Creek area it is deeper, and could serve as another confining

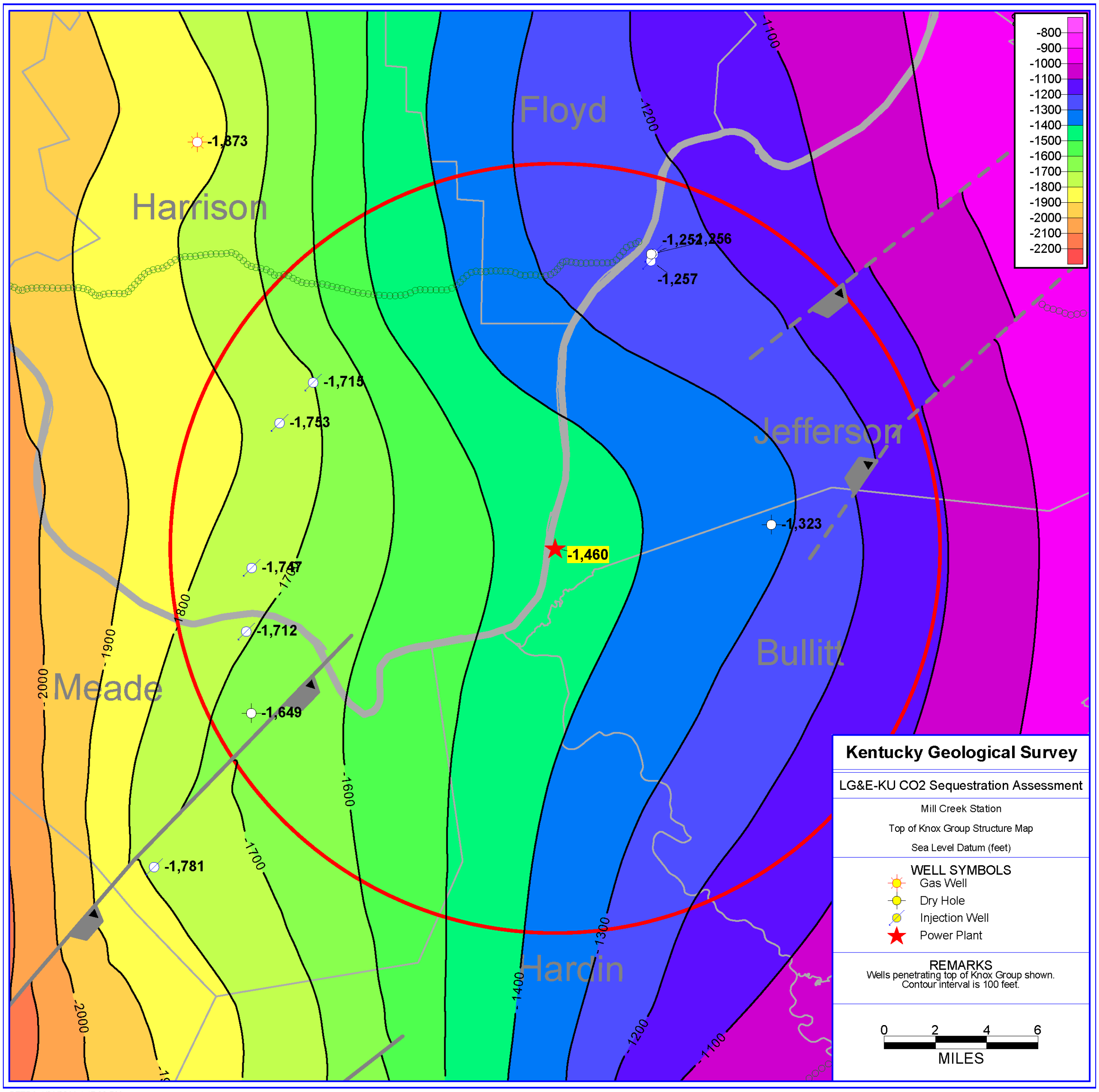

Figure 4-10. Structure on the top of the Knox Group. Contour interval is 100 ft. The top of the Knox is a regional erosional surface, and the structure deepens to the west toward the Illinois Basin. The upper part of the Knox is too shallow for carbon storage in this area.

interval. It overlies the Trenton Limestone. In the DuPont No. 1 WAD well, the top of the Maquoketa is 437 ft below the surface (28 ft above sea level) and is 565 ft thick. The Maquoketa thickens to the south and is interpreted to be 625 ft thick at the Mill Creek site. Figure 4-11 is a thickness map of the Maquoketa Shale interval at Mill Creek.

Cross Sections

Two regional cross sections were constructed using geophysical well logs. Interpreted interval tops at the Mill Creek and Trimble County Stations were included on the sections for reference (Fig. 4-12). Section A–A' (Fig. 4-13) is a north-south

