Kentucky Geological Survey
University of Kentucky, Lexington

Phase 1 Geologic Evaluation of the Kentucky Geological Survey Marvin Blan No. 1 Deep Saline Reservoir CO_2 Injection Test Well, Hancock County, Kentucky

J. Richard Bowersox, David A. Williams, David C. Harris

Contract Report 63

Series XII, 2016

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General **Intermediate** **Technical**

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Phase 1 Geologic Evaluation of the Kentucky Geological Survey Marvin Blan No. 1 Deep Saline Reservoir CO_2 Injection Test Well, Hancock County, Kentucky

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Executive Summary

The Kentucky Geological Survey's Marvin Blan No. 1 well was drilled in east-central Hancock County, Ky., about 4 mi southwest of the Ohio River, to demonstrate CO_2 injection in the Western Kentucky Coal Field, following the mandate and partial funding from Kentucky's House Bill 1, August 2007. Results of this test will be used by the Kentucky Geological Survey to calibrate CO_2 storage reservoir models and further evaluate the storage capacity within the Knox Group in Kentucky. All units used in this summary are U.S. standards. Unless otherwise stated, CO_2 refers to supercritical CO_2. Supercritical CO_2 is a liquid phase-state of CO_2 at elevated pressures and temperatures where the density of CO_2 increases to approximately 250 times that of gaseous CO_2 but the properties of a gas are retained. The increased density of the CO_2 corresponds to a decrease in the volume it occupies, and thus reduces the volume of reservoir strata required for its storage.

Drilling and Injection Testing

The Marvin Blan No. 1 well commenced drilling on April 24, 2009, after 18 mo of planning, drill-site due diligence and construction, and regulatory-agency permitting. It reached its total depth of 8,126 ft in Precambrian Middle Run Sandstone on June 15 after 63 days of drilling. A total of 395 ft of whole-diameter 4-in. cores was cut and recovered from the well. The Devonian New Albany Shale, Ordovician Maquoketa Shale, Black River Group, and basal Wells Creek Formation were cored to test reservoir sealing properties. The Knox Group was cored in three intervals to test reservoir characteristics and rock properties. The Precambrian Middle Run Sandstone was cored to test for any CO_2 storage potential below the Paleozoic rocks.

The testing program commenced on July 25, 2009, and was successfully completed on August 22, 2009. Several zones in the Knox were identified as principal reservoirs in the well during injection tests with potassium chloride brine. Total brine injected in the first testing phase was 18,454 bbl (approximately 779,000 gal). A total of 323 tons of supercritical CO_2 (equivalent to 1,765 bbl of fluid or 5,646 mcf of gaseous CO_2) was injected at

the pumping equipment maximum rate of 4.1 bbl/min. The wellbore was then temporarily abandoned with downhole pressure monitoring in place pending additional testing.

Estimated CO_2 Storage Capacity

Total Knox reservoir pore volume calculated in the Marvin Blan No. 1 well is estimated to be 216 porosity-ft, a measure of the void space in the formation. Applying a 5-percent porosity cutoff for defining effective porosity, reservoir pore volume is conservatively estimated to be 172 porosity-ft, of which 50 percent lies within the upper 1,600 ft of the Knox. At the average Knox reservoir depth in the Marvin Blan No. 1 of 5,590 ft, reservoir pressure is 2,420 psi and measured reservoir temperature is 113°F. Under these conditions, estimated storage capacity of supercritical CO_2 in the Marvin Blan No. 1 well at a 5-percent porosity cutoff is approximately 50 tons per acre-foot of reservoir, using an industry-standard efficiency factor of 5 percent.

Estimated CO_2 storage capacity in the Marvin Blan No. 1 well is 8,600 tons of CO_2 per surface acre of reservoir. Therefore, a CO_2 storage well comparable to the Marvin Blan No. 1 would require approximately 120 surface acres to store 1 million tons of CO_2, or approximately 3,500 surface acres of reservoir to store 30 million tons of CO_2. Thus, depending on well spacing, seven to 10 wells would be required to store 30 million tons of CO_2 in a supercritical state.

A regional evaluation was performed to identify the prospective area in western Kentucky for CO_2 storage in the Knox based on geologic information gained during the drilling and testing of the Marvin Blan No. 1 well. Using a lower depth limit of 9,000 ft, an upper depth limit where the base of the reservoir seal is above 2,500 ft, and a CO_2 storage capacity of 1 million tons per 200 surface acres, the prospective area for CO_2 storage in the Knox in western Kentucky includes nearly the entire Western Kentucky Coal Field and Rough Creek Graben, and the adjacent region to the south, or approximately 6,400 mi^2. Mitigating this estimate are faults in the subsurface, which may have the potential for leakage and for allowing CO_2 to migrate out of the storage reservoirs. Therefore, evaluation of faults in the prospective area will be necessary to determine whether they may act as seals for CO_2 storage or as leakage pathways, and their impact on overlying reservoir sealing intervals.

CO_2 Containment

Equally important for the evaluation of CO_2 storage potential in western Kentucky is the presence of adequate sealing intervals below 2,500-ft drill depth overlying any potential CO_2 storage reservoir. Black River Group carbonates and the Maquoketa Shale provide seals for the Knox CO_2 storage reservoir. Two samples from the Black River were analyzed for their reservoir seal properties and showed sufficiently low porosity and permeability, as well as rock strength, to adequately serve as a CO_2 storage reservoir seal. Analysis of 11 core samples showed the Maquoketa to have excellent sealing capacity for underlying strata, with both extremely low permeability and very high rock strength.

Conclusions

CO_2 injection into the Knox was demonstrated, as well as the presence of sealing strata capable of ensuring long-term CO_2 storage. Initial evaluation of the Marvin Blan No. 1 and other wells drilled into the Knox suggests that large areas of western Kentucky may have reservoirs in the Knox with CO_2 storage potential.

Introduction

The Kentucky Geological Survey's Marvin Blan No. 1 well was drilled in east-central Hancock County, Ky. (Figs. 1–2), about 4 mi southeast of the Ohio River, to demonstrate CO_2 injection in the Western Kentucky Coal Field, following the mandate and partial funding from Kentucky's House Bill 1, August 2007 (Kentucky Legislature, 2009). Industry funding was provided by Peabody Energy, ConocoPhillips Co., E.ON U.S., and the Tennessee Valley Authority, through the Western Kentucky Carbon Storage Foundation, the Illinois Office of Coal Development, and the U.S. Department of Energy, National Energy Technology Laboratory. The well was located on the easternmost margin of the Western Kentucky Coal Field in order to evaluate the CO_2 storage characteristics of the Knox Group, which has a broad distribution in Kentucky, at its shallowest depth. Secondary targets included the St. Peter Sandstone overlying the Knox, and the underlying Mount Simon Sandstone. The Marvin Blan No. 1 well commenced drilling on April 24, 2009, after 18 mo of planning, drill-site due diligence and construction, and regulatory-agency permitting (Bowersox and others, 2009). It reached its total depth of 8,126 ft below the drilling-rig kelly bushing in Precambrian Middle Run Sandstone on June 15, 2009. The top of the Knox, the Beekmantown Dolomite, was penetrated at 3,780 ft; the Gunter Sandstone (Illinois Basin correlative of the Rose Run Sandstone of the Cincinnati Arch and Appalachian Basin) from 5,040–5,230 ft; the Copper Ridge Dolomite at 5,347 ft; and the base of the Knox–top of the Eau Claire Formation at 7,397 ft. A total of 3,617 ft of Knox section was encountered in the well. The St. Peter and Mount Simon were absent in the Marvin Blan No. 1. Drilling through the Knox proved to be difficult: Borehole deviation greater than 5° required specialized equipment to return it to vertical and maintain a vertical borehole, circulation was lost in a fracture at 5,581 ft, and core-barrel jamming resulted in only 19 ft of core being cut in the Copper Ridge.

Surface conductor pipe was cemented at 52 ft, 13⅜-in. surface groundwater protection casing was cemented at 441 ft, and 8⅝-in. casing was cemented at 3,660 ft, 120 ft above the Knox. The hole was left uncased below 3,660 ft to facilitate testing. The testing program commenced on July 25, 2009, and was successfully completed on August 22, 2009. All testing was in the open hole below the casing at 3,660 ft. The wellbore was then temporarily abandoned, with downhole pressure monitoring in place pending additional testing. Additional testing of the Marvin Blan No. 1 well, to commence in mid-2010, has been made possible by a U.S. Department of Energy grant from the American Recovery and Reinvestment Act to the University of Illinois and several partners, including the Kentucky Geological Survey, to further evaluate the CO_2 storage potential of deep saline reservoirs underlying much of the Midwest.

The purpose of this report is to present a geologic evaluation of the Marvin Blan No. 1 well. Stratigraphy and formation ages in this paper are after Swezey (2009). Appendices 1–6[1] contain basic well data, seismic data, and core analysis; written reports by others, including the U.S. Environmental Protection Agency permit application file and permit; well-drilling plat, permit, and drilling program; injection test program; injection testing report; and selected presentations and public outreach. File formats have been selected for optimal access and use by end users and have been compressed as zip archive files to conserve disc space. These files can be extracted using the Microsoft Windows Explorer[2] file manager.

Logging and Coring Programs

The Marvin Blan No. 1 drilled through the characteristic Paleozoic section of western Kentucky from the Lower Pennsylvanian to the Middle Cambrian, and reached its total depth in the Precambrian Middle Run (Fig. 3). Selected tops of formations penetrated by the well, as well as those of the groundwater monitoring well drilled on the Marvin Blan No. 1 drill site and the Knight Brothers No. 1 well, are listed in Table 1. The depths of formation tops recorded on log runs 2 and 3 apparently are 4 ft shallower than the correct depth (discussed below). Three electric-log runs were

[1]Contact the Public Information Center at KGS for a copy of the appendices on DVD.
[2]The use of manufacturer and trademark names does not constitute an endorsement of the product by the Kentucky Geological Survey or the University of Kentucky.

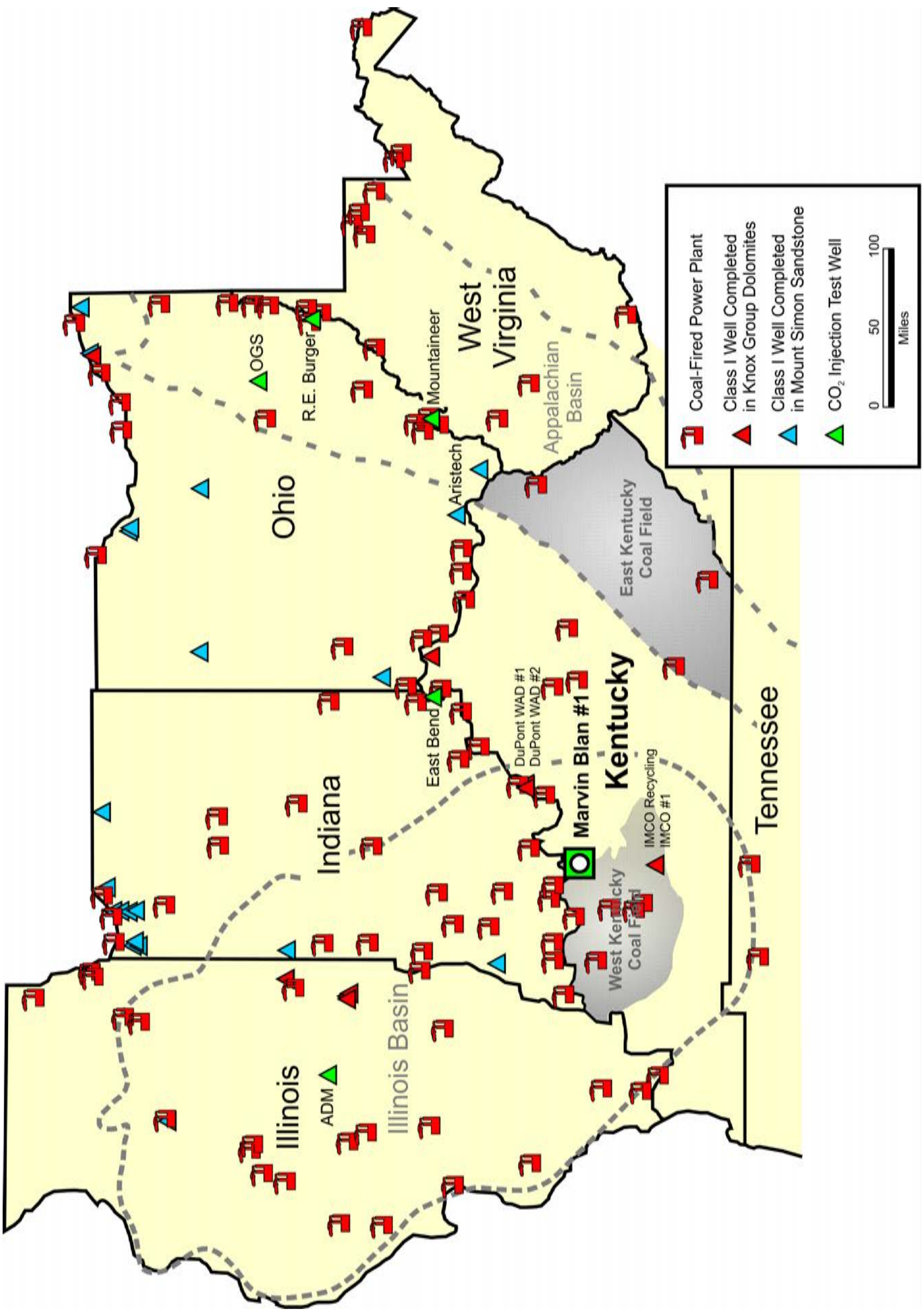
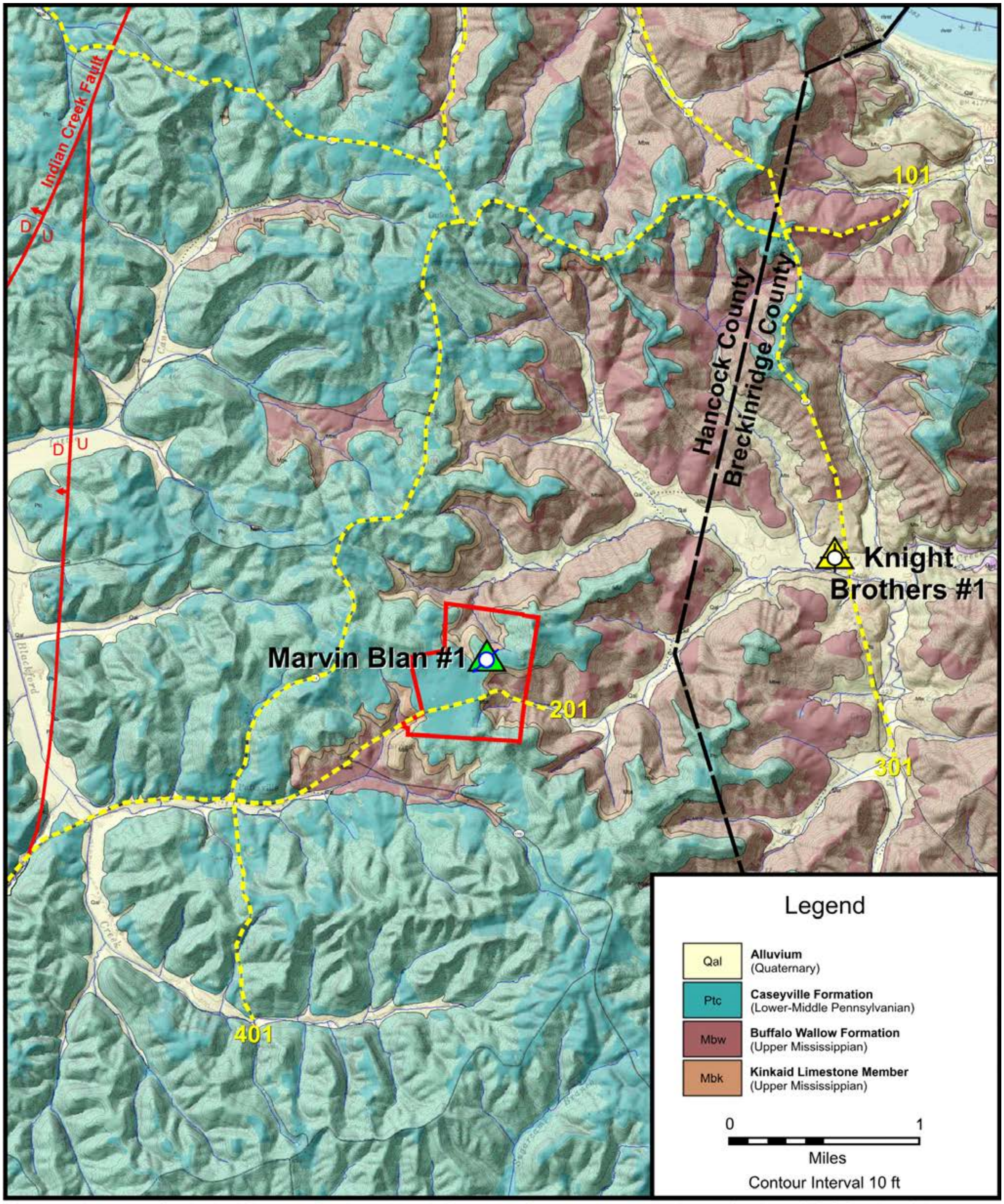


Figure 1. The Marvin Blan No. 1 well is located in east-central Hancock County, on the northeast margin of the Western Kentucky Coal Field, along the Ohio River industrial corridor. Regional locations of coal-fired power plants, U.S. Environmental Protection Agency Class I hazardous-waste injection wells completed in the Knox (red triangles) and Mount Simon Sandstone (blue triangles), and CO_2 injection tests (green triangles) are shown for reference.



Source: Kentucky Geological Survey, Geologic Map Information Service, *kgsmap.uky.edu/website/KGSGeology/viewer.asp*

Figure 2. Surface geology in the vicinity of the Marvin Blan No. 1 well. Yellow dashed lines show the locations of 2-D reflection-seismic lines acquired as part of the well-site evaluation program. Well-site lease is outlined in red. Approximately 25 ft of Caseyville Sandstone unconformably overlying Buffalo Wallow Formation was penetrated during installation of the well's conductor pipe.