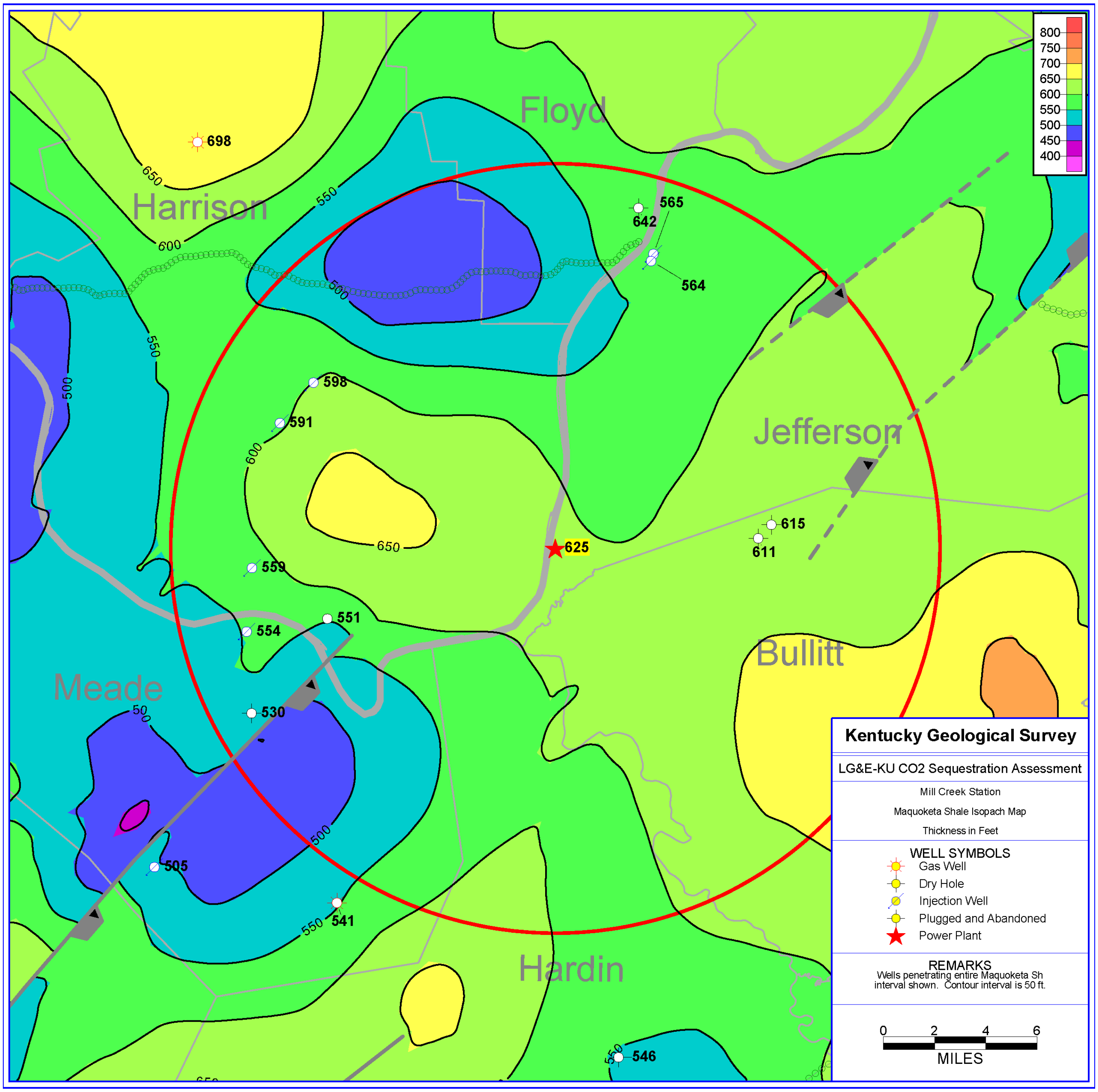

Figure 4-11. Thickness of the Maquoketa Shale. Contour interval is 50 ft.

line from southern Indiana through the DuPont well and Mill Creek location. Section B–B' (Fig. 4-14) is a southwest-northeast section. These sections illustrate the structure and stratigraphic variations across the study area, including the thinning of the Mount Simon Sandstone from north to south.

Deep Faults and Available Seismic Data

Seismic data available for the study area are primarily outside the 15-mi radius around Mill Creek. Figure 4-12 shows the locations of seismic lines used in the study—only one line is located within the 15-mi radius. These lines were used as control data for the structure and thickness maps

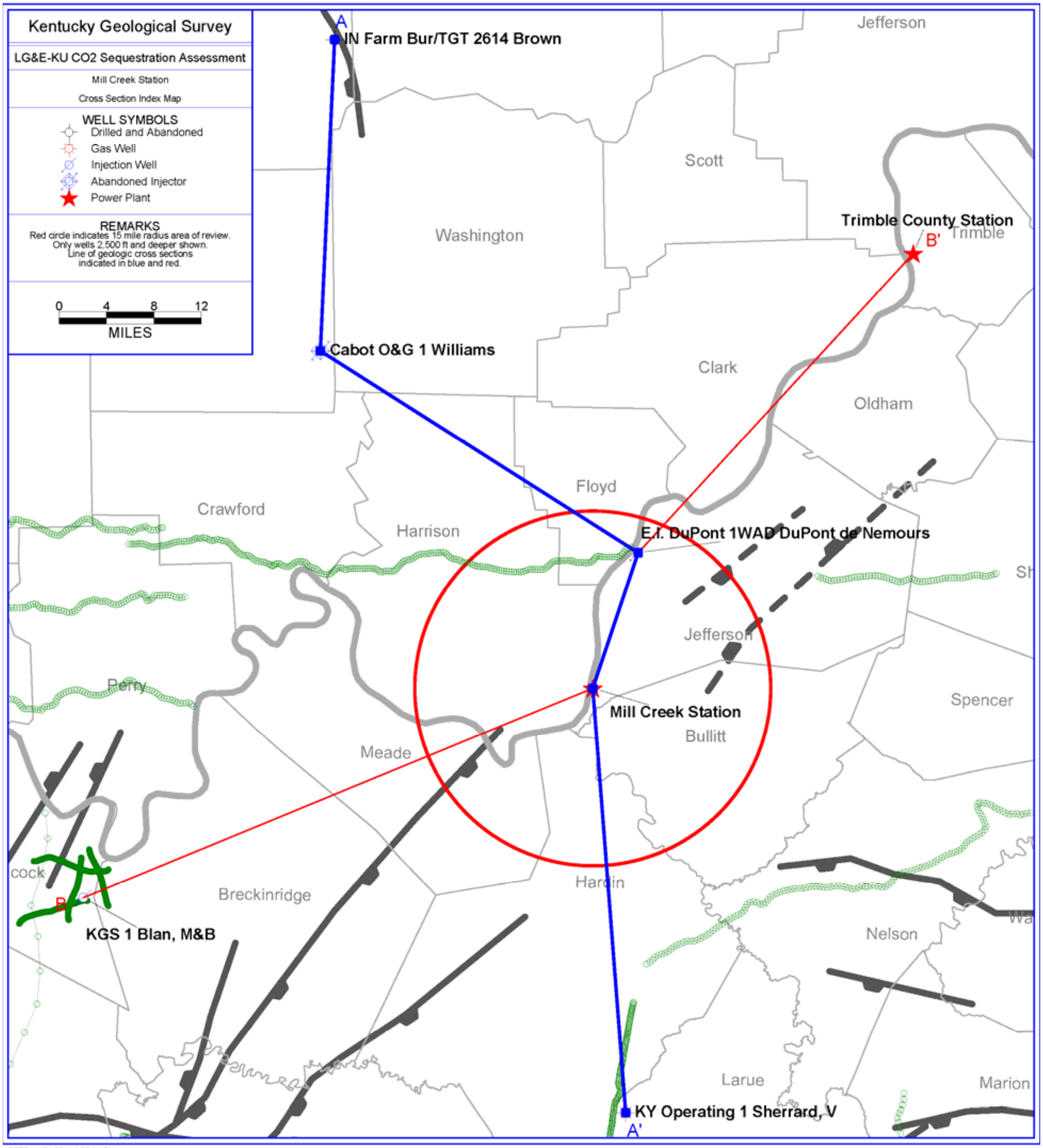

Figure 4-12. Locations of two structural cross sections, A–A' (Fig. 4-13) and B–B' (Fig. 4-14). Both sections include the DuPont waste-disposal well in Louisville and the interpreted geology at the Mill Creek site. Seismic lines used in the evaluation are shown by the lines of overlapping colored circles (shotpoint locations). Deep faults are shown by the solid dark gray lines.

discussed previously. Seismic data quality varies significantly, from very new, high-quality data around the KGS Blan well, to older data from southern Indiana and central Kentucky. The closest seismic line to Mill Creek is an east-west line that extends to the west from near the DuPont well