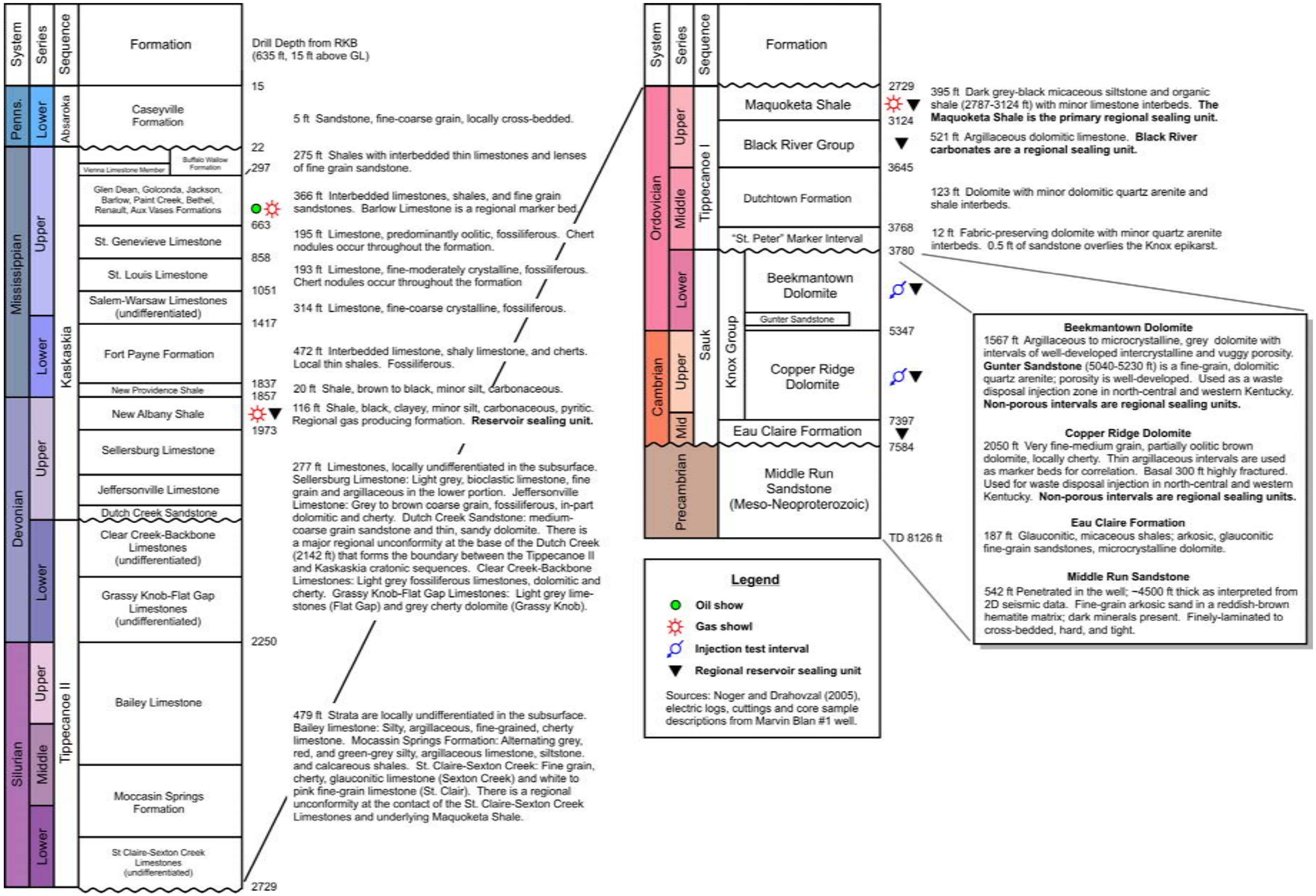


Figure 3. Generalized stratigraphy of the Marvin Blan No. 1 well. Regional reservoir seals were cored in the New Albany Shale, Maquoketa Shale, and Black River Group (inverted black triangles). Potential reservoir intervals were cored, and injection tests conducted, in the Beekmantown Dolomite, Gunter Sandstone, and Copper Ridge Dolomite. Subcommercial oil and gas shows were encountered during drilling in the shallow Upper Mississippian Aux Vases Formation and the Upper Devonian New Albany Shale.

Table 1. Formation tops penetrated in the Marvin Blan No. 1 well. Although the depths of log runs 2 and 3 tie together at the top of the Joachim Dolomite, log run 2 does not tie with log run 1 at the top of the Caseyville Sandstone. All depths are measured from KB.

Log Run: Date: Total Depth: Datum Elevation:	Monitor Well 9-Apr-2009 427 625 GL	1 24-Apr-2009 442 635 KB*	2 9-May-2009 3,660 635 KB*	3 15-Jun-2009 8,126 635 KB*	Knight Bros. #1 1972 6,035 407 KB**
Surface	0	NL	NL		NL
Caseyville Sandstone	8	26	22		absent
Buffalo Wallow Shale	15	32	28		absent
Palestine Sandstone	64	56	52		absent
Menard Limestone	86	83	79		absent
Vienna Limestone	226	241	237		absent
Tar Springs Sandstone	absent	absent	absent		absent
Glen Dean Limestone	284	301	297		32 est.
Golconda Limestone	373	387	383		111
Jackson Sandstone	NP	NP	459		166
Barlow Limestone			486		212
Cypress Sandstone			507		243
Renault Limestone			599		333
Ste. Genevieve Limestone			663		406
St. Louis Limestone			858		629
Salem Limestone			1,051		949
Fort Payne Formation			1,417		1,143
New Providence Shale			1,837		1,550
New Albany Shale			1,857		1,570
base, New Albany Shale			1,973		1,678
Sellersburg Limestone			1,973		1,678
Clear Creek Limestone			2,142		1,853
Bailey Limestone			2,250		1,951
Laurel Dolomite			2,486		2,162
Maquoketa Shale			2,729		2,402
Black River Group			3,124		2,811
Pecatonica Limestone			3,497	NL	3,184
Joachim Dolomite			3,585	3,585	3,272
Dutchtown Limestone			3,645	3,645	3,334
“St. Peter” marker			NP	3,768	3,459
Knox Group				3,780	3,472
Beekmantown Dolomite				3,780	3,472
Gunter Sandstone				5,040	4,750
base, Gunter Sandstone				5,230	4,898
Copper Ridge Dolomite				5,347	5,020
Eau Claire Formation				7,397	NP
Precambrian basement				7,484	
Middle Run Sandstone				7,584	

*KB 14.5 ft above GL
**KB 5 ft above GL
NL = not logged
NP = not penetrated

made during the drilling of the Marvin Blan No. 1: array induction (dual induction), SP, gamma ray, and borehole caliper at 442 ft TD to the surface; array induction, SP, gamma ray, spectral gamma ray with lithology analysis, photoelectric density and compensated neutron-porosity logs, dipole sonic with mechanical rock properties analysis, and array induction, SP, gamma ray, photoelectric density and compensated neutron-porosity logs, dipole sonic with mechanical rock properties analysis, Compact Formation Micro Imager (CMI) log and analysis, and borehole caliper at 8,126 ft TD to casing at 3,660 ft (Appendix 1). The gamma-ray log from electric-log run 1 (442 ft TD) records the top of the Caseyville at 26 ft KB, 11 ft below the surface, whereas the gamma-ray log from electric-log run 2 (3,662 ft TD) records the same top at 22 ft, or 7 ft below the surface (Table 1). The top of the Caseyville recorded on electric-log run 1 approximates that noted during installation of the cellar and conductor pipe. This suggests that electric-log runs 2 and 3 (8,126 ft TD), though internally depth-consistent, are recorded 4 ft higher than their true depth. The Marvin Blan No. 1 was mudlogged from the surface to its total depth at 8,126 ft in 5-ft intervals. The mudlog is included in Appendix 1. Formation tops and lithologies correlated and recorded on the mudlog vary from those correlated from the electric logs by as much as several hundred feet. The well-site survey plat, Kentucky Division of Oil and Gas Conservation drilling permit, EPA injection permit application and permit, operations report by Sandia Technologies for drilling and testing the Marvin Blan No. 1, and tabulation of public outreach efforts are included as Appendices 5–6.

Whole-diameter 4-in. cores were cut and recovered from the New Albany Shale, Maquoketa Shale, and Black River Limestone to test sealing capabilities of these intervals, and in the Beekmantown, Beekmantown-Gunter, and Copper Ridge to test reservoir properties of porous and permeable intervals, and reservoir seal properties of impermeable intervals within the Knox. A total of 395 ft of cores was cut and recovered from the New Albany (1,875–905 ft; 30 ft), Maquoketa (2,800–2,831 ft; 31 ft), Black River (3,335–3,396 ft; 61 ft), basal Wells Creek Formation–St. Peter–Beekmantown (3,760–3,883 ft; 123 ft), Beekmantown-Gunter (5,021–5,122 ft; 101 ft), Copper Ridge (6,130–6,149 ft; 19 ft), and Middle Run (8,000–8,030 ft; 30 ft). Correlation of core gamma-ray log depths with open-hole gamma-ray log depths (electric-log runs 2 and 3) are given in Table 2. Core depths as drilled differ from electric-log depths by approximately 0.5 to 5.5 ft. Photographs and analyses of the cores are compiled in Appendix 3.

Hydrocarbon Shows During Drilling

Hydrocarbon shows were logged in several intervals during drilling of the Marvin Blan No. 1: a gas show in the Barlow Limestone at 496–500 ft, four slight gas shows in the interval 500–600 ft, an oil and gas show in the Aux Vases Limestone at 687–696 ft, a slight gas show at 1,017–1,019 ft, and a gas show in the New Albany at 1,857–1,973 ft. No commercial production has been established in the surrounding area in any of the intervals with hydrocarbon shows in the Marvin Blan No. 1, although many exploratory wells have been drilled to both shallow intervals and through the New Al-

Table 2. Depths and recoveries of cores from the Marvin Blan No. 1. Gamma-ray logs were recorded in the laboratory for each core in order to correlate core depths to electric-log depths. Note the offset of core depths versus log depths.

		Core Interval				Top Core
Core	**Formation**	**Top (ft KB)**	**Base (ft KB)**	**Cut (ft)**	**Recovery (ft)**	**(Log, ft KB)**
1	New Albany Shale	1,875	1,905	30	30	1,876.0
2	Maquoketa Shale	2,800	2,831	31	31	2,802.0
3	Black River Limestone	3,335	3,396	61	61	3,333.0
4	Wells Creek–Beekmantown	3,760	3,883	123	123	3,760.0
5	Beekmantown-Gunter	5,021	5,122	101	101	5,021.5
6	Copper Ridge	6,130	6,149	19	19	6,126.0
7	Middle Run Sandstone	8,000	8,030	30	30	7,994.5
			Total Cored	395	395	

bany. Five noncommercial wells completed in the New Albany were drilled in Hancock County near Victoria Crossroads, about 3 mi south of the Marvin Blan No. 1, in 2006. No hydrogen sulfide was encountered during drilling.

Geology of the Marvin Blan No. 1 Well

The subsurface stratigraphy of western Kentucky penetrated in the Marvin Blan No. 1 well is summarized in Figure 3. Strata were deposited in four cratonic sequences (Sloss, 1963) (Fig. 3): upper Precambrian–Lower Ordovician Sauk sequence, Lower Ordovician–uppermost Ordovician Tippecanoe I subsequence of Noger and Drahovzal (2005), basal Silurian–Middle Devonian Tippecanoe II subsequence of Noger and Drahovzal (2005), and the Middle Devonian–uppermost Mississippian Kaskaskia sequence. In general, the stratigraphic succession of these sequences and subsequences consists of a basal transgressive, shallow-marine to nonmarine sandstone overlain by deeper-water to basinal shales, limestones, and dolomites with rare, lenticular sandstones in the section. The Tippecanoe II subsequence is incomplete in western Kentucky and is missing the basal sandstone (Fig. 3). Oil and gas in Hancock County have been produced, or hydrocarbon shows noted, in the shallow upper Kaskaskia sequence (Upper Mississippian sandstones and limestones), and in the lower Kaskaskia sequence (uppermost Devonian naturally fractured New Albany) (Fig. 3). Elsewhere in Kentucky, oil and gas are produced and gas stored in Knox reservoirs (Gooding, 1992). EPA Underground Injection Control Class I injection wells have been developed at depth in upper Sauk sequence Knox dolomites in central Kentucky and in Knox dolomites and the Mount Simon in Illinois, Indiana, and Ohio (Fig. 1).

Surficial Geology

Two formations are present at the surface in the vicinity of the well site in east-central Hancock County: the Early Pennsylvanian Caseyville Sandstone and the Late Mississippian Buffalo Wallow Formation shale and its Kincaid Limestone Member (Figs. 2–3). Approximately 100 ft of nearly horizontal fluvial deposits of the Caseyville are exposed in the hills surrounding the well site, unconformably overlying approximately 20 ft of the Late Mississippian marine Kincaid at a slight angular discordance, dipping southerly, truncating the Kincaid east of the well site, where Caseyville lies directly on the Buffalo Wallow at the surface (Fig. 2). The soil profile penetrated on the well pad during installation of the cellar and conductor pipe was estimated to be 10 ft thick, and the original soil profile is estimated to have been approximately 12 ft thick prior to site preparation. A 6-ft section of Caseyville overlying 24 ft of Buffalo Wallow was penetrated in the Marvin Blan No. 1 well.

The Caseyville–Kinkaid/Buffalo Wallow contact is a major unconformity in western Kentucky, truncating progressively older Mississippian strata northeastward across the state (Rice, 2001), and represents the Kaskaskia-Absaroka cratonic sequence boundary of Sloss (1963) (Noger and Drahovzal, 2005). A maximum of approximately 130 ft of Buffalo Wallow shales, thin limestones, and lenticular sands are exposed in the valleys surrounding the well site (Fig. 2). Valley bottoms are filled by Quaternary alluvium with a maximum thickness of approximately 25 ft (Fig. 2). The Caseyville is an important aquifer in Hancock County (Carey and Stickney, 2005), although no groundwater was encountered during the drilling of the Marvin Blan No. 1. The Kincaid is karstic, and sinkholes are apparent 500 ft north and 2,500 ft southwest of the well site; however, the Kincaid was absent in the Marvin Blan No. 1 well. A shallow-subsurface geotechnical seismic survey was completed prior to drilling as part of the well-site due diligence (Bowersox and Williams, 2008a). This survey ruled out the presence of shallow karstification that would have compromised the ability of the proposed drill site to support the weight of the drilling rig and auxiliary equipment and tanks.

Subsurface Geology Summary

The shallow subsurface geology includes the interval penetrated from the surface to the short-string, groundwater-protection casing point at 441 ft in the Marvin Blan No. 1 well. A groundwater monitoring well was required as a condition of drilling the Marvin Blan No. 1 (U.S. Environmental Protection Agency, 2009). The purpose of this well was to monitor the groundwater from the Tar Springs Sandstone for any migration of CO_2 from the deep storage reservoir to the shallow aquifer (Bowersox and Williams, 2008a). It was drilled 155 ft northwest of the Marvin Blan No. 1, on the same well-site pad, to a total depth of 427 ft from surface ground level. The monitoring well penetrated the Golconda Limestone at 373 ft (Fig. 4), 4 ft structurally lower than in the Marvin Blan No. 1 when compared to electric-log run 1 (Fig. 4, Table 1). The Tar Springs is approximately 8 ft thick in the Inklebarger Drilling Quinn No. 1 well, 1,860 ft northwest of the Marvin Blan No. 1 and 16 ft structurally lower at the top of the underlying Glen Dean Limestone. The Tar Springs was absent, however, apparently pinched out between the Quinn No. 1 and the monitoring well, and no water was encountered at any depth in the well. The groundwater monitoring well was subsequently plugged and abandoned.

The intermediate subsurface section, the section from the short-string casing point at 441 ft to the long-string casing point at 3,660 ft, includes the Middle Mississippian to Middle Ordovician strata. This is a section dominated by carbonates, although there are thin sandstones in the Mississippian section and the New Albany and Maquoketa Shales in the Devonian and Ordovician sections, respectively. The section below the top of the Laurel Dolomite at 2,486 ft includes the primary seals for the underlying Knox CO_2 storage reservoir. The deep-subsurface section in the Marvin Blan No. 1, below the casing cemented at 3,660 ft, penetrated Middle Ordovician to Precambrian (Neoproterozoic?) strata. This section extends from the basal Wells Creek to Middle Run, largely consisting of the Knox CO_2 storage reservoir, and includes the underlying Eau Claire Formation, a major regional sealing interval where underlying Mount Simon is present.

At TD, the Marvin Blan No. 1 had encountered 542 ft of Middle Run unconformably below the Eau Claire at 7,584 ft, the only Middle Run section penetrated in western Kentucky. The deepest well nearest the Marvin Blan No. 1, the KY Operating Co. Braden No. 1 well in southern Breckinridge County, about 16 mi southeast of the Marvin Blan No. 1 (Fig. 5), penetrated 458 ft of unnamed Precambrian rhyolite and basalt nonconformably

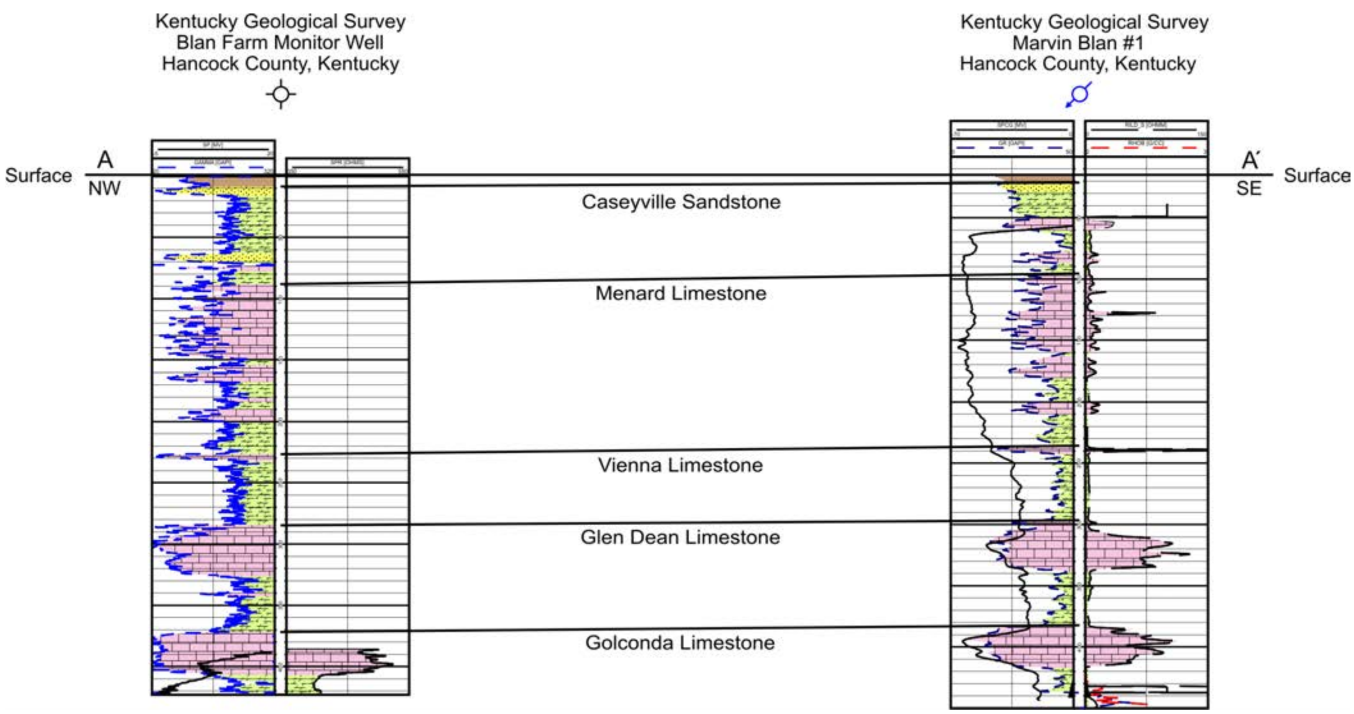


Figure 4. Shallow-subsurface structural cross section correlating the Blan farm monitoring well to the Marvin Blan No. 1. These wells are approximately 120 ft apart at the surface. The Tar Springs Sandstone aquifer, lying between the Glen Dean and Golconda Limestones 1,900 ft to the northwest in the Inklebarger Drilling Co. Ray Quinn No. 1 well, was the targeted interval in the monitoring well. The absence of the Tar Springs and lack of water entry into the monitoring well led to its subsequent abandonment.

overlain by the Eau Claire at 6,045 ft. Interpretation of regional seismic data demonstrates that the Middle Run (sequence 3 of Drahovzal and Harris, 2004; pC1* of Drahovzal, 2008) penetrated in the Marvin Blan No. 1 nonconformably overlies the volcanic section (sequence 4 of Drahovzal and Harris, 2004; pC4* of Drahovzal, 2008) penetrated in the Braden No. 1 in an onlapping relationship (Drahovzal, 1997, 2008, 2009). The Middle Run in the Marvin Blan No. 1 well is a reddish brown, fine-grained, crossbedded, arkosic sandstone. X-ray diffraction mineralogical analysis showed an average composition of 59 percent quartz, 15 percent feldspars (2:1 plagioclase versus orthoclase), 5 percent ferroan dolomite, and 2 percent hematite. The Middle Run is interpreted as having been deposited in a low-relief, fine-grained meander-belt fluvial environment. Paleocurrent analysis of crossbed orientation interpreted from the CMI log suggests a westerly transport direction consistent with the Grenville uplift to the east.

Structural Geology of Hancock County

Generalized subsurface structural contours on top of the Knox are shown in Figure 6. In western Kentucky and the Hancock County region, strata dip homoclinally approximately 0.5° westerly above the Knox unconformity and 1° below the unconformity. Seismic data suggest that Eau Claire and deeper strata dip 6° to the south in Hancock County (*see,* for example, Drahovzal, 2009). The surface fault nearest the Marvin Blan No. 1 is a strand of the Indian Creek Fault Zone, lying approximately 2.2 mi west of the well (Figs. 2, 6–7). The Rough Creek Graben, a major structural feature in western Kentucky, lies approximately 18 mi south of the Marvin Blan No. 1. No subsurface faulted sections can be demonstrated in the Marvin Blan No. 1, although fractures with small offsets were interpreted from the CMI log.