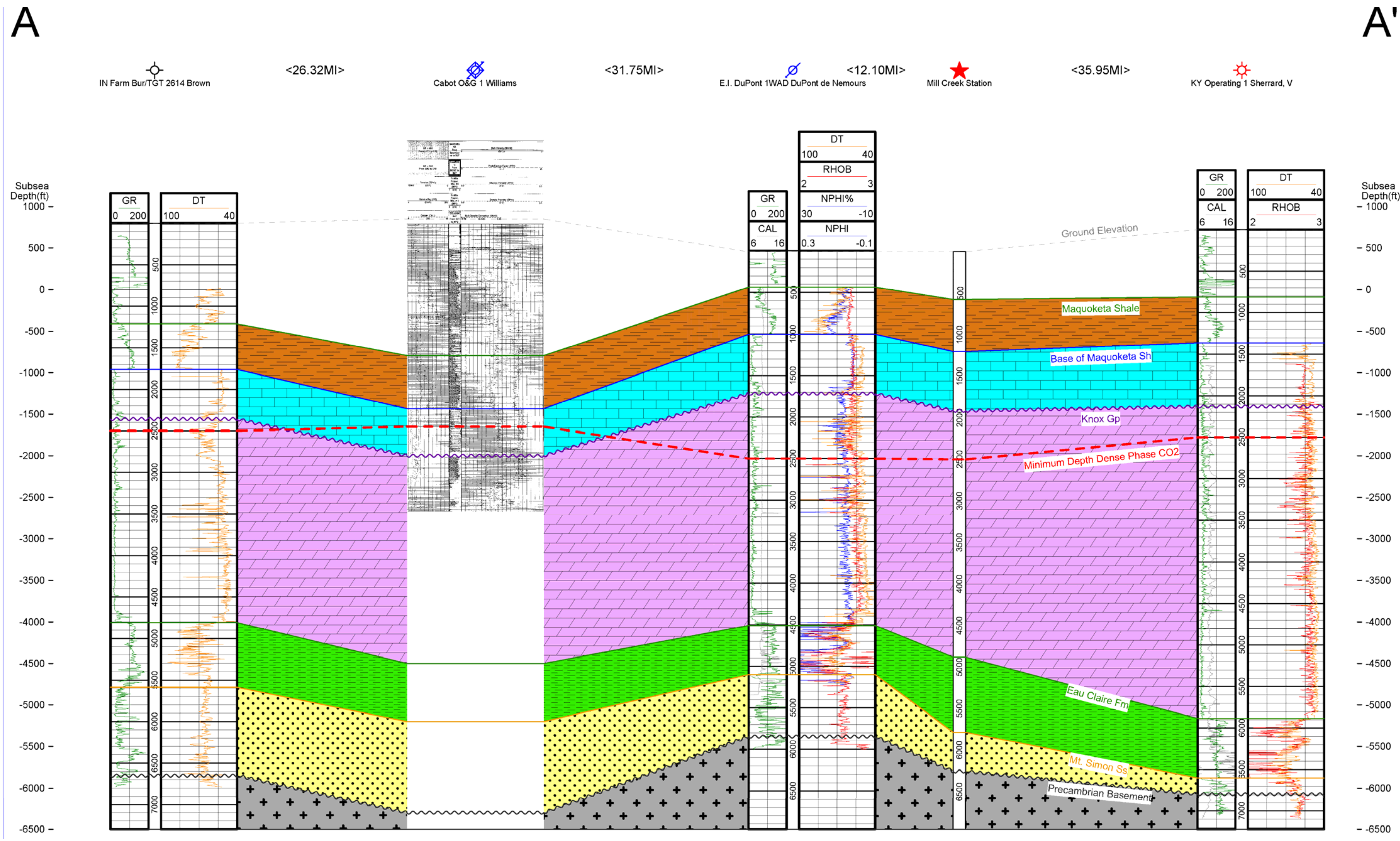

Figure 4-13. Cross section A–A' runs north-south through the Mill Creek property. The Mount Simon Sandstone thins to the south (right).

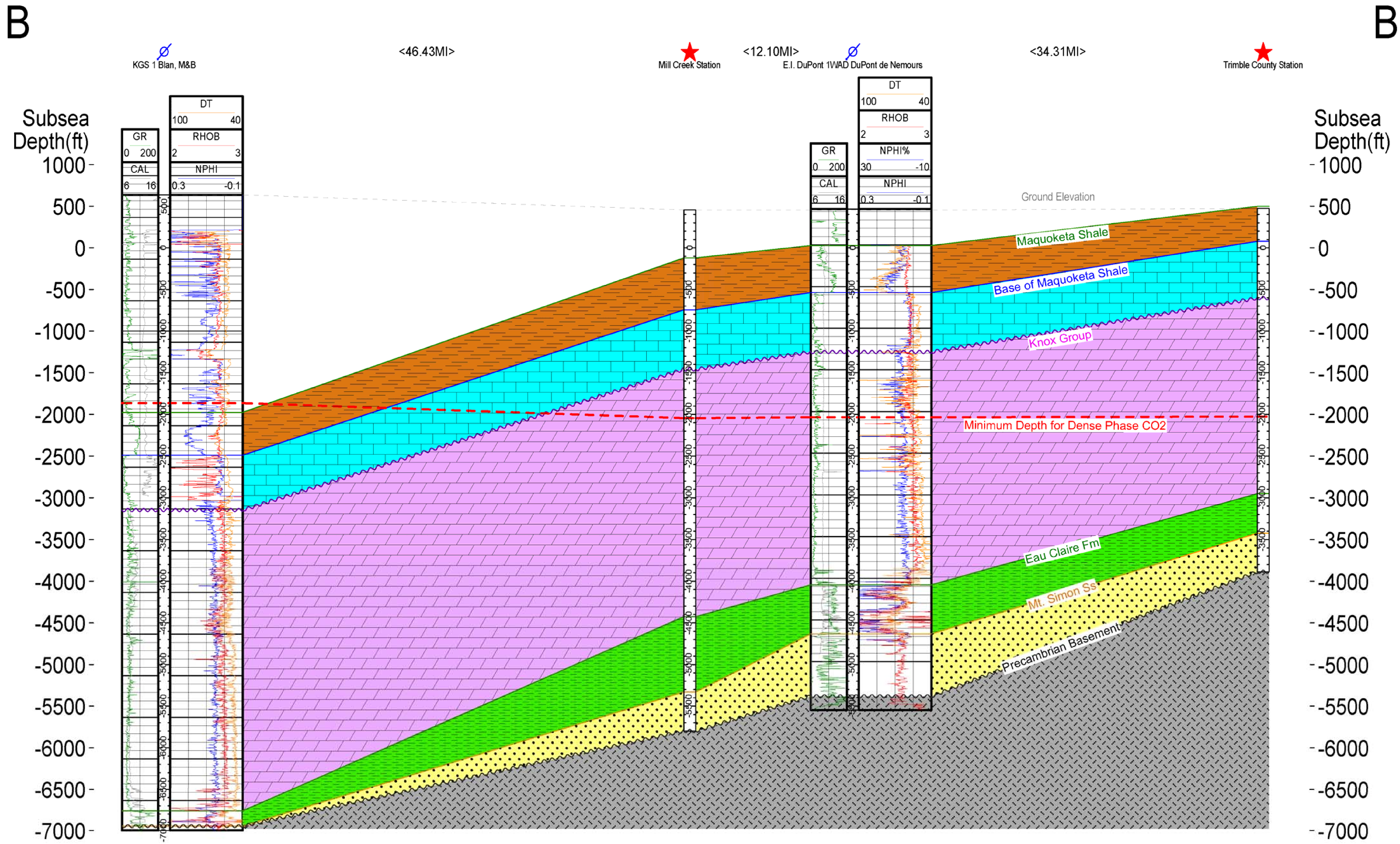

Figure 4-14. Cross section B–B' runs from the KGS No. 1 Blan well on the southwest (left) to the Trimble County Station on the northeast (right).

in Louisville, across Floyd, Harrison, and Crawford Counties, Ind. This line shows some deep faulting in the Precambrian section, but none that penetrates the younger Paleozoic rocks where sequestration would occur.

There is some faulting in the Mill Creek area. Figure 4-12 shows several deep fault trends that extend to basement level. The dashed faults on this map are inferred; data suggest there may be faults present, but they have not been imaged on seismic data or mapped at the surface. Southwest of Mill Creek, a northeast-trending fault extends part way into the 15-mi area. This fault could extend closer to the Mill Creek property, but there are no seismic data available to determine this.

Reservoir Quality and Injection Zone Thickness

In order to calculate carbon sequestration capacity, the average porosity and thickness of the storage zone is required. Since there are no wells drilled to the Mount Simon Sandstone at the Mill Creek site, we must calculate reasonable estimates for porosity and net injection zone thickness from nearby well control. Data from the DuPont No. 1 WAD well are helpful, since good well logs and some core data are available from this well.

Regional Porosity Trends

As with many sandstones, porosity in the Mount Simon Sandstone decreases with increasing burial depth. This is primarily because of cementation and compaction, and is a result of increased temperature, pressure, and the amount of time the rocks have been buried. A substantial set of Mount Simon porosity and permeability data from across the Midwest has been published by Medina and others (2011). Their cross-plots of porosity versus depth established a general correlation between porosity and depth. They found a dramatic decrease in porosity at depths below 7,000 ft. This depth generally corresponds to a porosity value of 7 percent, although there is significant variability in the data.

At Trimble County and Ghent (chapter 1), porosity varies significantly in the Mount Simon, and they correlated with burial depth (Fig. 4-15). The DuPont No. 1 WAD well in Louisville was drilled to more than 6,000 ft to test the Mount Simon for hazardous-waste injection. Initial injection tests determined it lacked sufficient porosity and permeability for commercial waste disposal. An alternate zone in the shallower Knox Dolomite was eventually used as the injection zone. The average depth of the Mount Simon in the DuPont well is 5,600 ft, and the average log-derived sandstone porosity is 6.5 percent. The regional depth/porosity correlation proposed by Medina and others (2011) suggests that the Mount Simon should have about 8.4 percent porosity at 5,600 ft. This means that the DuPont well has *lower* porosity than predicted for its depth. The reason for this is not known, but the DuPont well provides a key control point that must be considered as we evaluate Mill Creek.

Site-Specific Porosity Estimates

Both well-log and core porosity data were used to estimate porosity at Mill Creek. Core measurements are the most accurate method of determining porosity and permeability. Core-derived porosity and permeability data for the Mount Simon are available from limited cores from the DuPont No. 1 WAD well in Louisville.

Cores typically are only recovered for relatively thin intervals in a formation, and may not be representative of the entire formation. Porosity (but not permeability) data are also derived from geophysical well logs, especially the bulk-density log. Logs provide a continuous data set for the entire formation, but are not as accurate as core data.

Core data from the DuPont No. 1 WAD well (Louisville) and the Duke Energy East Bend well (Boone County) are presented in Figures 4-15 and 4-16. The porosity and permeability versus depth plots (Figs. 4-15a, b) also include data from the overlying Eau Claire Shale core from East Bend. The Mount Simon core data help to illustrate the range of porosity and permeability in the area. There is considerable variation in porosity and permeability within the limited depth range of the cored intervals. Despite this, the DuPont core data show overall lower porosity and permeability than the cores at East Bend. As discussed previously, this is thought to be related to the greater depth of the Mount Simon at Louisville.

Plotting porosity versus permeability illustrates the apparently positive correlation between the two measurements (Fig. 4-16). This plot allows

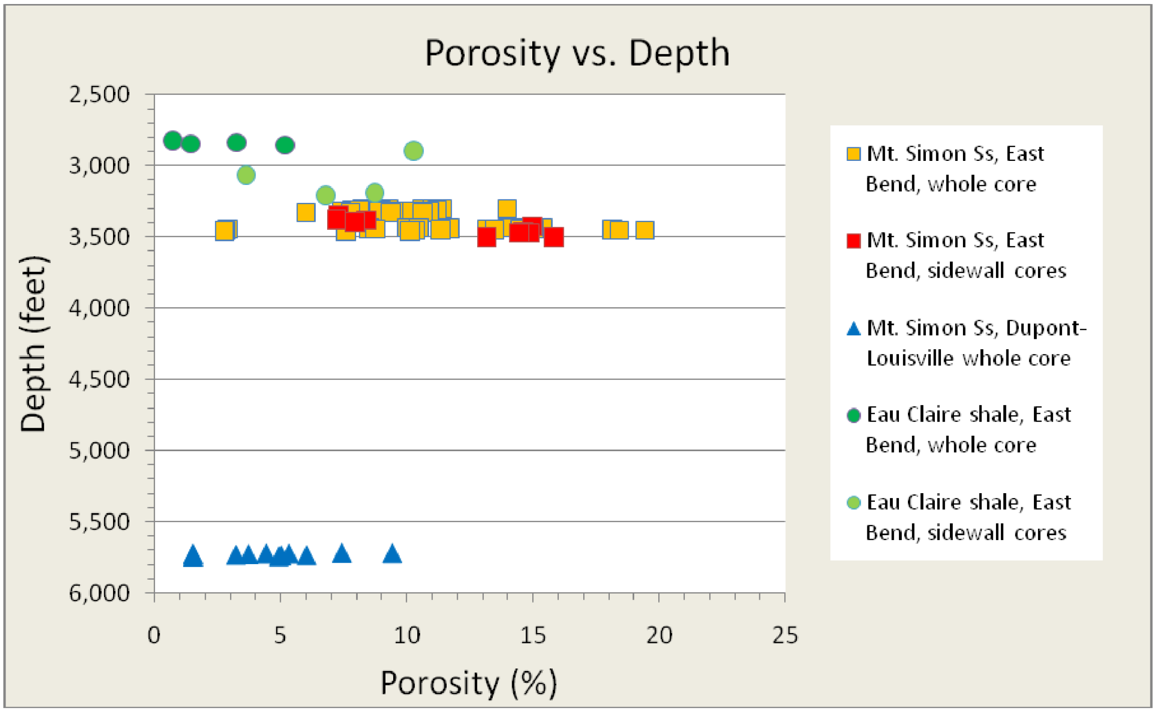

Figure 4-15a. Core porosity versus depth below surface for Mount Simon Sandstone (reservoir) and Eau Claire Formation (seal) core from the Duke East Bend and DuPont No. 1 WAD wells. Mount Simon porosity is significantly lower in the DuPont cores because of its deeper burial depth. Average porosity for the DuPont core plugs is 4.3 percent.