Potential CO_2 Storage Reservoirs in Western Kentucky

Hancock County, Ky., lies on the southeastern flank of the Illinois Basin and on the northeastern margin of the Western Kentucky Coal Field (Fig. 1), as defined by the outcrop of Pennsylvanian strata (Fig. 2). In the Illinois Basin, reservoir temperature and pressure necessary to maintain CO_2 in a supercritical state occurs at depths greater than 2,500 ft (Finley, 2005; Harris, 2007; Bowersox, 2008; U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, 2008; Williams and Bowersox, 2008). Potential test reservoirs were first screened for their presence underlying the Western Kentucky Coal Field, reservoir thickness, and estimated drill depth to the reservoir, then for their estimated reservoir properties of porosity, permeability, and presence of an overlying sealing interval. Drill depth was a primary concern for any potential reservoir underlying the Western Kentucky Coal Field in consideration of controlling drilling costs (Williams and Bowersox, 2008). The consortium members agreed upon 8,000 ft as the deepest practical drill depth to fully penetrate the deepest prospective reservoir interval. With the Mount Simon as a primary test objective, the 8,000-ft drill-depth limit ruled out all of the Western Kentucky Coal Field west of central Hancock County (Williams and Bowersox, 2008).

Planning of the Marvin Blan No. 1 well included evaluation of both CO_2 storage reservoirs and reservoir seals. There are two generally recognized deep-saline reservoirs with potential for CO_2 storage in the Illinois Basin and underlying parts of western Kentucky: the Middle Ordovician St. Peter (Fig. 3) and Middle Cambrian Mount Simon (U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, 2007, 2008). A third interval, the Middle Cambrian–Early Ordovician Knox, including the Beekmantown, Gunter, and Copper Ridge, was not initially considered a primary deep-saline reservoir test objective although the Rose Run Sandstone, the stratigraphic equivalent of the Gunter (Noger and Drahovzal, 2005), is noted as a potential CO_2 storage reservoir in the Appalachian Basin (U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, 2007, 2008). Early evaluations of potential CO_2 storage reservoirs in western Kentucky eliminated the Mount Simon for lack of sufficient porosity at depth to meet minimum reservoir storage volumes, however (Bowersox, 2008). Likewise, the St. Peter was eliminated as a potential reservoir target because it is thin in western Kentucky. The reservoir properties and

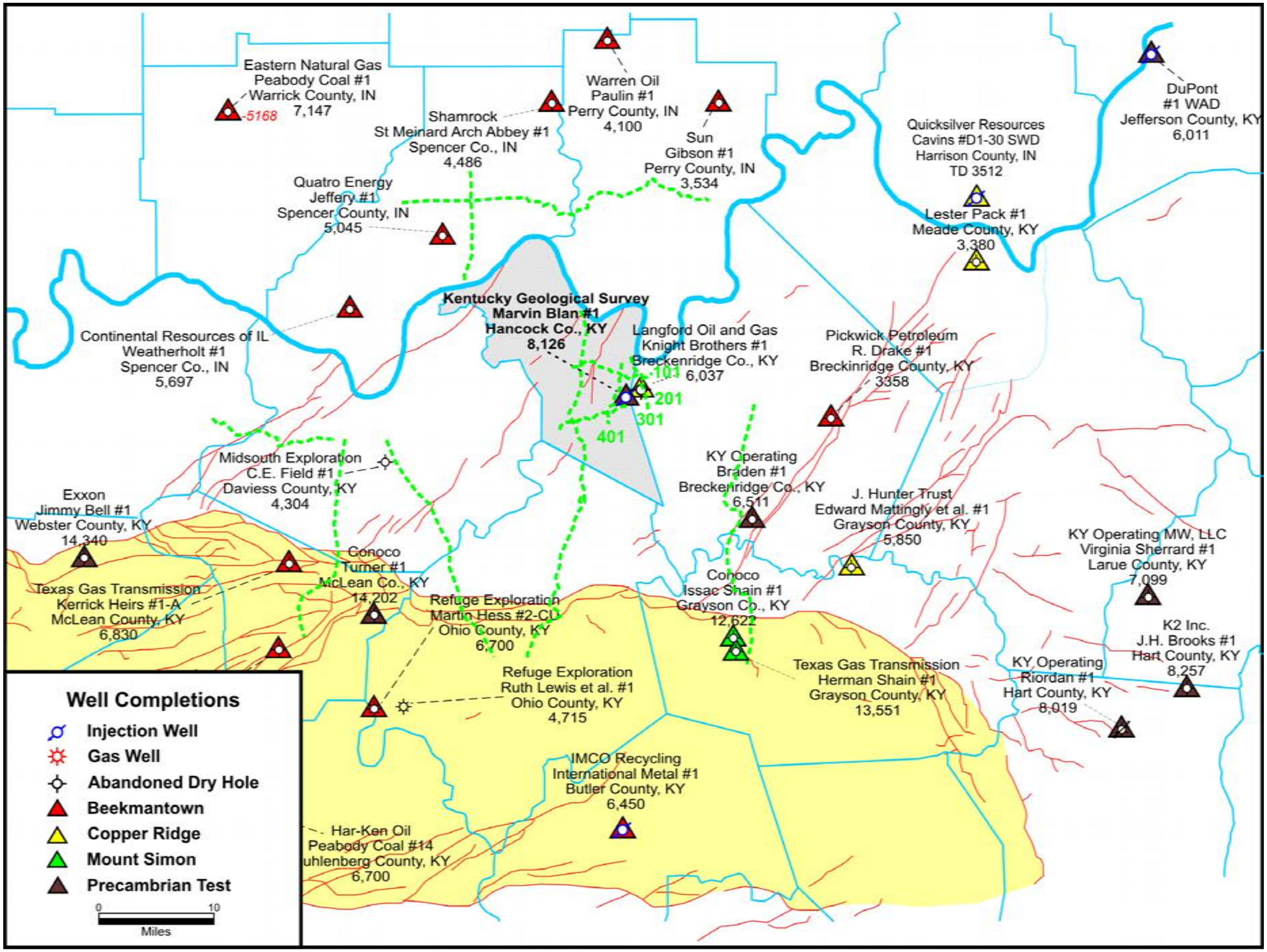


Figure 5. Locations of selected deep test wells in the project region. Hancock County is shaded gray. The formation at the deepest penetration depth is indicated with colored triangles. The 2-D reflection-seismic lines used for well-site evaluation are indicated with green dashed lines. This region covers about 9,300 mi^2; 37 penetrations into the Knox Group and deeper strata are known (one Kentucky well, under the legend, and 10 wells in Harrison County, Ind., immediately north of Meade County, Ky., are not shown). At a regional average of one deep test per 250 mi^2 (10.9 million acres), much of western Kentucky and adjacent southern Indiana is underexplored.

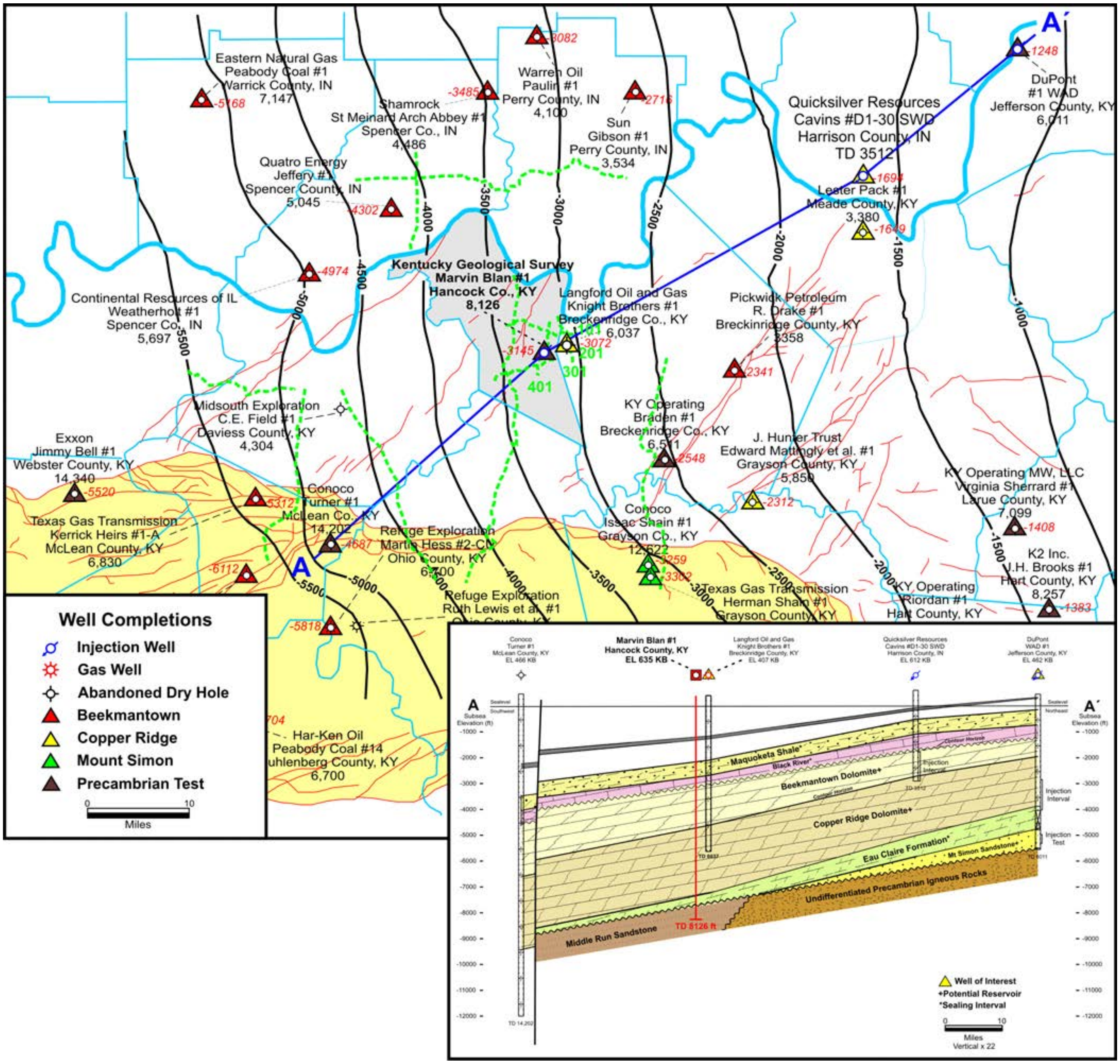


Figure 6. Generalized structure on top of the post-Knox unconformity, with inset structural correlation cross section A-A′. Vertical exaggeration in the cross section is approximately 20 X. The Gunter was too thin to show on the cross section. Early uplift of the Cincinnati Arch and consequent erosion of the Knox prior to deposition of the Middle Ordovician strata truncated the Beekmantown to the northeast. Dip on the post-Knox unconformity is approximately 0.5°SW.

CO_2 storage capacity of the Meso- to Neoproterozoic Middle Run were unknown within the region (Drahovzal and Harris, 2004) (Fig. 3), and thus the Middle Run was also evaluated in the Marvin Blan No. 1. Consequently, the Knox became the primary storage reservoir target for evaluation in the Marvin Blan No. 1.

Knox Group CO_2 Storage Reservoir

Knox dolomites became the primary reservoir test objective in the Marvin Blan No. 1 well, where as many as five intervals with suitable reservoir properties were anticipated. Details of the Knox reservoirs in the Marvin Blan No. 1 are discussed

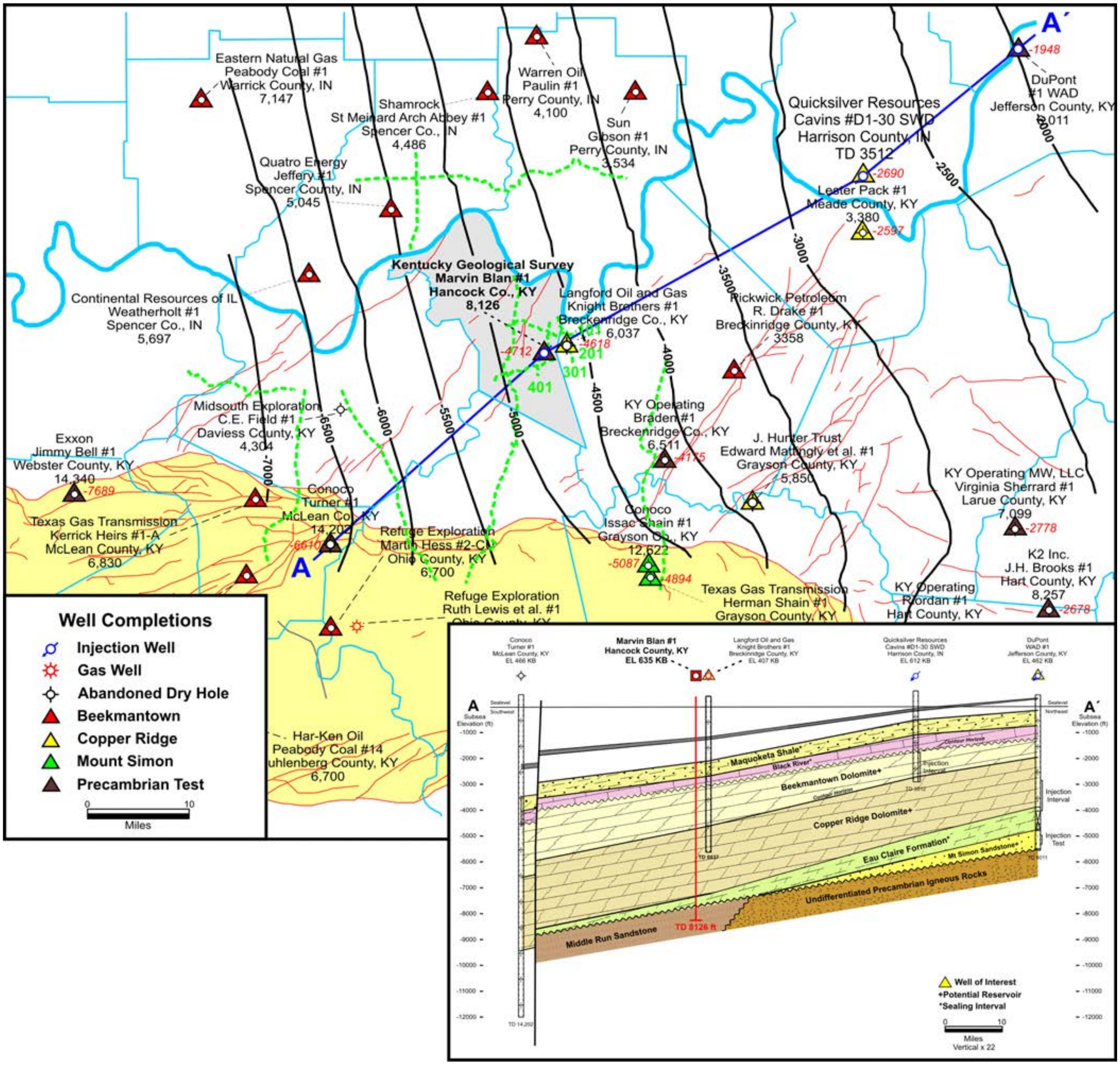


Figure 7. Generalized structure on top of the Copper Ridge, with inset structural cross section A-A′. Vertical exaggeration in the cross section is approximately 20 X. Dip at the top of the Copper Ridge is 1°SW. Thinning of the Copper Ridge as it approaches the Cincinnati Arch suggests that uplift of the Cincinnati Arch may have commenced as early as the Late Cambrian. The thin Eau Claire section in the Marvin Blan No. 1 well and pinchout of the Mount Simon northeast of the Knight Brothers No. 1 well suggests pre-Knox uplift in the Hancock County region.

below. Injection into the Knox dolomites has been demonstrated in Kentucky in three waste-acid disposal EPA UIC Class I injection wells: DuPont No. 1 WAD and No. 2 WAD in Jefferson County, and IMCO Recycling No. 1 International Metal in Butler County (Fig. 1). An old well, Sohio Petroleum Co. Latonia Refinery Caustic Disposal No. 1, drilled in Kenton County in 1947, injected petroleum refinery effluent into 605 ft of commingled Black River–Knox (Fig. 1). UIC Class I injection wells developed in the Knox Group have been permitted in Illinois and Ohio (U.S. Environmental Protection Agency, 2009) (Fig. 1). In addition, the Knox Group is used for the disposal of oil-field brines and utility natural-gas storage (discussed below). The Knox dolomites are not homogeneous, however, and reservoir zones tend to be thin and widely distributed throughout the Knox interval (Harris, 2007), although porous intervals within the Knox can generally be correlated from the Cincinnati Arch southwesterly to the Rough Creek Graben (Bowersox and Williams, 2008b).

Porosity distribution from electric-log analysis of the No. 1 WAD well averaged 5.5 percent (Bowersox and Williams, 2008b). Because of erosional truncation, only the lower Beekmantown was preserved in the DuPont No. 1 WAD well and the most porous intervals in the lower Beekmantown and lower Copper Ridge. In the DuPont No. 1 WAD well, the most permeable interval proved to be in the lower Copper Ridge section, and this interval was completed for injection (Bowersox and Williams, 2008b). Dolomitization and porosity and permeability in the Knox appeared to be related to several generations of diagenesis of parent limestones and early-stage dolomites by the flow of late-stage hydrothermal fluids (Pittenger, 2008) (Appendix 3). Karst development associated with the post-Knox unconformity is found in south-central Kentucky (Gooding, 1992), but was not evident in cores farther to the north (Appendix 3). Although an epikarst developed on top of the Knox was observed in the core from the Marvin Blan No. 1, no evidence of karstification was encountered in the Marvin Blan No. 1. Undisturbed bedding and a lack of any collapse breccias in the 4-in. core does not preclude karstification away from the wellbore, however.

The unconformity at the top of the Knox Group truncates the Beekmantown east of Hancock County (Bowersox and Williams, 2008b) (Fig. 6). This suggests uplift during the Early Ordovician, and the development of about 1° of southwesterly dip at the top of the Copper Ridge in western Kentucky (Fig. 7). In the DuPont No. 1 WAD well, the Knox is only 2,796 ft thick, whereas in the KII Inc. J.H. Brooks No. 1 well, Hart County, 55 mi southeast of the Marvin Blan No. 1 well, 3,624 ft of Knox is present. In the Braden No. 1 well to the southeast of the Marvin Blan No. 1 (Fig. 4), about 800 ft of the Copper Ridge section is cut out by a normal fault at 5,092 ft, leaving a total Knox section of only 2,768 ft. The Knight Brothers No. 1 well penetrated 2,306 ft of Knox and reached total depth approximately midway through the Copper Ridge (Bowersox and Williams, 2008b). Thus, approximately 4,000 ft of Knox was expected to be penetrated by the Marvin Blan No. 1, and a 3,617-ft section was found in the well.

Summary of Knox Lithology

Photographs of thin sections, petrographic descriptions, and interpretations of sample plugs from cores recovered from the Knox in the Marvin Blan No. 1 are in Appendix 4. The Beekmantown was penetrated at 3,780–5,347 ft in the Marvin Blan No. 1 well, a gross interval of 1,567 ft. A total of 172 ft of whole-diameter 4-in. core was cut and recovered from the Beekmantown. Excluding the Gunter, the 1,427-ft net section consists of fabric-preserving primary dolomite and fabric-destructive secondary dolomite, vug-filling saddle dolomite, vug-lining chert, chert nodules and fracture fills, and nodular to disseminated pyrite. Primary sedimentary structures observed in Beekmantown cores suggest deposition in supratidal to shallow-subtidal carbonate-platform environments with many episodes of transgression and regression. Epikarsts observed in cores at the Knox unconformity and within the Beekmantown demonstrate episodic subaerial exposure and weathering during its history. No structures indicative of karst development were observed in the Beekmantown cores. Minor stylotization was observed in these cores. Salinity of formation-water samples recovered from the Knox in the Marvin Blan No. 1 well fall along the general trend of increasing water salinity with depth for Knox reservoirs in Kentucky (Takacs and others, 2009). Analysis of a water sample recovered from the top of the Beekmantown at 3,800–3,823 ft yielded 56,776 ppm of total dissolved solids, almost entirely sodium chloride, with 3,070 ppm calcium, 739 ppm magnesium, 1,573 ppm sulfate and dissolved sulfur, and minor to trace amounts of other ions.

The Gunter was penetrated at 5,090–5,230 ft, interbedded with the Beekmantown, lying 117 ft above the Beekmantown–Copper Ridge contact. It is composed of fine-grained, well-rounded quartz sand in a dolomite matrix interbedded with thin dolomites. Sandstone comprises a net 90 ft, or 64 percent of the 140-ft section. Whole-diameter 4-in.

core cut and recovered from the uppermost 32 ft of the Gunter showed the mixed lithology of this formation (discussed below). Planar bedding and herringbone crossbeds were observed in the sand beds, indicative of beach and shallow-nearshore deposition. Dolomite interbeds were characterized by vuggy porosity developed in fabric-destructive dolomites, solution-enhanced fractures, and pervasive styolites. Consequently, two primary porosity systems are developed in the Gunter sandstone facies versus dolomite facies: intergranular porosity in the sandstones, averaging 11.5 percent, and the dolomite complex, averaging 3.5 percent porosity. Analysis of a formation-water sample recovered from the upper Gunter at 5,120–5,144 ft yielded 97,192 ppm of TDS, nearly all sodium chloride, with 5,440 ppm calcium, 1,250 ppm magnesium, 2,950 ppm sulfate and dissolved sulfur, and minor to trace amounts of other ions.

The Copper Ridge was penetrated at 5,347–7,397 ft, a gross interval of 2,050 ft. It overlies the thin, 187-ft section of Eau Claire Formation encountered in the Marvin Blan No. 1 (Fig. 7). Sedimentary structures observed in the core recovered from 6,130–6,149 ft included solution-collapse breccias with coarsely crystalline anhydrite nodules filling vugs lined with saddle dolomite, a preserved layer of ooid dolograinstone, microbial mats, stromatolites, edgewise conglomerate, fabric-preserved burrows, and dolomitized fabrics characteristic of sabkha environments. Borehole rugosity in the interval from 7,126–7,392 ft suggests intense fracturing at the base of the Copper Ridge. Sparse hydrocarbon shows of dead oil were observed in cuttings from the basal Copper Ridge. Interpretation of the CMI log suggests that the porosity system in the Copper Ridge consists of intercrystalline matrix porosity enhanced by vugs and open fractures. An attempt to collect a formation-water sample from the Copper Ridge was unsuccessful.

Knox Porosity Systems

The Knox porosity system is a complex of (1) matrix porosity, vugs, fractures and solution-enhanced fractures, and relict primary porosity associated with stromatolites in the dolomite sections (Figs. 8A–D, 9A), (2) siliceous fabrics of microporous chert and moldic and interparticle pores associated with silicified peloidal grainstones observed in thin sections (Appendix 4), and (3) intergranular porosity in Gunter sandstone facies (Fig. 9B). Features on the CMI log appearing to be vugs were not found to necessarily be representative of vugs when compared to cores, however (Fig. 10). Calculating porosity in the Knox is somewhat problematic. The Knox lithology is heterogeneous and the dolomites comprising 96 percent of the section contain varying amounts of siliciclastic detritus and chert, anhydrite, authigenic feldspars and pyrite, and fracture fillings of mixed mineralogies. The borehole has substantial rugosity through most of the Knox section, particularly the Beekmantown and basal Copper Ridge, and the Weatherford Photo-Density tool appears to be sensitive to borehole diameters greater than 10.5 in., and formation bulk density recorded through rugose wellbore sections is incorrectly low. Correlation of porosity measured in the Knox cores and porosities calculated from the density log could not be demonstrated (Fig. 11). Grain densities measured in cores fall into three classes: grain densities of 2.64 to 2.66 g/cm^3 in Gunter sandstone intervals; about one-third of dolomite plugs in intervals with appreciable silica content have grain densities of 2.70 to 2.80 g/cm^3, and about two-third of dolomite plugs have grain densities of 2.81 to 2.85 g/cm^3 (Fig. 12). For the purposes of this report, porosity in the Beekmantown, Gunter dolomitic intervals, and Copper Ridge was calculated from the density-log data using an average matrix density of 2.84 g/cm^3, the mode of the measured grain densities and the highest recorded bulk density recorded in the Beekmantown dolomites, and a matrix density of 2.66 g/cm^3 for the Gunter sandstone intervals. Grain densities measured from core plugs and calculated from X-ray diffraction mineralogy analysis correspond to within approximately 1 percent. Matrix-interval transit time used to calculate Knox porosity in this report was determined from frequency analysis of sonic data using the histogram module in Petra. The matrix-interval travel times thus determined were 43.5 μs/ft for Beekmantown, Gunter, and Copper Ridge dolomite facies and 55.5 μs/ft for Gunter sandstone facies. Measured formation-fluid density used to calculate porosity was 1.05 g/cm^3, and interval transit time used was 188 μs/ft for water of 97,000 ppm sodium chloride at 100°F (Gearhart-Owen Industries Inc., 1976).

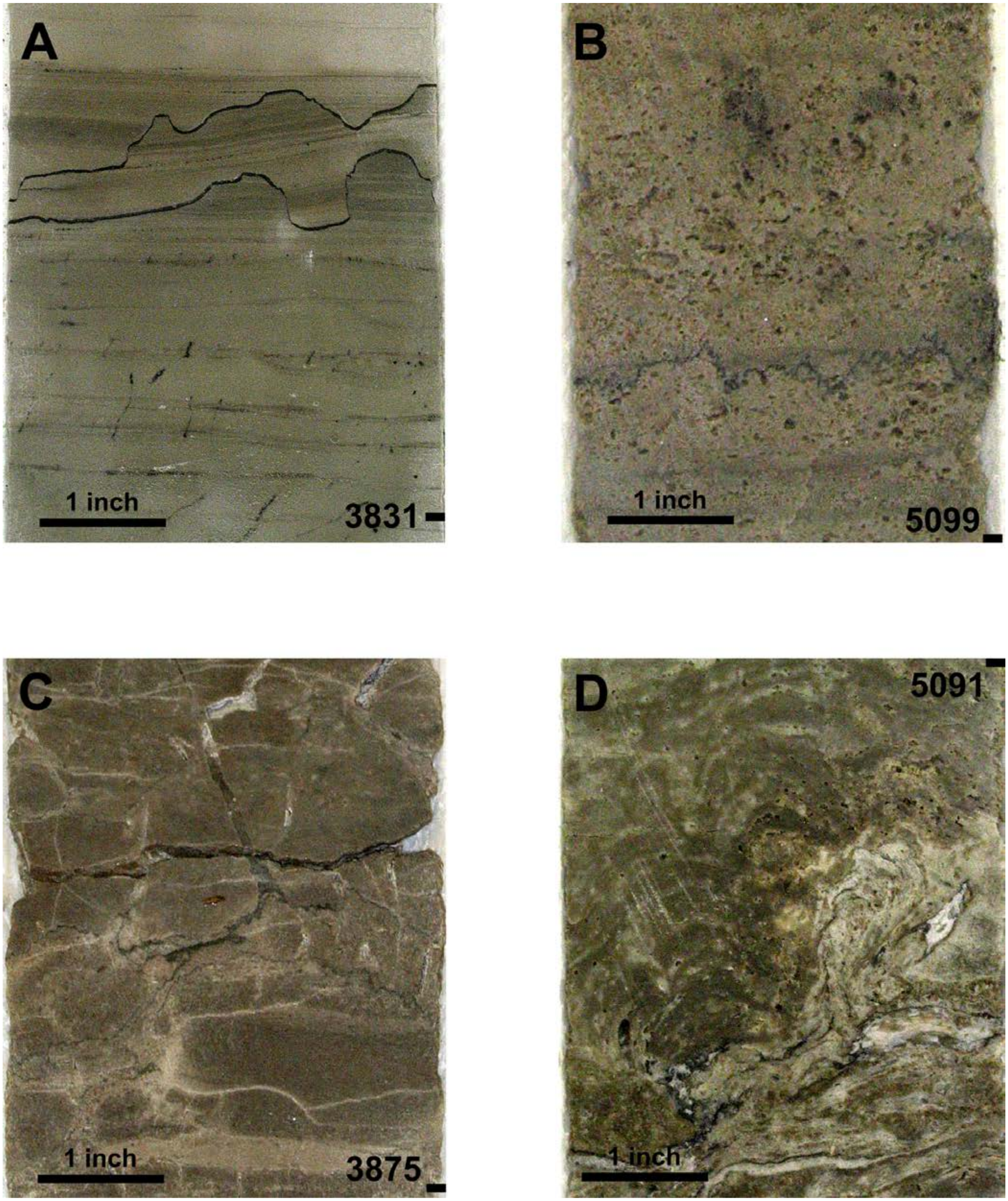


Figure 8. Typical dolomite-facies reservoir fabrics in the Beekmantown. (A) Intercrystalline porosity in relict microbial mat facies with an inverted, styolitized rip-up clast, 3,830.5–3,831.0 ft. (B) Styolitized vugular porosity developed in lagoonal facies, 5,098.5–5,099.0 ft. (C) Shoreface collapse breccia with solution-enhanced fractures, 3,874.5–3,875.0 ft. (D) Vugular porosity developed in a preserved stromatolite, 5,091.0–5,091.5 ft.

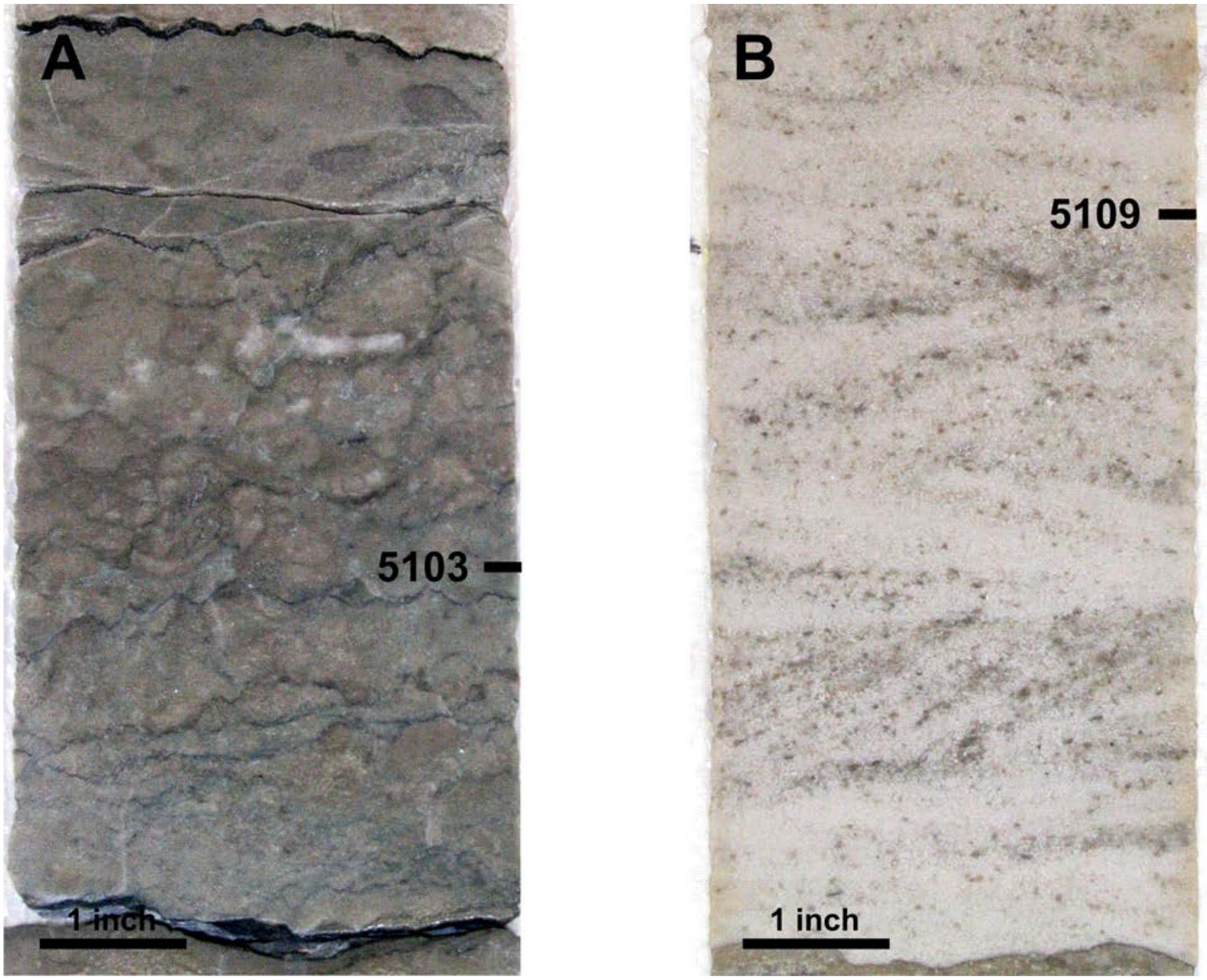


Figure 9. Facies developed in the Gunter. (A) A complex of heavily styolitized, pervasively bioturbated collapse breccia in a Gunter dolomite lagoonal facies. Gunter dolomite facies are generally low porosity (less than 4 percent porosity). (B) Herringbone crossbeds indicative of beach and intertidal deposition in a Gunter sand facies. Sand facies are high porosity, averaging 8.7 percent.

Density and sonic porosity of the Beekmantown and Copper Ridge were calculated using the equation expression module in Petra (ver. 3.2.6.0):

density porosity (percent):

$$\varphi_d = ((\rho_{ma} - \rho_b) / (\rho_{ma} - \rho_r)) \times 100 \qquad (1)$$

where ρ_{ma} is the formation matrix or grain density, ρ_b is the formation bulk density recorded by the density log, and ρ_r is the formation fluid density;

sonic porosity (percent):

$$\varphi_s = ((\delta t_{log} - \delta t_m) / (\delta t_f - \delta t_m)) \times 100 \qquad (2)$$

(the Wylie time-average equation) where δt_{log} is the interval transit time recorded by the sonic log, δt_m is the interval transit time of the formation matrix, and δt_f is the interval transit time of the formation water. Gunter porosity, because of the mixed sandstone-dolomite lithology, was calculated in a Quattro Pro X4 spreadsheet using logic tests to differentiate lithologies. The three porosity files thus created were then merged into a single file using the splice curves module in Petra. For this evaluation, density porosity was substituted for all porosity terms unless noted. Average porosity of the Beekmantown, Gunter, Copper Ridge was calculated in the histogram module of Petra (Figs. 13A–D, Table 3) for total porosity and at cutoffs of 5 to 10 percent porosity, and summed to yield the Knox porosity in toto. Porosity values at depths with a corresponding borehole caliper of greater than a 10.5-in. cutoff were excluded to mitigate the effects of borehole rugosity overstating porosity; thus, porosity and net intervals are conservatively estimated. Average porosity calculated from the density log of the entire Knox section above the basal fractured interval, and excluding intervals with borehole diameter greater than 10.5 in., was 6.3 percent (Fig. 13D, Table 3). Total reservoir pore volume was estimated to be 216 porosity-ft (Table 3, Fig. 14A). Assuming a 5-percent porosity cutoff, reservoir pore volume in the borehole is 172 porosity-ft (Fig. 14A), of which 50 percent lies within the upper 1,600 ft of the Knox (Fig. 14B), from the top of the Knox to just below the top of the Copper Ridge.

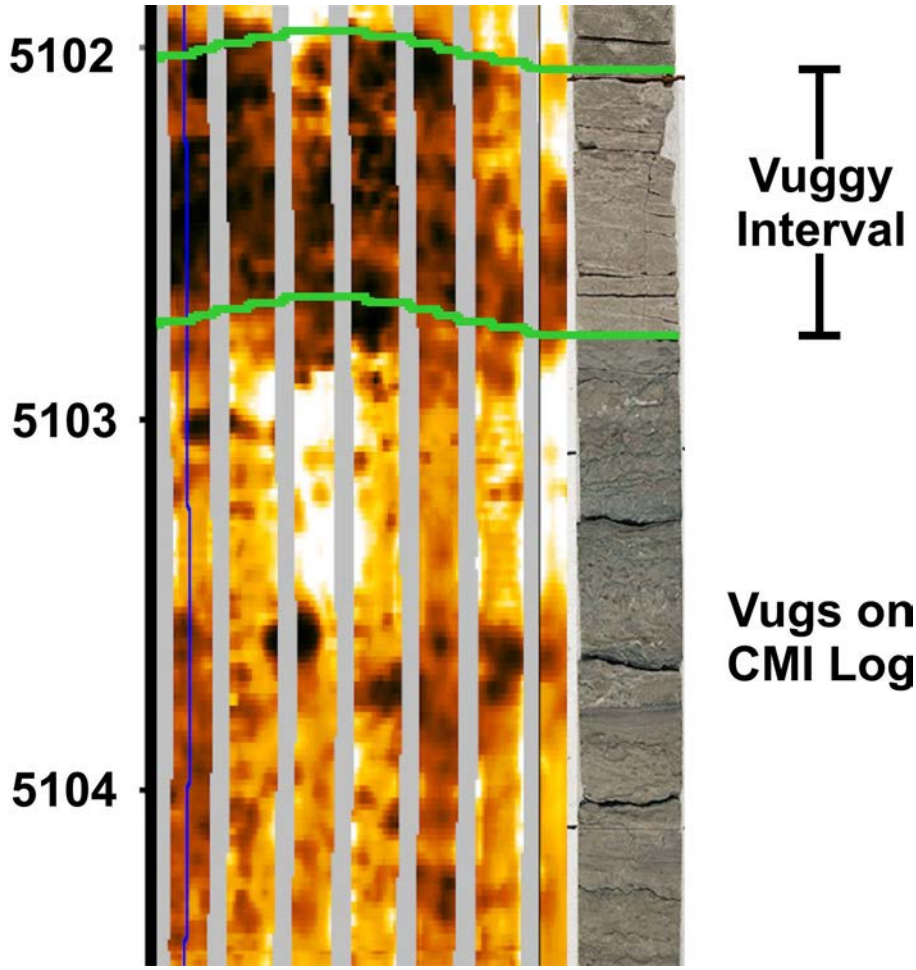


Figure 10. Comparison of the processed CMI log and core from the interval 5,101.9–5,104.4 ft demonstrating the unreliability of the CMI log as an indicator of vugular porosity. Vugs appear as patches darker than the background color. A core slab with vugs corresponding to the CMI log is noted at 5,201.0–5,202.8 ft. The interval 5,102.8–5,104.4 ft appears vuggy on the CMI log, although no vugs are present in the corresponding cored interval.

Evaluation of Fracture and Vugular Porosity

The 271-ft fractured interval in the Copper Ridge below 7,126 ft was evaluated in the histogram module in Petra using a corresponding 10.5-in. borehole-caliper cutoff to mitigate the effects of borehole rugosity overstating porosity in washed-out sections. This interval includes 115 net ft of lower-porosity, largely nonreservoir, unfractured strata with porosity less than 7 percent, and 47 net ft of higher-porosity, fractured strata of more than 7 percent porosity (Fig. 15, Table 4). The lower-porosity strata averaged 4.1 percent porosity with a mode of 3.9 percent, and had a total pore volume of 5 porosity-ft. The higher-porosity strata averaged 11.7 percent with a mode of 8.7 percent. The balance of the interval, 39 net ft of washed-out, fractured strata, was assumed to have properties similar to the higher-porosity strata. Thus, total fracture volume of the higher-porosity strata was estimated to be 10 porosity-ft. The total pore and fracture volume of the basal Copper Ridge section below 7,126 ft was estimated to be 15 porosity-ft.