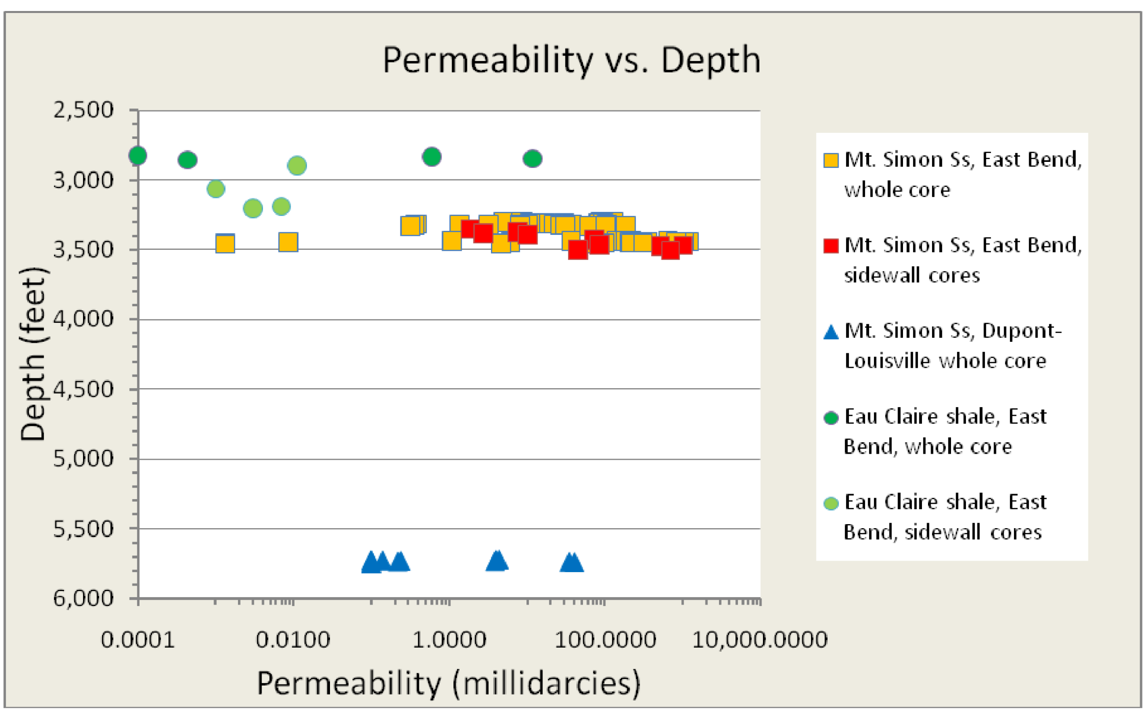

Figure 4-15b. Core permeability versus depth below surface for the Mount Simon Sandstone and Eau Claire Formation. Permeability is quite variable, but is lower in the DuPont cores and in the Eau Claire shales. Average permeability for the DuPont core plugs is 6.1 md.

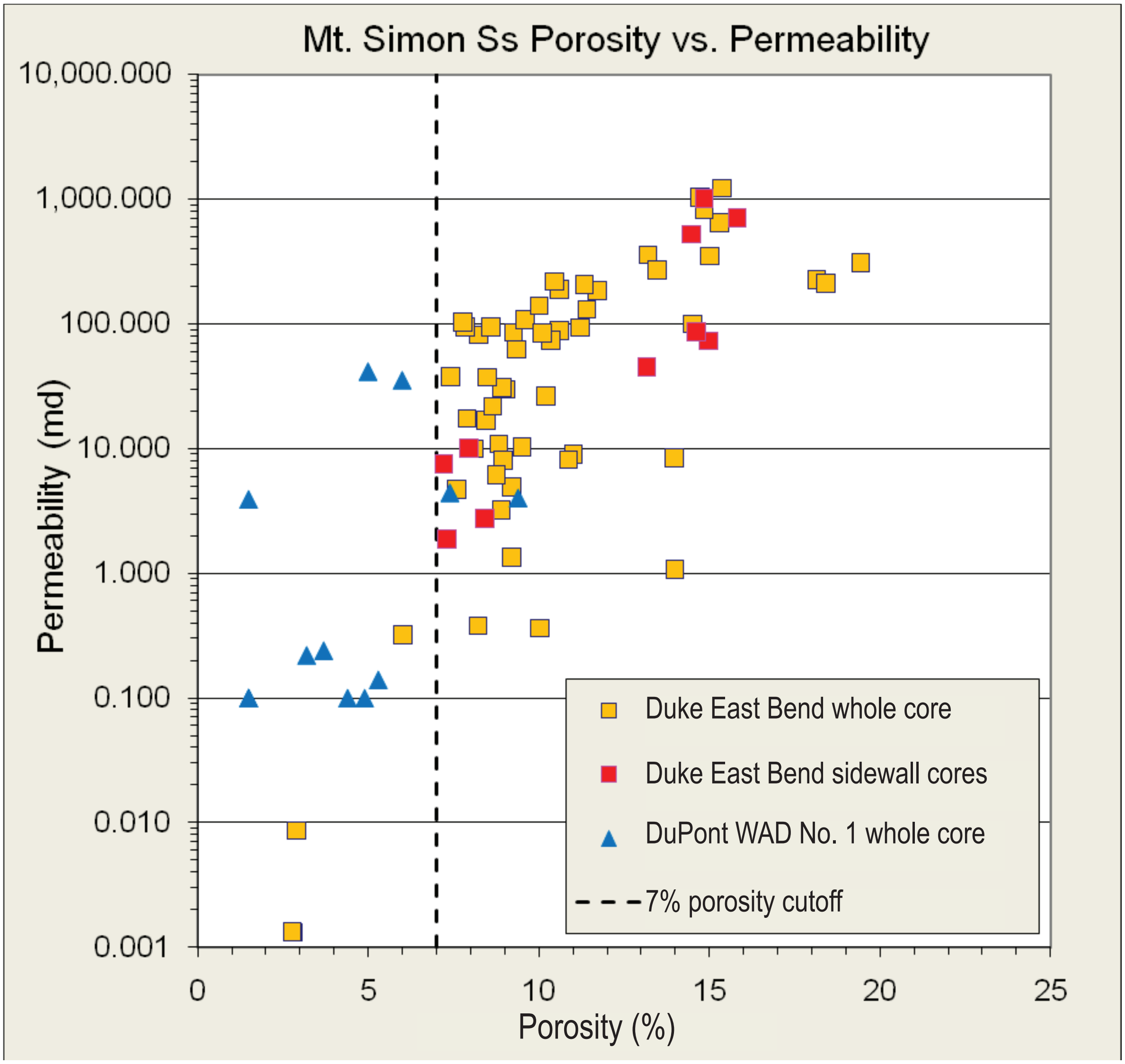

Figure 4-16. Mount Simon Sandstone core porosity versus permeability for the Duke East Bend and DuPont No. 1 WAD wells. Many of the DuPont analyses fall below the 7 percent cutoff, indicating limited injectivity for this interval. In general, permeability decreases rapidly below 7 percent porosity, and this trend was the basis for the 7 percent porosity cutoff used to calculate net reservoir thickness.

a minimum porosity to be interpreted for sandstone with acceptable permeability for injection. Because porosity can be measured with downhole logs and permeability cannot, a porosity cutoff allows the net thickness of rock with suitable porosity and permeability for injection to be summed from porosity geophysical-log data alone.

Based on the core data shown in Figure 4-16, a minimum porosity of 7 percent was chosen as the porosity cutoff for the Mount Simon. The 7 percent line separates the majority of the East Bend data (acceptable porosity and permeability) from the DuPont core data, where fluid injection was not successful. Medina and others (2011) also used a 7 percent porosity cutoff for the Mount Simon across the Midwest in their calculation of CO_2 sequestration capacities. Their cutoff, based on a much larger data set, is supported by the core data used in this study. Figure 4-16 shows that most of the core analyses from the DuPont well fell below the 7 percent cutoff. This suggests the core interval is not a good injection zone, but there are some intervals with porosity above the cutoff.

Calculation of Net Porous Sandstone

Once a porosity cutoff was chosen, the thickness of net porous sandstone and average porosity of sandstones above the cutoff were determined for use in CO_2-capacity calculations. The DuPont well is the only well near Mill Creek for which data are available for the Mount Simon. The reservoir calculations for Mill Creek are based on this single well.

The Mount Simon Sandstone contains thin shales and some shaly sandstones with poor reservoir quality. Since only clean, nonshaly sandstone should be included in the net sandstone calculation, a gamma-ray cutoff was used. The natural gamma-ray log is the best discriminator of clay and shale, and a cutoff of 80 API units was used to identify clean sandstone. Intervals with 80 API gamma-ray units or less were classified as sandstone. This 80 API unit cutoff is very close to the 75 API cutoff used by Medina and others (2011) in their Mount Simon study.

A log-analysis program (Petra) was used to calculate the net feet of Mount Simon with a gamma-ray reading of less than 80 API units and density porosity (calculated using a sandstone matrix) greater than or equal to 7 percent. The results of the net sandstone calculation are shown in Table 4-1. Average log porosity and total porosity-feet (thickness of void space) were also calculated. Gross thickness is the total Mount Simon thickness. A net-to-gross sandstone ratio was calculated to allow a similar thickness to be calculated at the Mill Creek site using the mapped thickness. The net-to-gross ratio is 0.15 in the Louisville DuPont well. Average log-derived porosity of the net sandstone interval is 8.7 percent in the DuPont well.

Table 4-1 also includes calculated data for the Mill Creek site. The gross thickness was taken from the thickness map of the Mount Simon (Fig. 4-7). Then net sandstone footage was calculated using the net-to-gross ratios determined from the DuPont well. This yields a net sandstone estimate of 70 ft for Mill Creek. The Mill Creek site is about 400 ft deeper than the DuPont well, so a slightly lower average porosity of 8.2 percent was used.

Comparison with regional data suggests the DuPont well has lower porosity than it should for its depth (Medina and others, 2011). If this is a local anomaly, Mill Creek may have better porosity than the conservative number used here.

CO_2 Capacity Calculations

Using the compiled and calculated data, CO_2 storage volume was calculated. CO_2 storage capacity is based on the porosity, thickness, and area of the injection zone, and density of the injected CO_2. CO_2 density is a function of reservoir pressure and temperature. The Mount Simon interval is deep enough for supercritical-phase CO_2 injection at the Mill Creek Station. CO_2 density calculations were made using the CO_2 properties calculator at the MIDCARB project Web site: www.midcarb.org/calculators.shtml. The Midcontinent Interactive Digital Carbon Atlas and Relational dataBase was a research consortium composed of the state geological surveys of Illinois, Indiana, Kansas, Kentucky, and Ohio, funded by the U.S. Department of Energy. Calculated CO_2 density is shown in Table 4-2.

Table 4-1. Mount Simon reservoir data for the DuPont No. 1 WAD well and calculated data for the Mill Creek site.

Mount Simon Sandstone Well-Log Data	*Average Depth (below surface, ft)*	*Gross Thickness (ft)*	*Net Porous Sandstone < 80 GR and > 7% Porosity (ft)*	*Net-to-Gross Ratios*	*Average Log Porosity of Net Porous Sandstone (%)*	*Porosity-Feet*
DuPont No. 1 WAD	5,600	748	111.5	0.15	8.7	9.6
Calculated data						
Mill Creek Station	6,020	470	70	0.15	8.2	5.7

Table 4-2. Calculated CO_2 density at reservoir conditions.

Site	*Reservoir Pressure (psi)*	*Reservoir Temperature (°F)*	*CO_2 Density (lb/ft^3)*	*CO_2 Density (kg/m^3)*
Mill Creek Station	2,800	116	49.65	795.32

These parameters are required to calculate CO_2 storage capacity:

Reservoir pressure: assumed hydrostatic and calculated at 0.433 psi/ft for the reservoir depth
Temperature: taken from well-log data from Boone and Jefferson Counties
Reservoir thickness: the net porous sandstone thickness as calculated above
Reservoir area: standard area of 100 acres
Reservoir porosity: the average porosity for the net reservoir footage

The equation for CO_2 storage capacity was modified from Medina and others (2011):

$$SC = A_n * h_n * \Phi_n * \rho_{CO2} * \dot{\varepsilon} / 1{,}000$$

where SC is the storage capacity in metric tons, A_n is the area in square meters, h_n is the net reservoir thickness, Φ_n is the average porosity of the net reservoir, ρ_{CO2} is the density of CO_2 at reservoir conditions, and $\dot{\varepsilon}$ is the storage efficiency factor (discussed below).