Bimodal distribution of porosity in the Beekmantown and Copper Ridge, with modal peaks at approximately 6 percent and 13.5 percent (Figs. 13A–C), suggests a porosity system in the dolomites consisting of primary intercrystalline porosity at the lower modal peak and a minor contribution of secondary vugular and fracture porosity at the higher peak. There appears to be a similar, though weaker, bimodal porosity distribution in the Gunter, with an intergranular porosity mode at approximately 8 percent, and a secondary porosity mode, likely the result of vugs in dolomite intervals, at 13.5 percent porosity (Fig. 13B). In order to approximate the contributions of these higher-porosity intervals, the less-fractured interval above 7,126 ft was evaluated separately from the heavily-fractured basal Knox interval below 7,126 ft

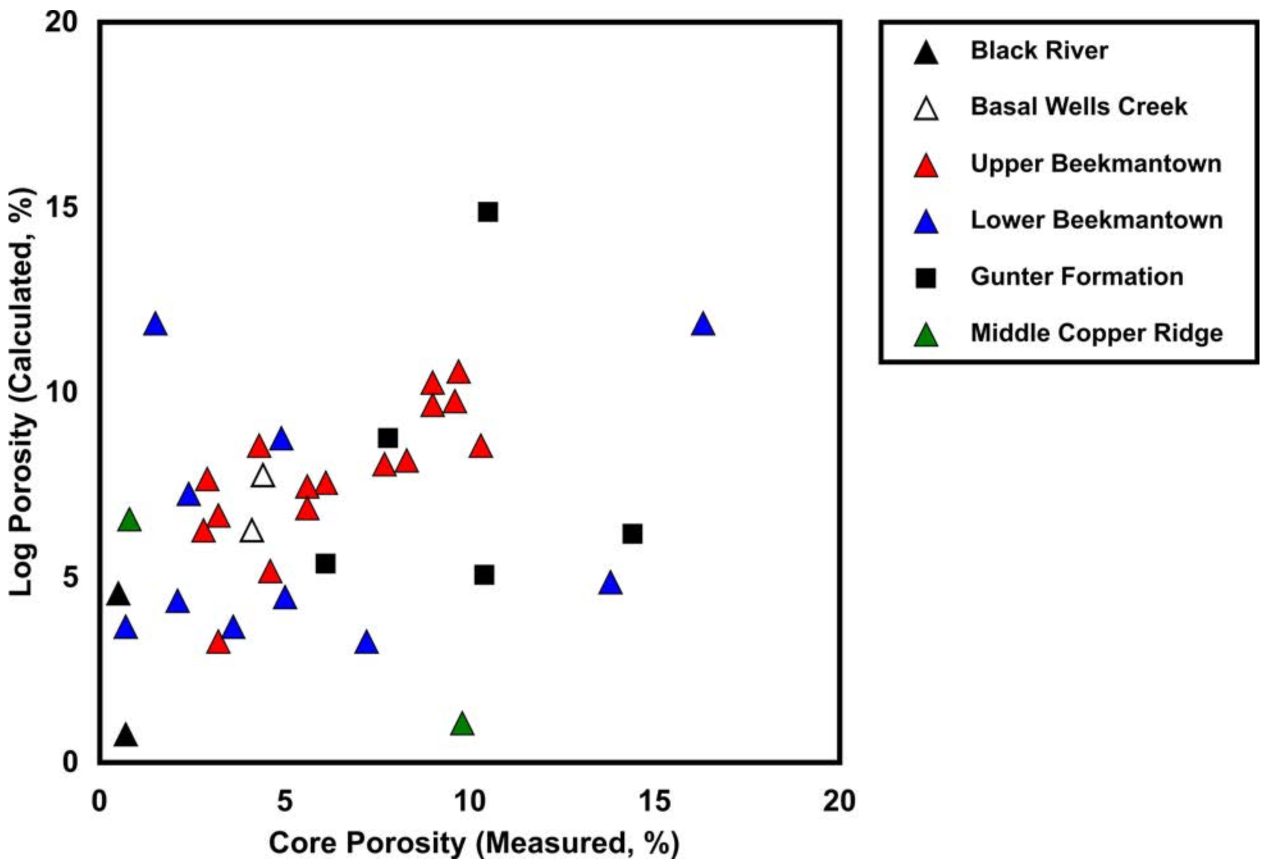


Figure 11. Comparison of porosity calculated from the compensated-density log compared to porosity measured in core plugs from all carbonate intervals. Although there appears to be a general trend that suggests a correlation between calculated and measured porosities, with calculated porosities approximately 3.5 percent higher than measured porosities, no relationship could be statistically demonstrated.

(discussed above). Evaluation was performed in Petra's histogram module using the corresponding 10.5-in. wellbore-diameter cutoff to exclude rugose intervals. The contributions of the low- and high-porosity intervals to the total Knox porosity above 7,126 ft were calculated at a 12-percent porosity cutoff to differentiate the intervals. The lower-porosity intervals have a mode of 4.6 percent and average 6.0 percent. Total pore volume of the low-porosity intervals was 190 porosity-ft, or 89.5 percent of the total Knox volume. The intervals with porosity greater than 12 percent have a mode of 13.2 percent and average 14.0 percent. Total pore volume of the high-porosity intervals is 20 porosity-ft, or 10.5 percent of the total Knox volume. Regional deep wells showing this dual porosity distribution are noted on Figure 16. These wells appear in a trend extending from the WAD No. 1 well, Jefferson County, to the Exxon Jimmy Bell No. 1, Webster County. Weaker expressions of dual porosity are present in wells in Grayson County to the south and Warrick, Spencer, and Perry Counties, Ind., to the north (Fig. 16).

Effects of Compaction on Knox Porosity

In carbonates, the density log records total porosity with components of intercrystalline matrix and vugular and fracture porosity, whereas the sonic log records intercrystalline matrix porosity. Thus, porosity calculated from the sonic log will be too low in vuggy or fractured carbonates (Asquith and Gibson, 1982). This difference in log response allows the relative effect of compaction on the components of the total porosity to be determined. To test the effect of compaction on Knox porosity, a data subset was created from density- and sonic-log data sampled in 10-ft increments from the top of the Black River to the base of the Copper Ridge, including rugose intervals, a total of 428 samples each (Figs. 17A–B). Compaction in this dominantly

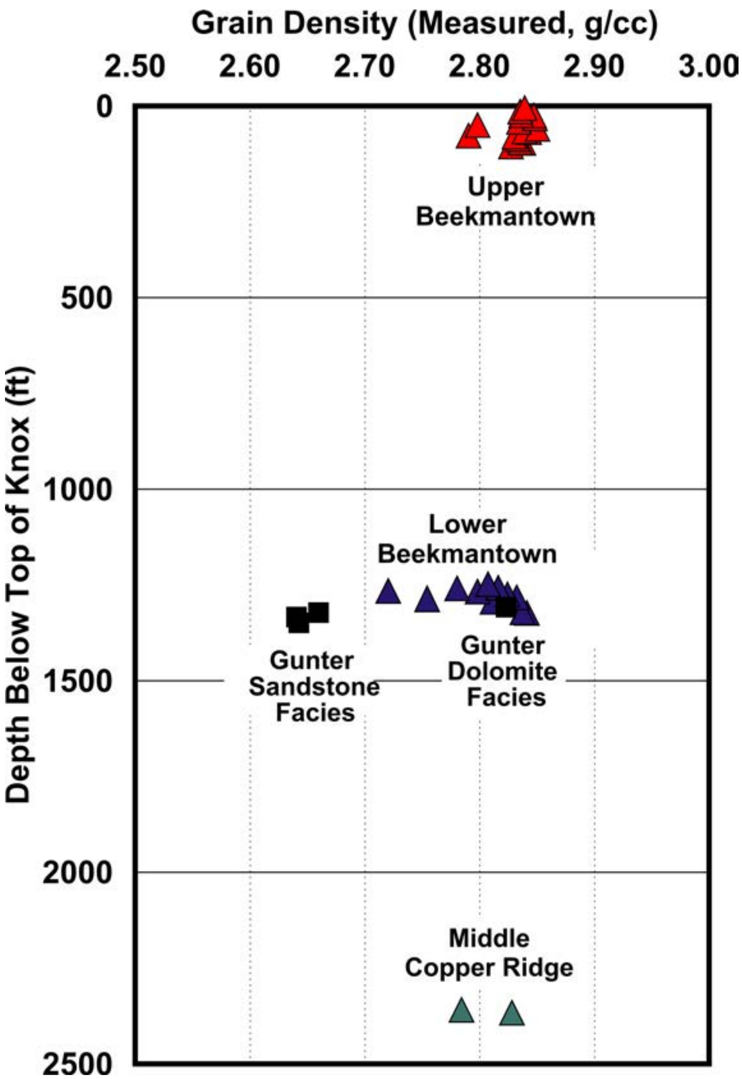


Figure 12. Grain density measured in core plugs from the Knox plotted at their stratigraphic depths below the top of the Knox. Grain densities measured in carbonate facies were above 2.70 g/cm^3, and dolomite facies greater than 2.80 g/cm^3, whereas sandstone facies in the Gunter were all below 2.70 g/cm^3.

carbonate section increases formation density by 0.034 g/cm^3 per 1,000 ft of depth below the top of the Black River ($r^2 = 0.125$, $p < 0.0001$) (Fig. 17A) and reduces interval transit time of the sonic log by 1.58 μs/ft per 1,000 ft of depth ($r^2 = 0.295$, $p < 0.0001$) (Fig. 17B).

Differential porosity is calculated by subtracting the sonic porosity from the density porosity. The effect of compaction on porosity in the Knox was estimated by calculating porosity from the reduced sets of density and sonic data (Fig. 18A):

differential porosity (percent):

$$\varphi' = \varphi_d - \varphi_s. \quad (3)$$

Average porosity calculated in the Knox from the sonic log is 1.6 percent lower than that calculated from the density log (intercept of the regression line in Figure 18A). The differential porosity in the Knox increases at a rate of 1.02 percent per 1,000 ft of depth below the top of the Knox ($r^2 = 0.0645$, $p < 0.0001$) (Fig. 18A), indicating that the sonic porosity was decreasing from compaction more than the density porosity. That is, the rate of matrix porosity decrease from compaction through the Knox is greater than that of the total porosity. This suggests that the relative contribution of vugular and fracture porosity to the total Knox porosity in the Marvin Blan No. 1 is greater than that of the matrix, intercrystalline porosity.

Differential porosity was detrended in the transform module in PAST (ver. 1.94b) to better explore the vugular and fracture porosity versus the matrix contribution to total porosity (Fig. 18B). Vugular porosity is predominant in the Beekmantown, and fracture porosity is evident in the Copper Ridge as positive spikes; however, matrix porosity dominates in the Copper Ridge (Fig. 18B). Intergranular porosity in the Gunter appears similar to vugular porosity (Fig. 18B). Compaction-reducing matrix porosity was seen as an increasingly negative trend in the detrended data below about 2,100 ft below the top of the Knox (about 5,900-ft drill depth) (Fig. 18B), approximately coincident with the deepest effective depth of injection in the Marvin Blan No. 1 (Appendix 4).

Knox Fracture System

A well-developed fracture system was interpreted from 105 fractures identified in the CMI log by the Weatherford analyst. Fractures primarily trend N70°W and dip 63°SW (Fig. 19A). Few fractures were identified in the Beekmantown (16 fractures) and Gunter (12 fractures) (Fig. 19B). Beekmantown fractures were found in the upper third and lower third of the section. Most of the 77 fractures identified in the Copper Ridge were found in the lower 1,300 ft of section below 6,100 ft (61 fractures) (Fig. 19B) and generally dipping to northern quadrants (Fig. 19C). Four times as many

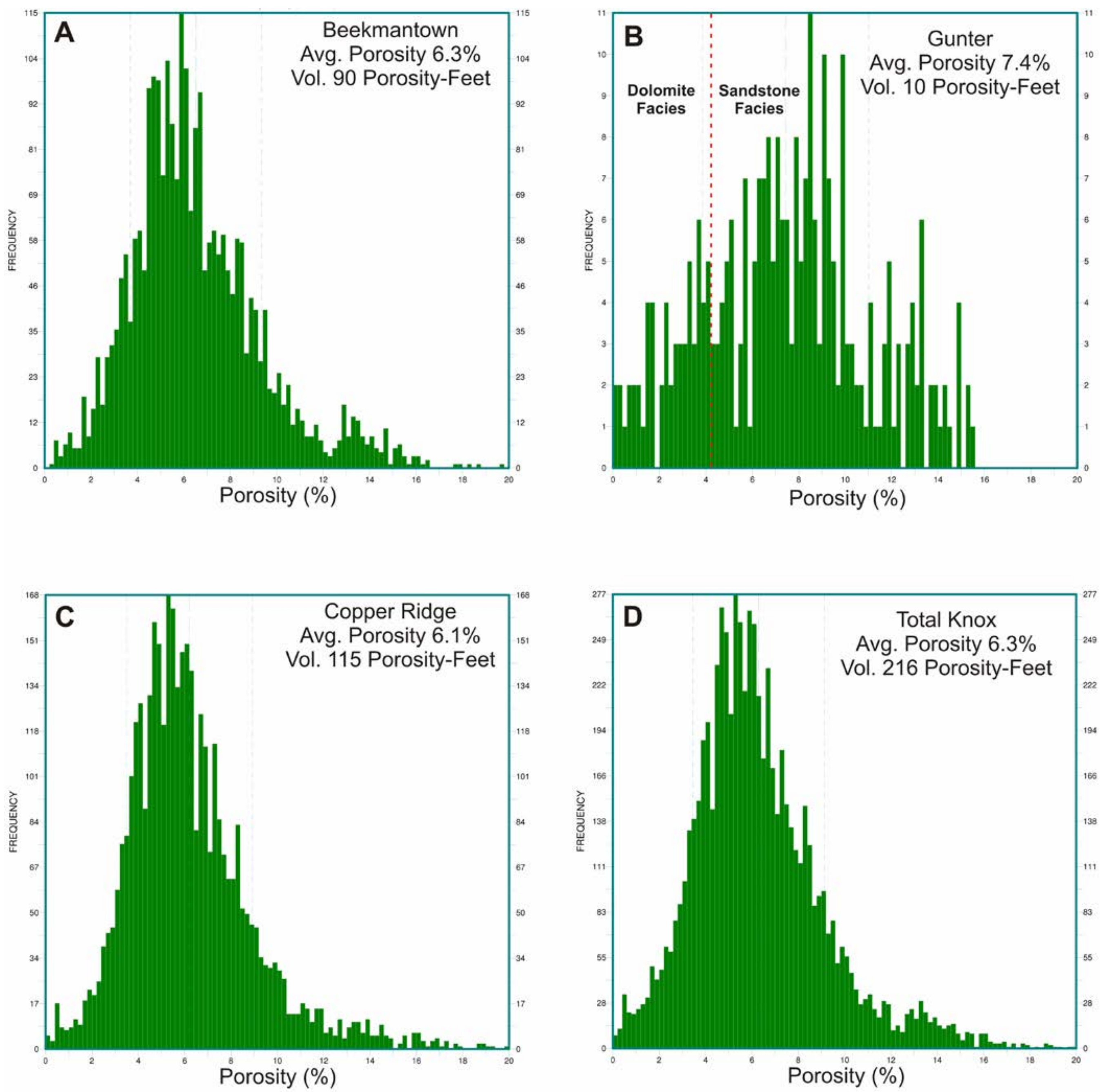


Figure 13. Porosity in the Knox calculated from the compensated-density log as described in the text. Porosity is positively skewed from the contributions of fractures and vugs to the total porosity. (A) Bimodal distribution of porosity is apparent in the Beekmantown. Fracture/vugular porosity contribution to total Beekmantown porosity is apparent in the modal peak at approximately 13.5 percent porosity. (B) Porosity of dolomite and sandstone facies in the Gunter are delineated at approximately 4.2 percent. A weak expression of fracture/vugular porosity is present above 11 percent porosity. (C) Porosity in the Copper Ridge is strongly positively skewed from the contribution of fractures near the base of the formation. Bimodal distribution is suggested at 13–15 percent porosity. (D) Total porosity in the Knox is normally distributed below 13 percent, and the second modal interval at porosities greater than 13 percent is positively skewed.

Table 3. Pore volume of the Knox calculated from the compensated-density log. Pore volumes at cutoffs were calculated from the histogram module in Petra version 3.2.6.0. Potential sealing intervals (intervals less than 2 percent porosity) are sparse within the Knox.

Porosity Cutoff (%)	Beekmantown			Gunter		
	Porosity (%)	Net Interval (ft)	Porosity-Feet	Porosity (%)	Net Interval (ft)	Porosity-Feet
None	6.3	1,413	90	7.4	141	10
> 5	7.9	925	73	9.1	103	9
> 6	8.5	687	58	9.4	94	9
> 7	9.3	480	45	10.0	78	8
> 8	10.6	233	25	10.7	63	7
> 9	11.4	214	24	11.4	47	5
> 10	12.5	138	17	12.5	31	4
Seal < 2	1.3	51	–	1.1	10	–

Porosity Cutoff (%)	Copper Ridge			Total Knox		
	Porosity (%)	Net Interval (ft)	Porosity-Feet	Porosity (%)	Net Interval (ft)	Porosity-Feet
None	6.1	1,893	115	6.3	3,446	216
> 5	7.4	1,218	90	7.7	2,246	172
> 6	8.3	852	71	8.5	1,633	138
> 7	9.5	634	60	9.5	1,192	113
> 8	10.3	527	54	10.4	823	86
> 9	11.7	272	32	11.5	532	61
> 10	12.7	182	23	12.6	350	44
Seal < 2	1.2	54	–	1.3	115	–

fractures were identified in the lower 1,300 ft of the Copper Ridge (Fig. 19D), as in the 1,310-ft section of the Beekmantown, consistent with evaluation of the porosity logs (Fig. 20).

Horizontal Versus Vertical Porosity in the Knox

Horizontal porosity within the Knox reservoirs was measured in cores from the upper Beekmantown (15 plugs), lower Beekmantown (10 plugs), Gunter (five plugs), and Copper Ridge (two plugs) (Fig. 21A, Appendix 2). Vertical porosity was measured in six plugs from the upper Beekmantown, two from the lower Beekmantown, two from the Gunter, and one from the middle Copper Ridge (Table 5, Fig. 21B). There is a corresponding trend of decreasing porosity measured in core plugs from the Beekmantown and Gunter dolomites with increasing depth (Fig. 21A), although too few plugs were analyzed from the Copper Ridge to make a similar conclusion. Porosity averages 6.1 percent in plugs from the top of the Beekmantown, whereas the lower Beekmantown-Gunter plugs average 3.8 percent porosity, a decrease of 2.3 percent over the 1,235-ft interval, or a decrease of 1.86 percent porosity per 1,000 ft of depth. Vertical porosity was measured in too few plugs to make a definitive determination of the effect of compaction, although there appears to be a trend of decreasing vertical porosity from the upper Beekmantown to the middle Copper Ridge (Fig. 21B). Vertical porosity describes reservoir homogeneity and affects pressure isolation between injection intervals and the potential for leakage from the Knox CO_2 storage reservoir. Vertical porosity was compared with horizontal porosity for all Knox plugs and plugs from the Black River and the basal Wells Creek (Fig. 22). Vertical porosity shows significant correlation with horizontal porosity ($r^2 = 0.92$, $p < 0.0001$) (Fig. 22). Average vertical porosity measured in those plugs was approximately 0.8 percent higher than the average horizontal porosity ($\varphi_v = 0.96\varphi_h + 0.91$) (Table 5, Fig. 22). This demonstrates a homogeneous Knox reservoir, thus requiring mechanical isola-

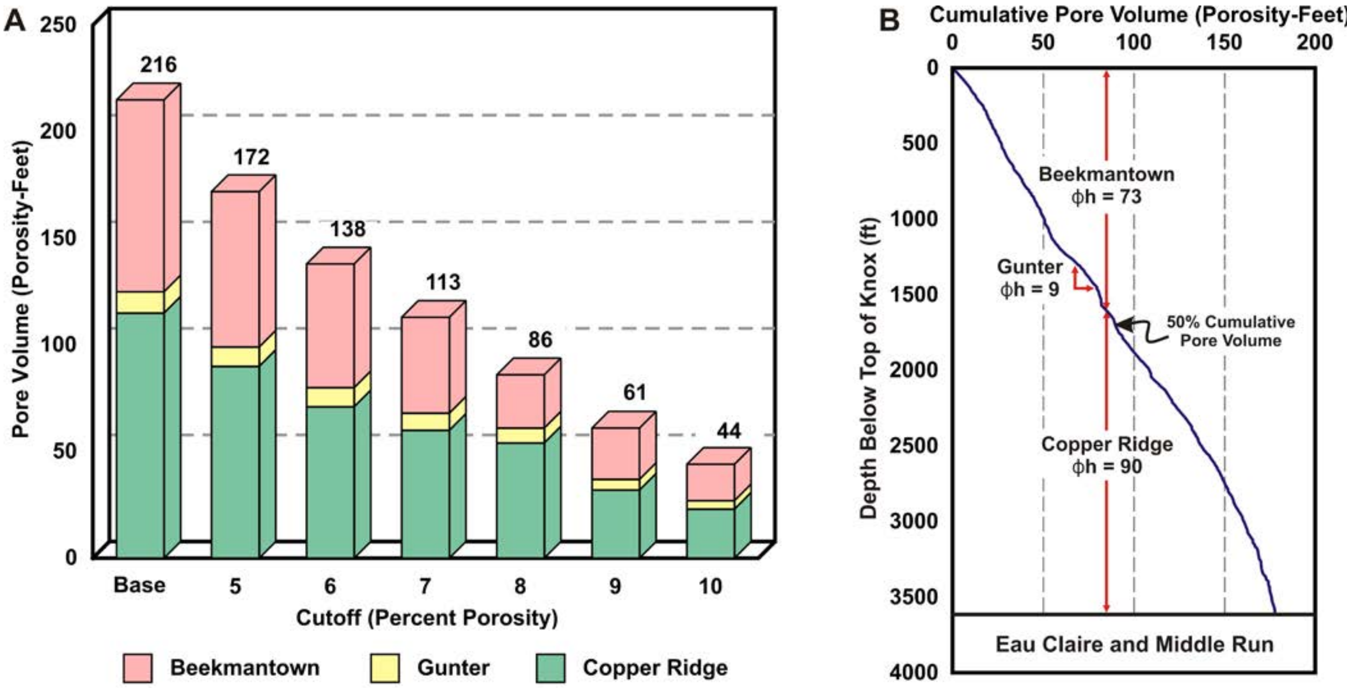


Figure 14. Knox pore volume (φh) in the Marvin Blan No. 1 well. (A) Pore volume in the Knox showing contributions of the three stratigraphic intervals penetrated by the well. Pore volume was calculated at different porosity cutoffs ranging from a base case that includes all porous strata to a very conservative case that includes only intervals with porosity greater than 10 percent. A 5-percent porosity cutoff was used in this study to estimate possible CO_2 storage capacity of the Marvin Blan No. 1 well. (B) Cumulative pore volume profile for the Knox section in the Marvin Blan No. 1 well. About 47 percent of the pore volume in the Marvin Blan No. 1 well was found in the Beekmantown-Gunter section and 53 percent in the Copper Ridge. Almost two-third of the pore volume encountered in the well is in the uppermost 2,000 ft of the section, in the interval above the deepest effective depth for CO_2 injection.

tion of injection intervals and competent seals to ensure long-term CO_2 storage.