The reservoir parameters used and CO_2 capacities calculated are shown in Table 4-3.

Efficiency of CO_2 Storage

The storage-capacity equation used above includes an efficiency factor, which reduces the CO_2 storage capacity. This factor is applied because 100 percent of the available pore volume is never completely saturated with CO_2 because of fluid characteristics and geologic variability within the reservoir.

Litynski and others (2010) calculated efficiency factors for carbon storage in various reservoir types that account for factors that reduce the volume of CO_2 that can be stored. These factors include:

Geologic Factors

- Net-to-total area ratio of a basin suitable for sequestration
- Net-to-gross thickness ratio of a reservoir that meets minimum porosity and permeability requirements
- Ratio of effective to total porosity (fraction of connected pores)

Displacement Factors

- Areal displacement efficiency: area around a well that can be contacted by CO_2
- Vertical displacement efficiency: fraction of vertical thickness that will be contacted by CO_2
- Gravity: fraction of reservoir not contacted by CO_2 due to buoyancy effects
- Displacement efficiency: portion of pore volume that can be filled by CO_2 due to irreducible water saturation

Combining all of these factors using a Monte Carlo simulation results in a probability range of total efficiency factors of 0.51 to 5.4 percent (P_{10} to P_{90} range) (Litynski and others, 2010). For the purposes of this assessment, the *geologic* factors are known and thus are equal to 1. In our 100-acre evaluation unit, the net-to-total area is the same, the net-to-gross thickness has already been calculated, and for clastic reservoirs (sandstones) we will assume that the porosity is well connected with a ratio of effective (connected) porosity to total porosity equal to 1. Litynski and others (2010) calculated efficiency factors for the *displacement* factors separately, and for sandstone reservoirs they range from 7.5 to 24 percent, with a P_{50} (most likely) efficiency factor of 14 percent. This means the most likely case is that 14 percent of the pore space can be filled with CO_2. The range of storage volumes using the probabilistic efficiency factors for the Mill Creek site is shown in Table 4-4.

Table 4-3. Reservoir parameters and calculated CO_2 storage capacity for a 100-acre area at 100 percent and 14 percent storage efficiency.

Site	*100-Acre Area (m^2)*	*Net Reservoir Thickness (ft)*	*Net Reservoir Thickness (m)*	*Porosity (%)*	*CO_2 Density (kg/m^3)*	*CO_2 Capacity at 100% Efficiency (metric tons)*	*Storage Efficiency Factor*	*CO_2 Capacity at 14% Efficiency (metric tons)*
Mill Creek	404,686	70	21.4	8.2	795.32	563,583	0.14	78,902

The application of an efficiency factor significantly reduces the storage capacities, but is necessary to estimate storage volumes.

Summary

The Mill Creek Station has limited potential for geologic storage of CO_2 beneath the site property. The Mount Simon Sandstone is the only formation with suitable porosity, permeability, and seal at depths required to store supercritical-phase sequestration. Excellent confinement for injected CO_2 is provided by the more than 500-ft-thick Eau Claire Formation.

Geologic data control for Mill Creek is fair, with one well to the reservoir within a 15-mi radius. This well, a hazardous-waste disposal well, was unable to establish fluid injection in the Mount Simon 12 mi from Mill Creek. Mapping indicates the reservoir at Mill Creek is thinner and deeper than at DuPont. This suggests the reservoir properties will be worse at Mill Creek than at DuPont. The nearest seismic data are from 11 mi from Mill Creek, not close enough to characterize the Mill Creek site. There is one surface fault mapped within a 15-mi radius. The Mount Simon structure map (Fig. 4-6) indicates that injected CO_2 would migrate slowly to the north, parallel to the Ohio River. Migration of some CO_2 under the river into Indiana is possible, but this would depend on the volume of CO_2 injected and the length of time. If this is a concern, an injection stimulation could be run to predict the CO_2 plume size and direction over time. KGS does not currently have this modeling capability, but it may be available in the near future.

It may be possible to use the Knox Group as a sequestration reservoir at Mill Creek. The Knox was used at the DuPont site for injection of hazardous waste. That project actually resulted in the formation and trapping of supercritical CO_2 in the Knox; the acidic waste dissolved the dolomite reservoir, forming a cavern. This limited amount of CO_2 was trapped in the injection zone, but larger volumes may not behave the same way. Our concern at Mill Creek is that the top of the Knox and the overlying seal are shallower than 2,500 ft. If CO_2 migrates upward within the Knox, it could reach depths where the supercritical phase is no longer stable, and a phase change to gaseous CO_2 would occur. This would result in a large volume increase, possibly fracturing the rock.

Using the most likely storage volumes at each site, the following volume of CO_2 could be stored at each site, using property owned by LG&E-KU (Table 4-5).

Table 4-4. Range of probabilistic storage volumes using DOE's displacement efficiency factors for clastic reservoirs (Litynski and others, 2010).

Site	*Minimum Volume (metric tons/100 acres) $\dot{\varepsilon}$ = 7.4% (P_{10})*	*Most Likely Volume (metric tons/100 acres) $\dot{\varepsilon}$ = 14% (P_{50})*	*Maximum Volume (metric tons/100 acres) $\dot{\varepsilon}$ = 24% (P_{90})*
Mill Creek Station	41,705	78,902	135,260

Table 4-5. Total site storage capacity at Mill Creek Station assuming 100 percent use of LG&E-KU property.

Site	*CO_2 Storage Volume (metric tons per acre)*	*Total Site Size (acres)*	*Total Site Storage Volume (metric tons)*
Mill Creek Station	789	548.8	432,988

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Appendix: LG&E-KU Carbon Storage Evaluation Ranking Criteria