Permeability of Knox Reservoirs

Horizontal permeability to air within the Knox reservoirs was measured in cores from the upper Beekmantown (15 plugs), lower Beekmantown (10 plugs), Gunter (five plugs), and Copper Ridge (two plugs) (Fig. 23A, Appendix 2). Permeability was also calculated from pressure buildup/falloff as part of injection testing (Appendix 5). Core permeabilities range from 0.0003 md in a sample from the upper Beekmantown to 206 md in a vuggy dolomite-facies sample from the Gunter (Fig. 23A). In general, strata with permeabilities less than 0.001 md are necessary for reservoir seals (discussed below). Knox Dolomite reservoirs have horizontal permeabilities to air between 0.001 md and 10 md, and Gunter plugs have horizontal permeabilities to air greater than 10 md (Fig. 23A). Permeability within the Knox calculated from pressure data collected during the injection testing program (Appendix 5) is summarized in Table 6. Calculated permeabilities range from 1.8 md in the basal Copper Ridge (test 1) to 36.8 md in the open wellbore below casing (test 4). All permeabilities calculated from pressure testing fall within the range of those measured in core plugs (Fig. 23A).

Vertical permeabilities to air measured in a limited number of plugs adjacent to the horizontal plugs fall within the range of horizontal permeabilities to air (Fig. 23B, Appendix 2). Vertical permeability to air for all plugs from carbonates, including one sample each from the Black River and basal Wells Creek, and from the Gunter sandstone facies, was plotted against horizontal permeability to air (Fig. 24). Vertical permeability in the section from the Black River to the middle Copper Ridge shows significant correlation with horizontal permeability ($r^2 = 0.91$, $p < 0.0001$), averaging approximately an order of magnitude lower than corresponding

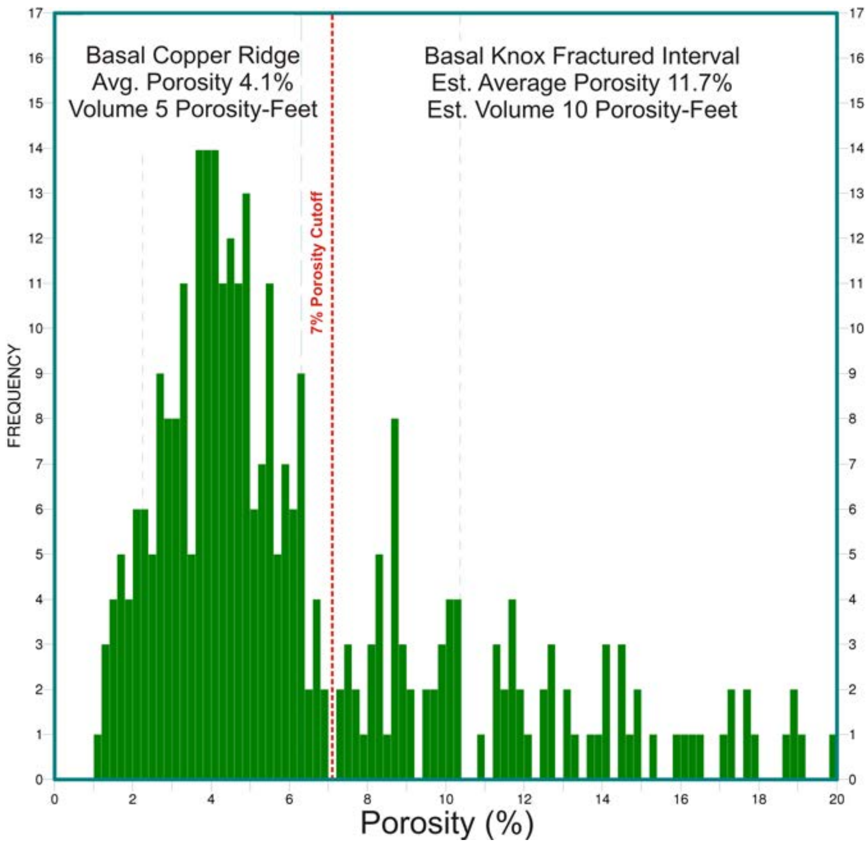


Figure 15. Estimating pore volume of the basal Copper Ridge section below 7,126 ft was problematic because large sections of the borehole showed substantial rugosity. Porosity was calculated from the compensated-density log for sections of the borehole without rugosity, then matrix versus fracture porosity differentiated at a 7-percent porosity cutoff. At a 5-percent porosity cutoff, fracture porosity greater than 7 percent accounts for an estimated 10 porosity-ft of pore volume in the basal Copper Ridge versus 4.1 porosity-ft of matrix pore volume.

horizontal permeability (Table 5, Fig. 24). This suggests a lesser potential for vertical migration of CO_2 from the Knox than that evaluated from vertical porosity measurements. Horizontal permeability was plotted against horizontal porosity for all plugs to evaluate the permeability-porosity relationship in potential reservoir and sealing intervals (Fig. 25). Permeability and porosity show significant correlation in plugs from potential CO_2 storage reservoirs ($r^2 = 0.59$, $p < 0.0001$); however, no correlation could be demonstrated in plugs from potential reservoir seals in the New Albany and Maquoketa Shales. Plugs from the Black River, basal Wells Creek, and middle Copper Ridge show permeability less than 0.001 md, and are sufficiently low to be reservoir seals (discussed below).

Estimated CO_2 Storage Capacity in the Knox

Reservoir pore volume (φh) in the Marvin Blan No. 1 is presented in Figure 14. For the purpose of calculating potential CO_2 storage capacity, these values may be considered as acre-feet for an area of 1 acre ($A = 1$). Estimated reservoir volume in acre-feet (V) is calculated as:

$$V = \varphi h A \tag{4}$$

where density porosity (φ_d) is substituted for total formation porosity (φ). One factor influencing CO_2 storage is its solubility in water, which increases as pressure increases with reservoir depth, and decreases with increasing temperature and formation-water salinity (Finley, 2005). Western Kentucky saline reservoirs are normally pressured at the hydrostatic gradient of 0.433 psi/ft of depth; thus, the CO_2 supercritical point is approximately 2,500 ft below the surface. Average geothermal gradient in western Kentucky reservoirs is about 1°F per 100 ft of depth (Bowersox, 2008); therefore, temperature is not likely to have a material impact on CO_2 storage capacity. Based on the formation-water samples recovered from the Marvin Blan No. 1, water salinity for the section at 5,500 ft is approximately 108,000 ppm. Thus, salinity will have a minimal impact on the solubility of CO_2 in the Knox reservoir in the Marvin Blan No. 1 (*see* Finley, 2005, and sources cited therein).

CO_2 storage capacity considers the efficiency of storage (e), the fraction of the pore space where water can be displaced entirely or filled with water saturated with supercritical CO_2. Estimates of CO_2 storage efficiency vary widely. Van der Meer (1995) estimated CO_2 storage efficiency from 3-D numerical modeling of 1 to 6 percent. Sugihardjo and others (1999) estimated CO_2 storage in carbonate reservoirs in Indonesia at 13.6 to 17.7 percent based on laboratory analysis of CO_2-saturated core plugs. They also found that the reaction of CO_2 with

Table 4. Four cases of Copper Ridge porosity and pore-volume analysis: The entire Copper Ridge section to the top of the basal, rugose interval (5,347–7,126 ft); the upper Copper Ridge section (5,347–6,100 ft); the middle–lower Copper Ridge section (6,100–7,126 ft); and the basal rugose section to the top of the Eau Claire (7,126–7,397 ft). The shaded values are porosity and pore volume in fractured sections separate from the unfractured dolomite sections, differentiated at 7-percent porosity (Fig. 15). Injection into the Copper Ridge will likely require mechanical segregation from the overlying Beekmantown-Gunter section

Porosity Cutoff (%)	Copper Ridge 5,347–7,126 ft			Copper Ridge 5,347–6,100 ft		
	Porosity (%)	Net Interval (ft)	Porosity-Feet	Porosity (%)	Net Interval (ft)	Porosity-Feet
None	6.2	1,778	110	7.1	752	53
> 5	7.4	1,188	88	7.9	586	46
> 6	8.3	840	70	8.6	456	39
> 7	9.2	548	50	9.3	341	32
> 8	10.1	449	45	10.2	236	24
> 9	11.2	212	24	11.2	149	17
> 10	12.3	131	16	12.2	91	11

Porosity Cutoff (%)	Copper Ridge 6,100–7,126 ft			Copper Ridge 7,126–7,397 ft		
	Porosity (%)	Net Interval (ft)	Porosity-Feet	Porosity (%)	Net Interval (ft)	Porosity-Feet
None	5.7	1,016	58	4.1	115	5
> 5	6.9	603	42	5.8	30	2
> 6	7.8	385	30	6.4	12	1
> 7	8.9	208	18	11.7	86	10
> 8	10.1	113	11	12.1	78	9
> 9	11.3	63	7	13.2	60	8
> 10	12.4	40	5	13.8	51	7

the carbonate reservoir rock tended to increase porosity and decrease permeability (Sugihardjo and others, 1999). Qi and others (2007) estimated storage efficiencies of 2.50 to 2.75 percent from 3-D numerical modeling of depleted North Sea oil and gas reservoirs. In contrast to this, Zhou and others (2007) estimated extremely low CO_2 storage efficiencies of 0.25 to 2.9 percent for open systems from pore-compressibility modeling, with a typical formation-scale efficiency of 0.5 percent. Using Monte Carlo simulations including areal and vertical displacement efficiencies and gravity, describing the effect of CO_2 buoyancy on displacement efficiency, and microscopic displacement efficiency related to irreducible water saturation in the pores, Frailey (2008) estimated the CO_2 storage efficiency of saline reservoirs to be 1 to 4 percent.

CO_2 storage capacity versus average depth for western Kentucky reservoirs is presented in Figure 26. At the average Knox reservoir depth in the Marvin Blan No. 1 of 5,588 ft, reservoir pressure is 2,420 psi and measured reservoir temperature is 113°F. The density of supercritical CO_2 under these reservoir conditions is approximately 1,000 tons/acre-foot. In order to simplify the volumetric calculation in this study, a storage efficiency (e) of 5 percent has been assumed, yielding a CO_2 storage capacity of approximately 50 tons/acre-foot (Fig. 26). Apparent CO_2 storage capacity *(S)* in the Marvin Blan No. 1 well is:

$$S = \varphi hAe = 8{,}600 \text{ tons/acre} \qquad (5)$$

where $\varphi hA = 172$ acre-ft at 5 percent porosity cutoff (Fig. 14). Therefore, a CO_2 storage well at the Marvin Blan No. 1 location would require approximately 116 surface acres to store 1 million tons of CO_2. Thus, seven to 10 wells distributed over approximately 3,500 surface acres would be required

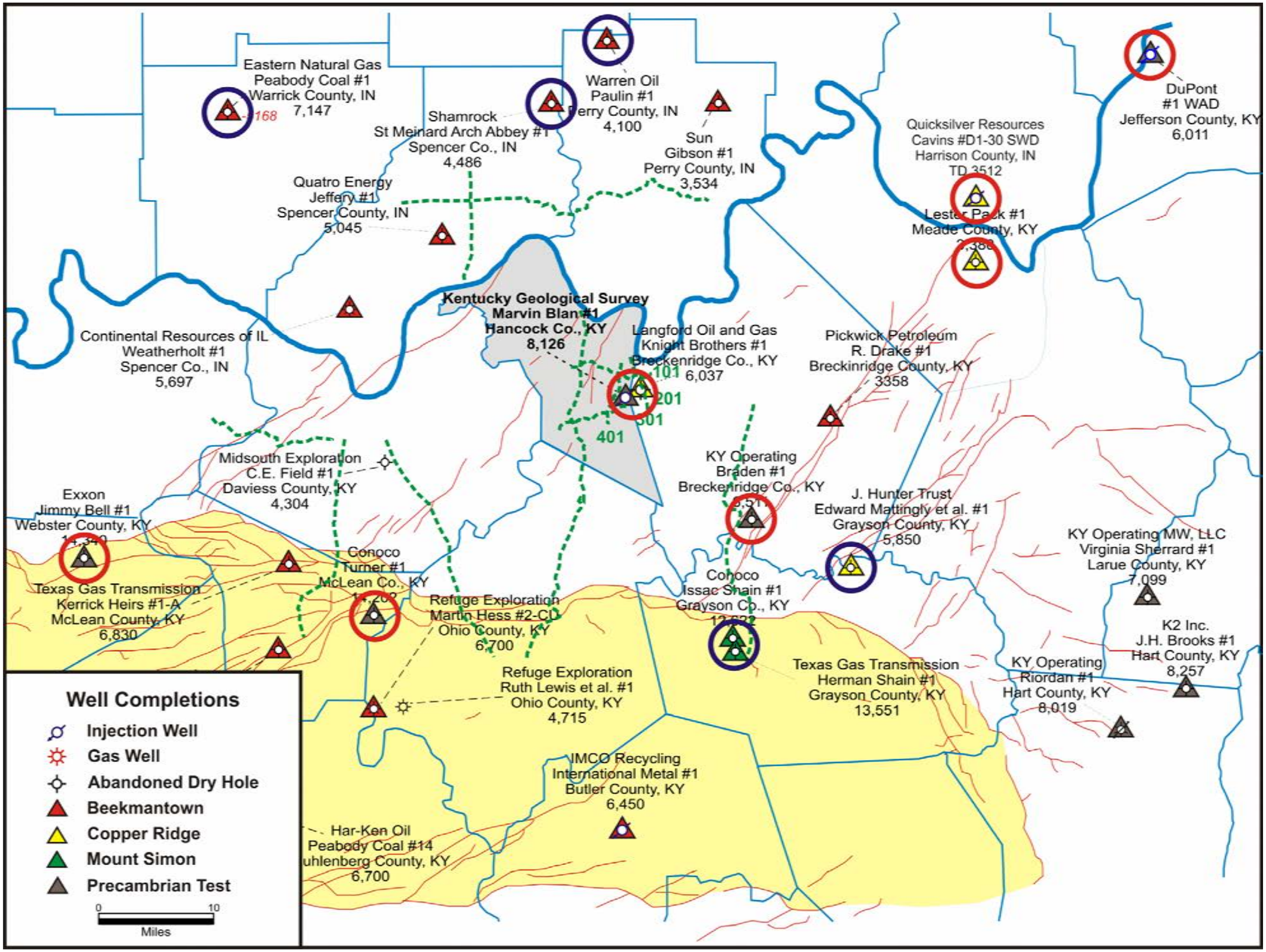


Figure 16. Locations of wells showing secondary porosity similar to that shown in Figure 15A. Wells are qualitatively denoted as those showing a large secondary porosity component of the total porosity (red circles), a small secondary porosity component (blue), and no apparent secondary porosity (uncircled wells).

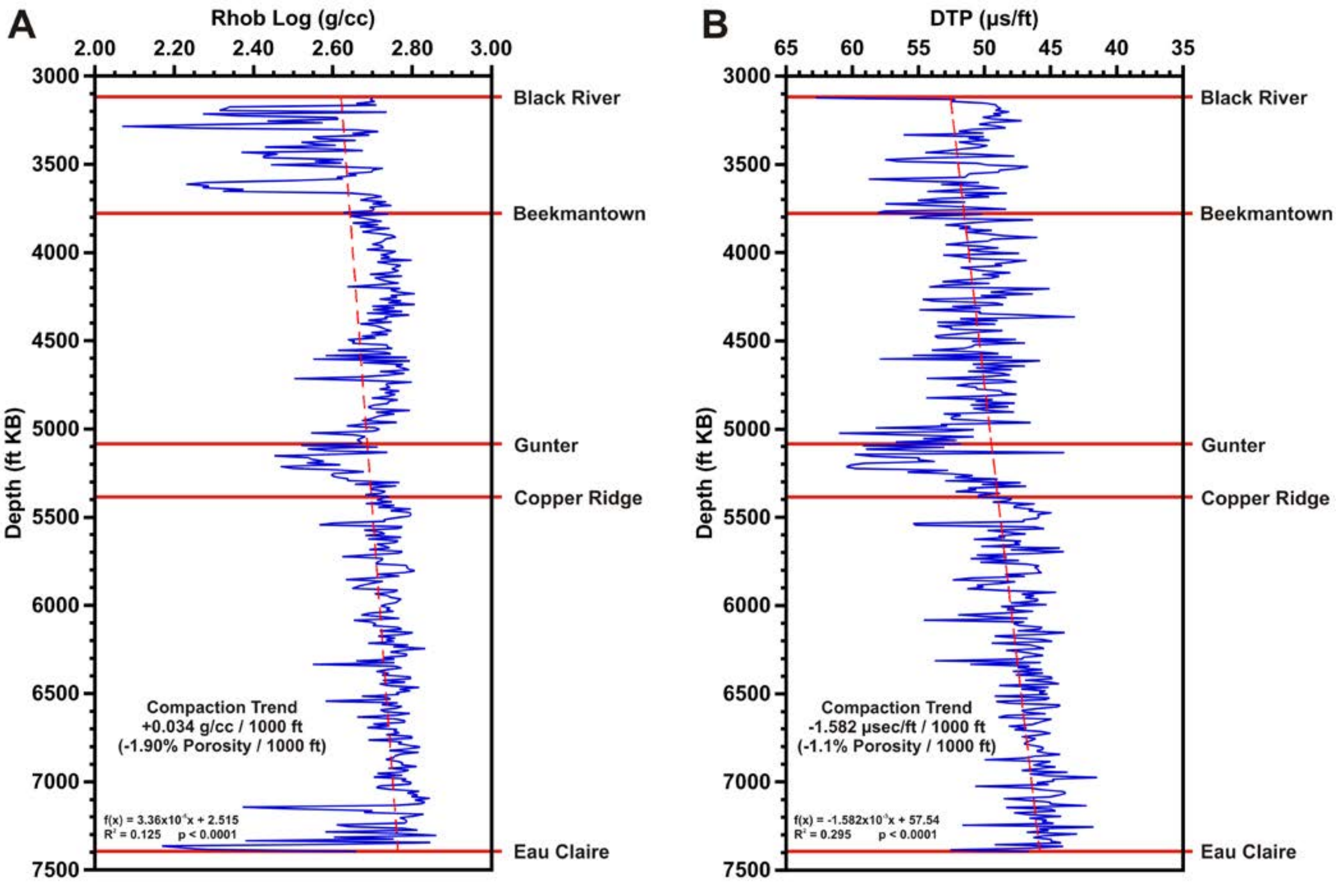


Figure 17. Compaction within the Knox is demonstrated by progressive increase in formation bulk density recorded by (A) the compensated-density log (ρ_b), and (B) decrease of interval transit time recorded by the compensated-acoustic log (DTP). Differences in compaction effect on the two logs illustrate the differences between log responses to porosity: The compensated-density log responds to total formation porosity, including vugs and fractures, whereas the compensated-acoustic log responds to matrix porosity.

to store in a supercritical state the estimated 30 million tons of CO_2 produced during the operational lifetime of a commercial coal-fired electric-power plant.

St. Peter and Mount Simon Sandstones

Evaluations by the Kentucky Geological Survey (Bowersox and others, 2008; Greb and others, 2008; Williams and Bowersox, 2008), Finley (2005), and U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory (2008) had identified the St. Peter and Mount Simon as potential CO_2 storage reservoirs in the southern Illinois Basin and underlying the northern half of the Western Kentucky Coal Field. Potential storage capacity of the St. Peter and Mount Simon in Kentucky was estimated to be 1.5 to 6.3 billion metric tons of CO_2 (U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, 2008). Initial evaluations of the St. Peter in western Kentucky suggested reservoir thicknesses greater than 100 ft in Henderson County, and thicknesses of 20 to 40 ft in Hancock County at a drill depth of approximately 3,700 ft (Williams and Bowersox, 2008). In the Illinois Basin, however, there is a rapid decline in St. Peter porosity to less than 10 percent below 3,000-ft drill depth because of diagenetic cementation (Hoholick, 1980; Hoholick and others, 1984). Pittman and others (1997) noted that St. Peter porosity is substantially reduced as it is more deeply buried because of compaction and cementation, and averages only 5 percent in the southern Illinois Basin. Subsequent reinterpretation of electric logs and well-cutting descriptions from the Langford Oil and Gas Co. Knight Broth-

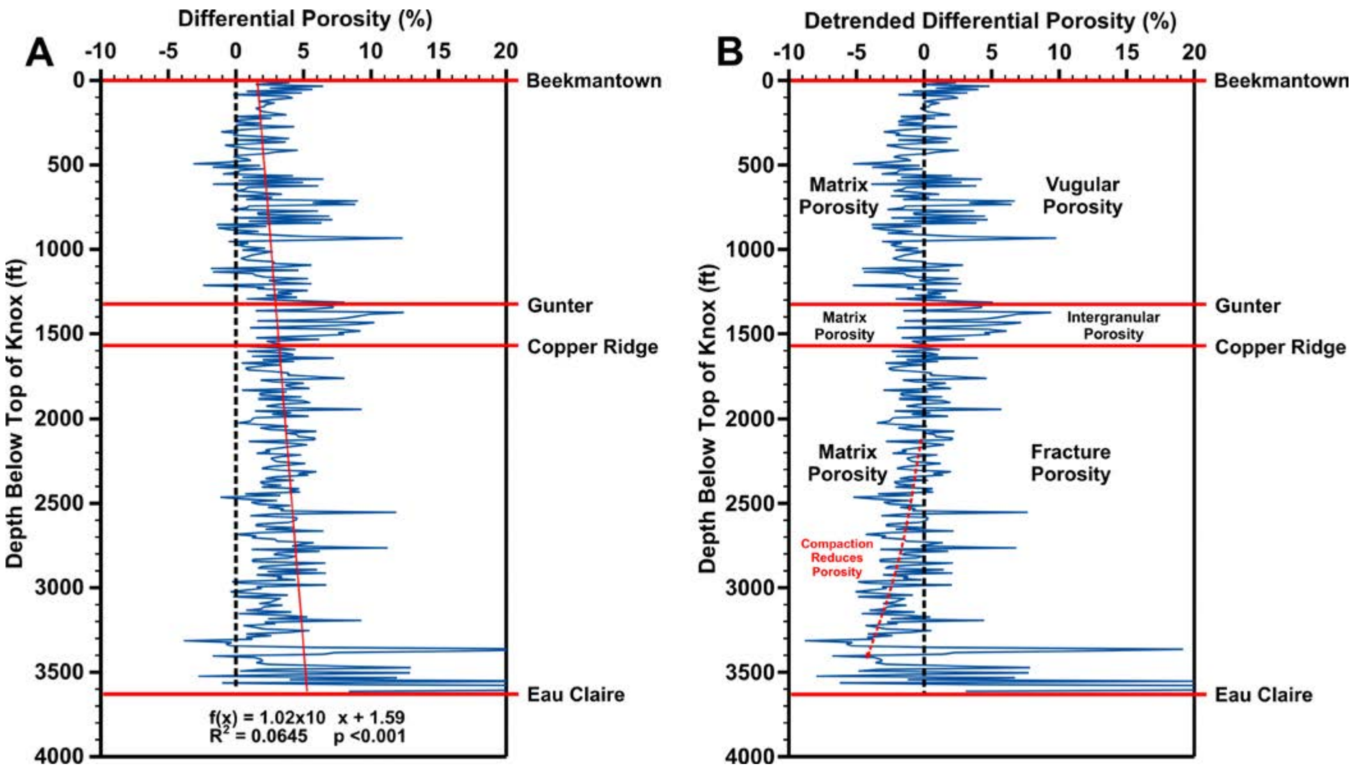


Figure 18. Differential porosity was calculated by subtracting porosity calculated from the compensated-acoustic log (matrix porosity) from porosity calculated from the compensated-density log (total porosity). This difference is often referred to as secondary porosity, but it includes both fracture porosity and vugular porosity. (A) Differential porosity with compaction trend. (B) Differential porosity detrended for compaction. Matrix compaction reduces porosity in the Copper Ridge beginning at approximately 2,000 ft below the top of the Knox, approximately coincident with development of fractures in the Copper Ridge (Figs. 19A–D).

ers No. 1 well, Breckinridge County, Ky., 2 mi east of the Marvin Blan No. 1 well (Figs. 2, 4), showed the stratigraphic interval including the St. Peter to be only 13 ft thick and with an average porosity of 4.7 percent. This suggested that the St. Peter would likely be very thin or absent, and have low porosity in adjacent Hancock County. Only 6 in. of St. Peter Sandstone was found in the Marvin Blan No. 1, lying on the Knox unconformity.

The Mount Simon has been extensively developed in UIC Class I injection wells (Fig. 1) and is the deep saline reservoir being targeted for CO_2 storage in much of the Midwest (U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, 2007, 2008). Initial evaluation of the Mount Simon in western Kentucky suggested an average thickness of 700 ft across Hancock County, and that it is absent south of the Rough Creek Fault Zone (Harris, 2007; Williams and Bowersox, 2008). Three characteristics of the Mount Simon made it largely unsuitable for injection in western Kentucky: (1) the Mount Simon is deepest in the subsurface of the southern Illinois Basin (Finley, 2005) and thinnest in western Kentucky (Bowersox and others, 2009), (2) interpretation of 2-D reflection-seismic data from line 301 (Fig. 4) suggested that it was absent under the Knight Brothers No. 1 location, and thus likely to be very thin or absent in the Marvin Blan No. 1 well (Bowersox and Williams, 2008a), and (3) results of three tests of the Mount Simon drilled approximately 50 mi southeast of the Marvin Blan No. 1, immediately east of the Western Kentucky Coal Field, and the DuPont No. 1 WAD well, 55 mi northeast of the Marvin Blan No. 1 well (Harris, 2007; Bowersox, 2008) (Fig. 4), suggest limited reservoir potential because of low porosity. The DuPont No. 1 WAD well encountered 761 ft of Mount Simon at a depth of 5,193 ft. Analysis of a whole core from this well showed low porosity and permeability, averaging 5.5 percent porosity and 6.9 md horizontal permeability, although analysis of electric logs suggests that there may be as much as 150 ft of Mount Simon with porosity greater than 10 percent in the well.

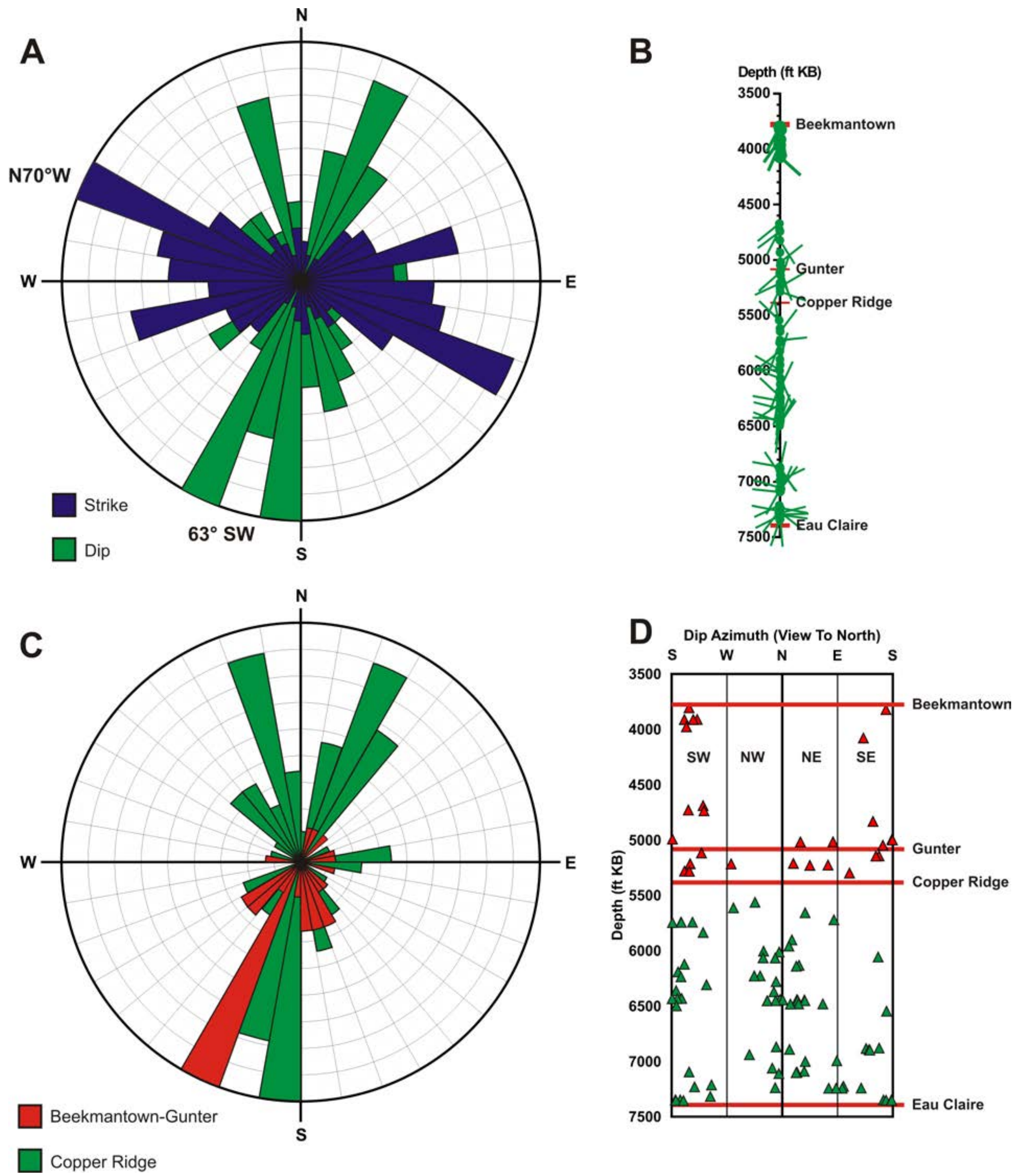


Figure 19. Fracture trends determined from analysis of the CMI log. (A) A rose diagram plotting the strike and dip of fractures. The primary fracture trend strikes N70°W and dips 63°SW, with a weaker conjugate fracture set striking N75°E and dipping 15°NW. (B) Projection of fracture dip azimuths into the borehole as viewed to the north; west to the left of the borehole and east to the right. Upward trend lines are projected into northern quadrants, whereas downward trend lines project into southern quadrants. Fracture trends suggest two generations of fracture development. Beekmantown and Gunter fractures dip almost entirely to the south. They occur at the top and base of the Beekmantown and sporadically in the Gunter. (C) Beekmantown-Gunter fractures were generally dipping in the southern quadrants. Copper Ridge fractures, present in the upper half and basal quarter of the formation, generally dip to northern quadrants, although with a strong southerly component. (D) View to the north showing the concentration of northerly-dipping fractures in the middle and lower Copper Ridge.

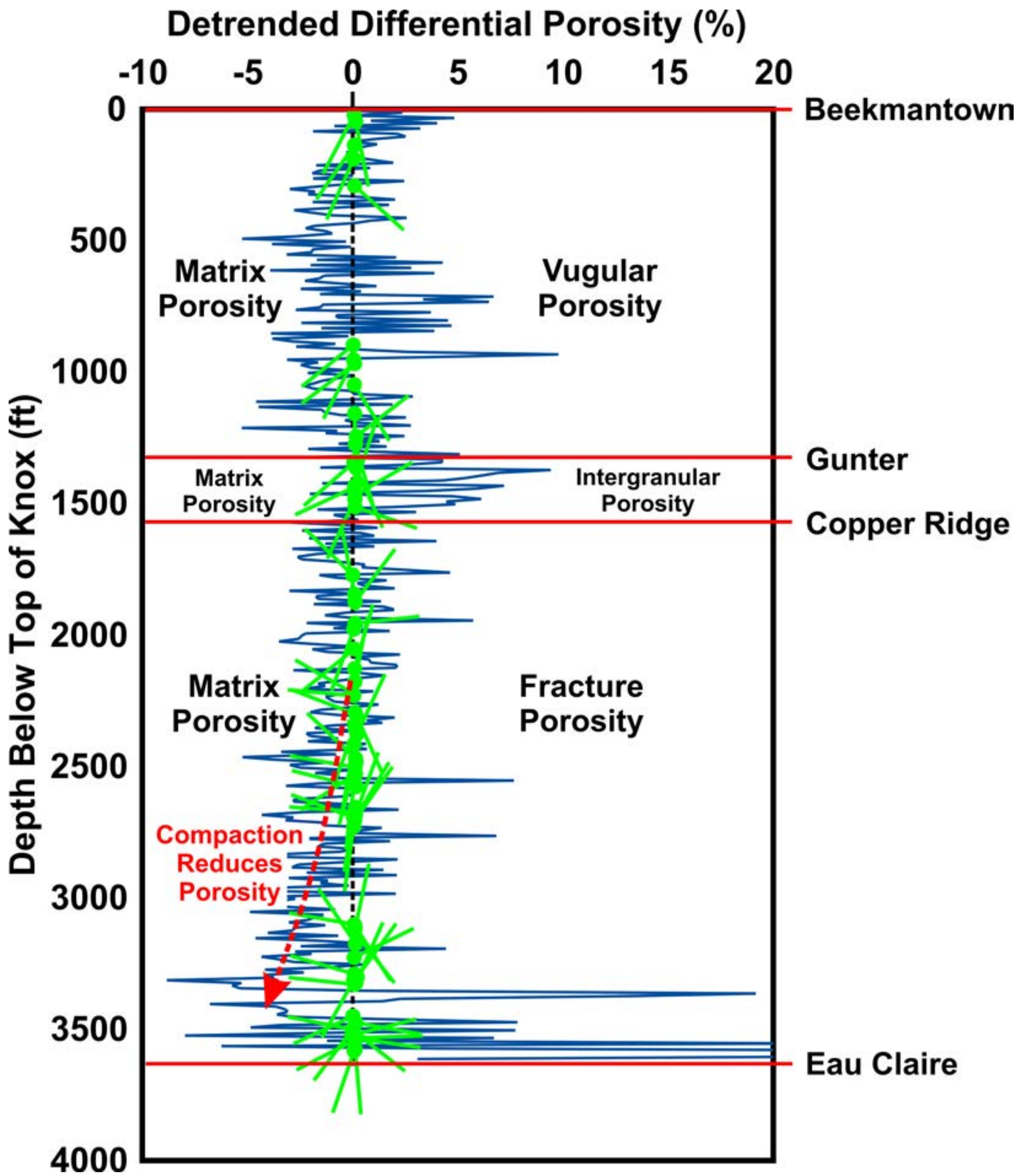


Figure 20. Identification of porosity classes from detrended differential porosity analysis. Differential porosity is calculated by subtracting matrix porosity calculated from the acoustic log from total porosity calculated from the compensated-density log. This technique is commonly used to determine unclassified secondary porosity. Detrending the differential porosity to remove the effects of compaction, when combined with fracture analysis from the CMI log, allows for classification into matrix, vugular, and fracture components.

After testing of the No. 1 WAD well, the Mount Simon was abandoned and the well recompleted on injection in the Knox (Harris, 2007; Bowersox, 2008).

Analysis of whole and sidewall cores from the Mount Simon throughout the Illinois Basin shows that porosity in the Mount Simon declines with depth (Metarko, 1980; Hoholick and others, 1984; Bowersox, 2008; Medina and others, 2008), with porosity typically falling below 5 percent below 7,000–8,000 ft (Bowersox, 2008; Medina and others, 2008). Data from wells drilled in deeper parts of the Illinois Basin indicate that porosity-reducing cements in the Mount Simon are quartz and potassium feldspar overgrowths with lesser amounts of hematite, kaolinite, chlorite, chert, and

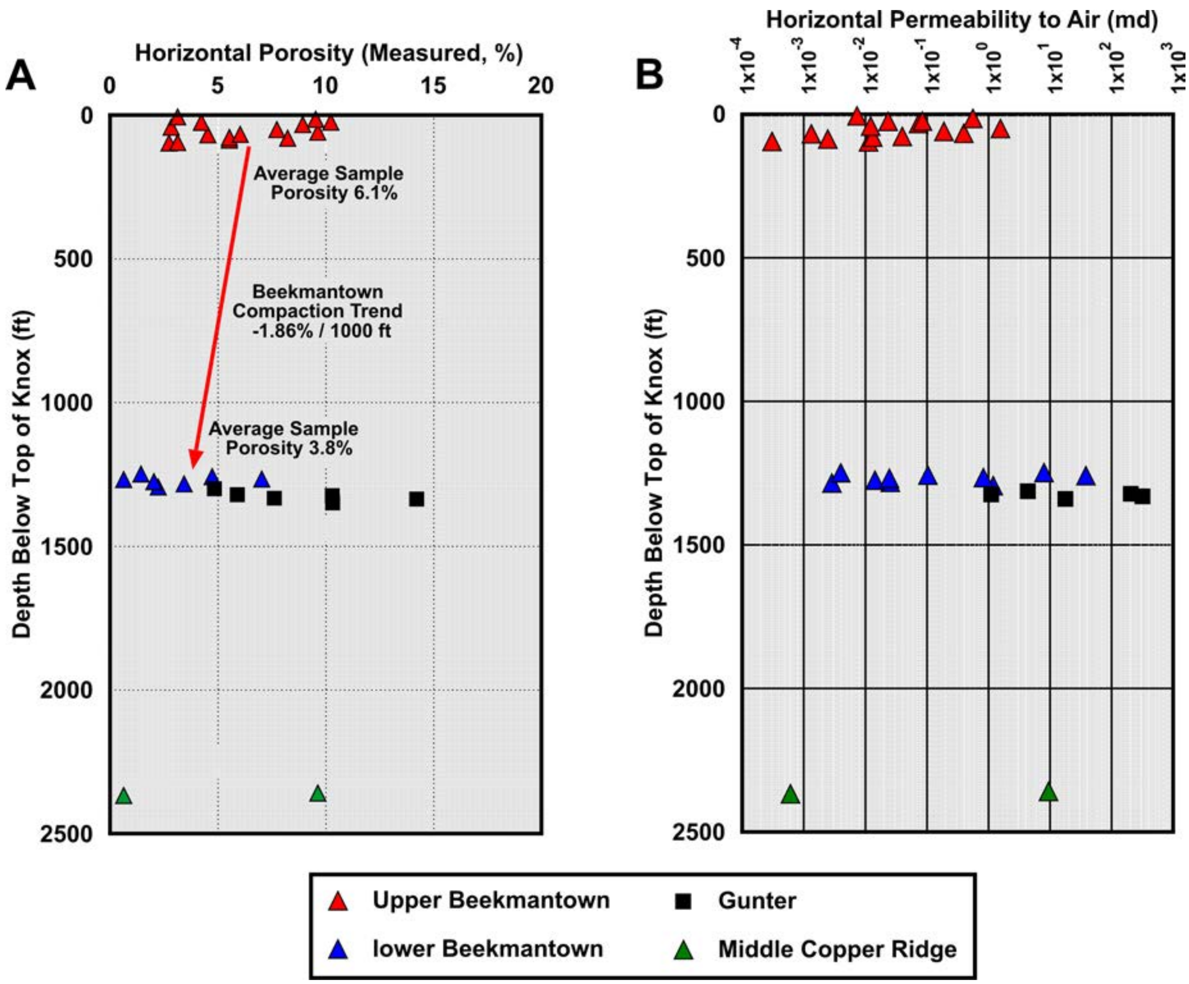


Figure 21. Horizontal and vertical porosity measured in core plugs is plotted by stratigraphic depth below the top of the Knox. These measurements will be used for modeling CO_2 storage volume in the Knox reservoir. (A) Horizontal porosity appears to show the effect of compaction in the dolomite facies of the Knox reservoir. (B) Compaction cannot be demonstrated in vertical porosity measurements, although there appears to be a trend of declining porosity with increasing depth.

carbonate (Kersting, 1980; Metarko, 1980; Hoholick and others, 1984; Makowitz and Milliken, 2003; Makowitz, 2004; Kunledare, 2005). The top of the Mount Simon was estimated to lie below approximately 7,500 ft (Finley, 2005; Williams and Bowersox, 2008) in western Kentucky north of the Rough Creek Graben. Therefore, it was unlikely that sufficient porosity would be developed in the Mount Simon for it to be a prospective CO_2 storage reservoir under the Western Kentucky Coal Field. In the end, the Mount Simon proved to be absent in the Marvin Blan No. 1 well.