LG&E-KU Carbon Storage Evaluation Ranking Criteria				Power Generating Station				
	Description	Criteria and Rationale	Criteria Scoring	Ghent	Trimble Co.	Green River	E.W. Brown	Mill Creek
1.0 Physical Characteristics								
1.1	Size	The area and linear dimensions of the plant site must accommodate additional carbon capture facilities and underground storage. This criterion addresses the availability of additional acreage at the plant site to support future expandability of the facility and for CO_2 storage onsite. Larger sites are preferred.	Site size: 15 ≥ 1,000 acres 10 500–1,000 acres 5 > 5–500 acres	15	15	5	15	15
1.2	Topography	This criterion addresses how much relative groundwork will be required at the site before it is suitably graded for facility construction. Flat sites requiring little no grading are preferred. Contoured sites with appropriate available bench width are considered flat, although staging facility process equipment in noncontiguous locations may increase capital costs.	5 Minimal to no groundwork required 3 Some groundwork required 1 Significant amount of groundwork required	5	5	5	3	5
1.3	Floodplain	The plant must have low potential for flood damage and plant shutdown. The site of the capture facility must be above the 100-year floodplain. Floodplain restrictions are not as important for land used for storage wells.	25 Carbon capture facility site above 100-year floodplain 15 Majority of the site is above 100-year floodplain; small impact on critical building area 0 Critical project elements within 100-year floodplain	25	25	15	25	25
1.4	Wetlands	It is preferable to avoid impacts to wetlands to the extent possible, for both the capture facility and the injection wells.	25 No wetlands affected 20 < 1 acre of wetlands affected 15 > 1–5 acres of wetlands affected 10 > 5–10 acres of wetlands affected 5 > 10 acres of wetlands affected	25	25	25	25	25
			Subtotal	70	70	50	68	70
2.0 Geologic Factors								
2.1	Seismic stability	Assuming DOE will use similar criteria as for FutureGen, the plant should have low risk from significant seismic events. Proven by supporting geologic data and calculations demonstrating peak ground acceleration less than 20 percent g, with a 10 percent chance of exceedance in 50 years. Peak ground acceleration is the most appropriate seismic-hazard criterion because of pipeline infrastructure and other shallow subsurface facilities.	10 0.05g MCE 8 0.10g MCE 6 0.20g MCE 4 0.30g MCE 2 0.50g MCE 0 > 0.50g MCE	10	10	8	10	10
2.2	Faults	Presence of mapped fault(s) within 15 mi of plant site or proposed injection area if offsite. Faults can be transmissive (leakage pathway) or sealing (forming a trap). Absence of faults is preferred.	5 No faults within 15 mi 0 Fault(s) within 15 mi of the site	5	0	0	0	0
2.3	Oil fields (immiscible EOR potential)	One or more oil fields within 15 mi and less than 2,500 ft depth. CO_2 injection is a demonstrated technology for enhanced oil recovery. Sequestration of CO_2 when combined with recovery of additional resources is mutually beneficial.	5 One or more oil fields within 15 mi and < 2,500 ft deep 0 No oil fields within 15 mi and < 2,500 ft deep	0	0	5	0	0
			Subtotal	15	10	13	10	10
3.0 Other Site Characteristics								
3.1	Existing land use around plant site	Current use on the plant site and surrounding existing land use must be consistent with the construction and operation of the carbon capture and storage facility. Construction and operation of the storage facility at the plant would be incompatible with nonindustrial uses such as residential areas.	25 Compatible: brownfield, heavy industry, or mineral extraction 15 Somewhat compatible: agriculture or forestry 0 Incompatible: recreational, institutional, or residential area within a 1-mi radius of the site property	0	0	15	0	0

LG&E-KU Carbon Storage Evaluation Ranking Criteria				Power Generating Station				
3.2	Public acceptance	Public perception and acceptance of carbon storage projects is a critical factor for success. This criteria is an attempt to evaluate local support or opposition for a carbon storage project.	25 Local familiarity with mining and oil and gas drilling operations, local support with no known opposition 15 No local mineral extraction industry, but support from local community, and no known environmental opposition 0 Visible or known organized opposition to coal-fired generation or carbon storage projects; little local support	15	15	25	15	15
			Subtotal	15	15	40	15	15
4.0 Regulatory and Permitting								
4.1	National Environmental Policy Act	DOE funding will require compliance with NEPA. The imposition of any requirements of NEPA (where applicable) on the construction and operation of the carbon capture and storage facility can have an impact on project or schedule (or both).	25 No NEPA requirements or the ability to adopt the federal NEPA document as adequate without delays 15 NEPA requirements, but directed to be done concurrently with the other State requirements 0 NEPA requirements to be done independently or after any State requirements	25	25	25	25	25
			Subtotal	25	25	25	25	25
5.0 Sequestration Potential								
5.1	Presence of deep saline reservoir	Current best practice indicates that deep saline formations are likely to have the largest capacity for long-term storage of CO_1 as a supercritical fluid. This criteria evaluates distance to wells demonstrating suitable thickness, porosity, and permeability that are 2,500–10,000 ft in depth and have at least one demonstrated overlying seal at least 20 ft thick. This criteria is intended to demonstrate the presence and utility of such a zone in the immediate vicinity of the plant site.	25 Well/core indicating reservoir and seal within 1 mi of site (proven) 15 Well indicating reservoir and seal between 1 and 15 mi from site (probable) 5 Well indicating reservoir and seal within 15 and 25 mi of plant site (possible) 0 No well/core indicating reservoir and seal within 25 mi	15	0	15	15	15
5.2	Multiple deep saline reservoirs	Two or more proven or probable saline reservoirs as defined above. Multiple stacked intervals increases the likelihood of sufficient capacity for sequestration.	10 Two or more saline reservoirs 0 Fewer than two saline reservoirs	0	0	0	0	0
5.3	Estimated CO_2 storage capacity	Storage capacity estimated for 100-acre area of the primary storage reservoir.	25 More than 200,000 metric tons/100 acres 15 100,000 to 200,000 metric tons/100 acres 5 Less than 100,000 metric tons/100 acres	25	15	5	25	5
5.4	Demonstrated closed trap for CO_2	Sufficient data to show structural closure (trap) on one or more of the available reservoirs for sequestration within 15 mi. Structural closure will limit migration of injected CO_2. Additional analysis is required to determine the volume of the closure to its spill point. A closed trap is desirable, but not required.	25 Structural closure on one or more available reservoirs 0 No structural closure on available reservoirs	0	0	0	25	0
5.5	Subsurface activity/ access	The presence of oil and gas fields, underground coal mines, or limestone/aggregate quarries or mines within 15 mi. Need to assess potential issues with respect to mining health and safety, ownership, and leases of the mineral estate, and potential subsurface access conflicts.	5 No sites within 15 mi 0 Sites within 15 mi	0	0	0	0	0
5.6	Well penetrations into primary seal	How many penetrations are there through the primary seal of the main target formation within a 15-mi area of review. Wellbores represent potential migration pathways for CO_2 leakage into underground sources of drinking water or to the surface. Need to assess integrity of the seal with respect to the density (number) of wellbores, their depths, and the possibility of unlocated holes to ensure CO_2 does not leak.	15 Fewer than four well penetrations within 15 mi 9 Four to six well penetrations within 15 mi 0 More than six well penetrations within 15 mi	9	15	9	0	15

LG&E-KU Carbon Storage Evaluation Ranking Criteria				Power Generating Station				
5.7	Availability of seismic-reflection data	Proximity of seismic-reflection data to the plant site. Seismic-reflection data are essential for use in assessing the nature and potential integrity of a unit for sequestration and modeling the geometry of the area of pore space to be contacted by CO_2.	15 Seismic lines available onsite or within 1-mi radius 12 Seismic lines available within 1.5-mi radius 9 Seismic data available within 5–10 mi 6 Seismic data available within 10–15 mi 3 No seismic data available within 15 mi of plant	6	3	12	9	6
			Subtotal	55	33	41	74	41
			TOTAL SCORE	180	153	169	192	161