Reservoir Seals

The evaluation of CO_2 storage potential in western Kentucky also requires the presence of an adequate sealing interval, at or below 2,500-ft drill depth, overlying any potential CO_2 storage reservoir. Each of the formations tested in the Marvin Blan No. 1 well have sealing units overlying them (Fig. 3). Throughout the Midwest and the southeastern Illinois Basin, primary reservoir seals are the Middle Cambrian Eau Claire, overlying the Mount Simon (Young, 1992a, b; Finley, 2005), and Ordovician Black River carbonates and Maquoketa shales and their stratigraphic equivalents overlying the Knox and its stratigraphic equivalents (Harris, 2007; *see* Swezey, 2009, for details of the correlations) and the St. Peter (Young, 1992a, b; Finley, 2005) (Fig. 3). The Devonian New Albany (Fig. 3) may act as a secondary seal for CO_2 storage in deeper saline reservoirs (Finley, 2005; U.S.

Table 5. Horizontal and vertical permeability and porosity measured in core plugs from carbonate rocks and Gunter sandstone. Horizontal and vertical permeability, horizontal and vertical porosity, and horizontal permeability and horizontal porosity were strongly correlated in the Marvin Blan No. 1 well (Figs. 22, 24–25).

Average Sample Depth (ft KB)	Permeability to Air		Ambient Porosity		Stratigraphic Interval
	k_h (md)	k_v (md)	φ_h (%)	φ_v (%)	
3,363.38	0.0009	0.0009	0.5	0.4	Black River
3,764.13	0.0018	0.0011	4.1	3.9	basal Wells Creek
3,791.55	0.5480	0.6260	9.6	9.5	upper Beekmantown
3,809.50	0.0720	0.0220	9.0	9.2	upper Beekmantown
3,836.48	0.1850	0.0570	9.7	9.8	upper Beekmantown
3,845.40	0.0013	0.0012	4.6	6.0	upper Beekmantown
3,863.48	0.0024	0.0015	5.6	6.2	upper Beekmantown
3,873.65	0.0110	0.1210	2.8	5.3	upper Beekmantown
5,088.58	4.38	9.63	6.1	8.7	Gunter Sandstone
5,098.33	206.0	15.0	10.4	10.6	Gunter dolomite*
6,143.45	0.0006	0.0009	0.8	0.8	middle Copper Ridge
Average	23.47	2.83	6.53	7.34	*vuggy

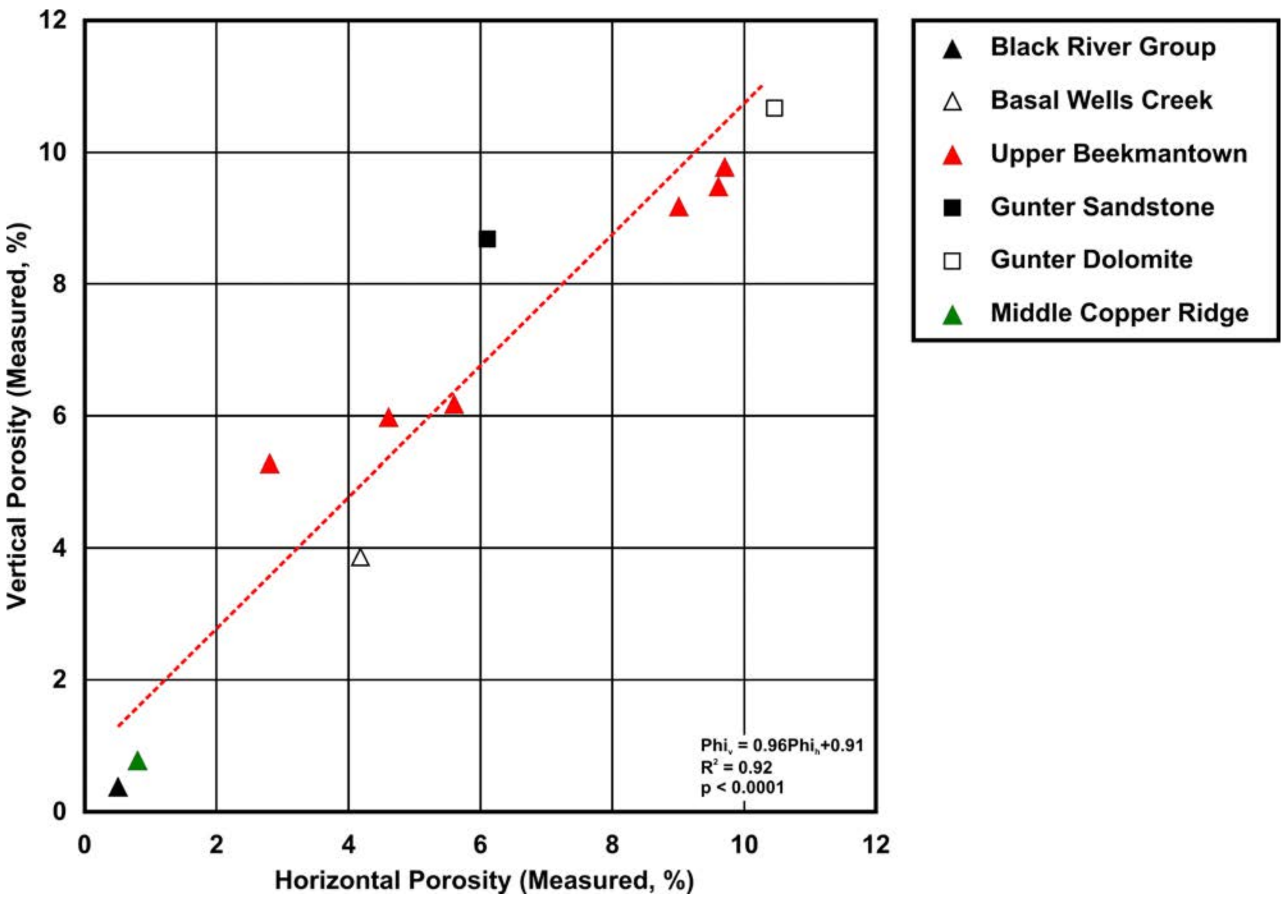


Figure 22. Crossplot of vertical versus horizontal porosity measured in core plugs from carbonate rocks. Vertical porosity (φ_v) is strongly correlated with horizontal porosity (φ_v). This relationship will allow calculation of vertical porosity from electric logs for reservoir modeling.

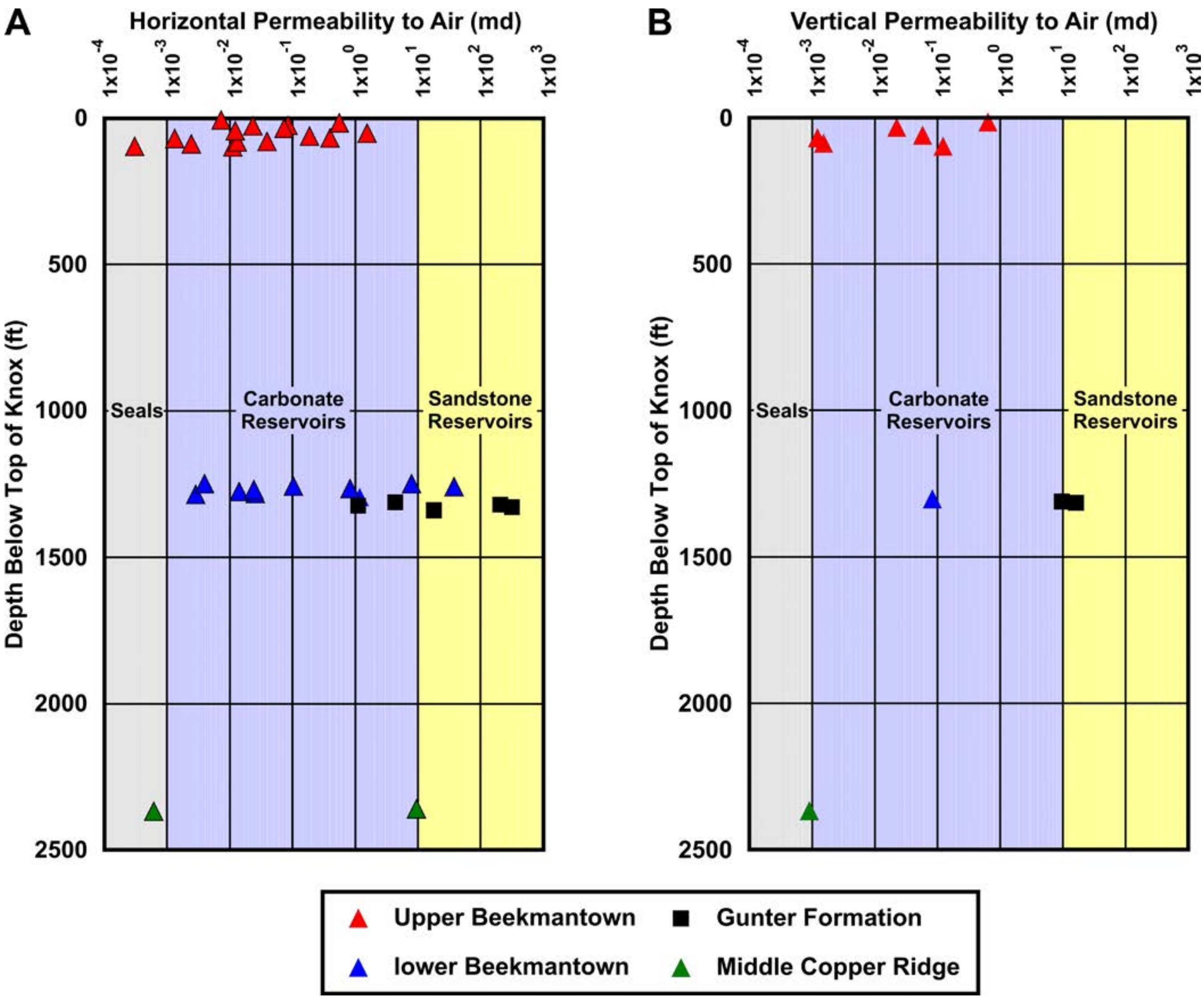


Figure 23. Horizontal and vertical permeability measured in core plugs is plotted by stratigraphic depth below the top of the Knox. These measurements will be used for modeling CO_2 storage migration and leakage potential in the Knox reservoir. Typical permeability ranges are color coded. (A) Horizontal permeabilities in Knox carbonate facies range over seven orders of magnitude, from permeabilities low enough to act as reservoir seals (less than 10^{-3} md) to those comparable to sandstone reservoirs (greater than 10 md). (B) Vertical permeabilities are comparable to horizontal permeabilities (Fig. 24). Magnitude of the permeabilities suggests that vertical migration of CO_2 within the Knox reservoir is probable.

Table 6. Permeabilities calculated from pressure buildup/falloff tests during injection testing. Calculated permeabilities were comparable to permeabilities measured in core plugs from the Knox.

Test	Formation	Test Interval (ft)	Effective Height (ft)	Fluid Injected	Calculated k_h (md-ft)	Calculated k (md)
1	basal Copper Ridge	7,175–7,450	275	2% KCl	493	1.8
2	upper Copper Ridge	5,515–5,790	275	2% KCl	3,570	13.0
2A	upper Copper Ridge	5,453–5,728	275	2% KCl	1,580	5.7
3	lower Copper Ridge	6,089–7,400	908	2% KCl	4,370	4.8
4	entire Knox	3,620–7,400	785	borax	28,900	36.8
5	entire Knox	3,620–7,400	118	CO_2	1,080	9.2

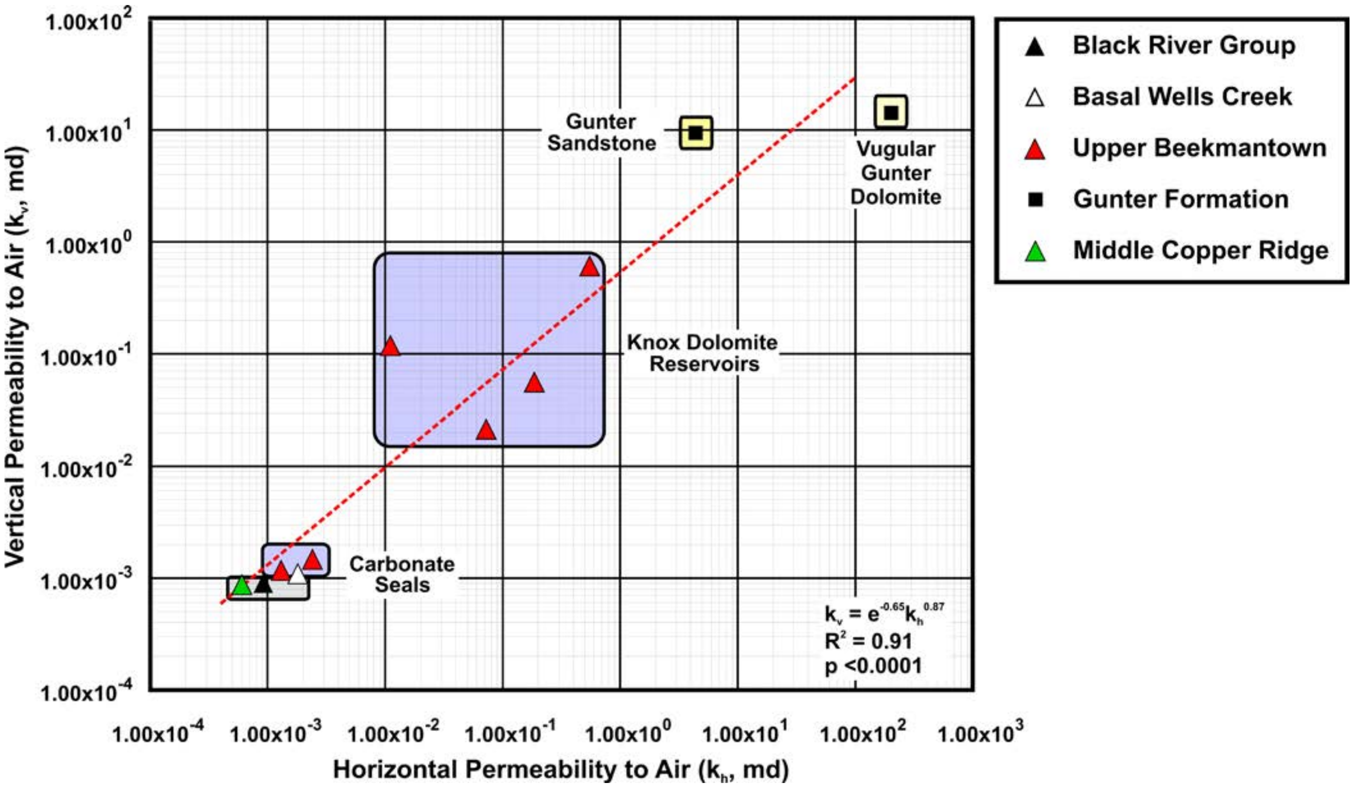


Figure 24. Vertical versus horizontal permeabilities measured in core plugs from carbonate rocks shows strong correlation; vertical permeabilities are approximately half an order of magnitude lower than horizontal permeabilities.

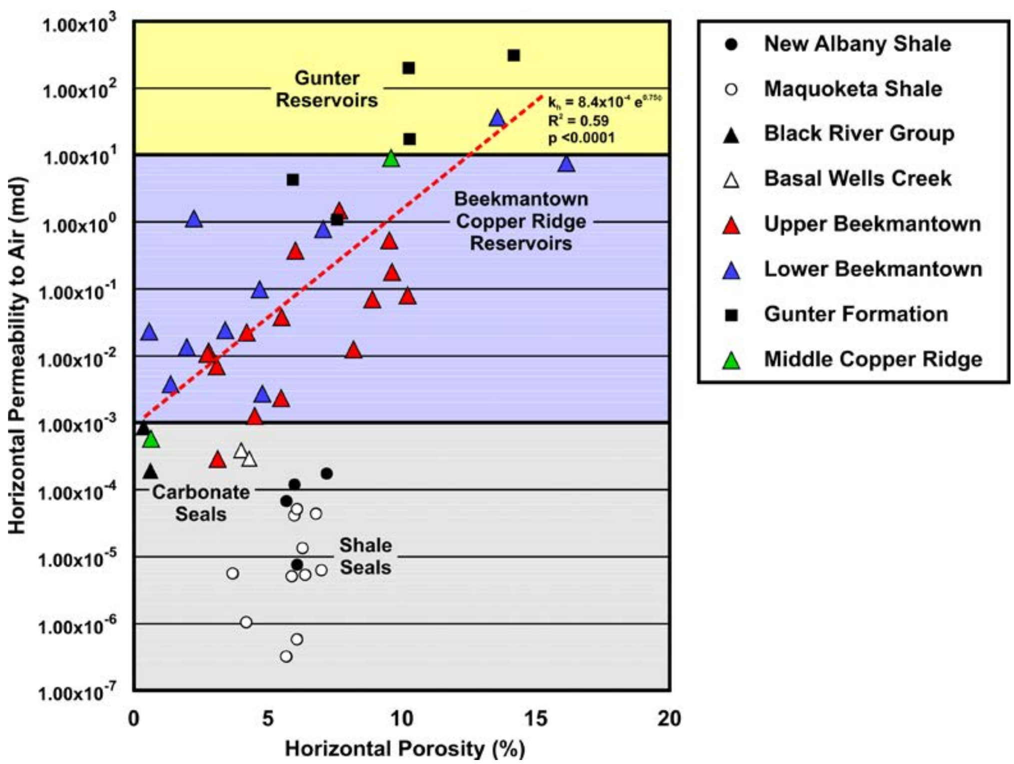


Figure 25. Horizontal permeability versus horizontal porosity for all core plugs. Although permeability and porosity are strongly correlated in core plugs from carbonates and sandstones, no relationship could be demonstrated for core plugs from shales.

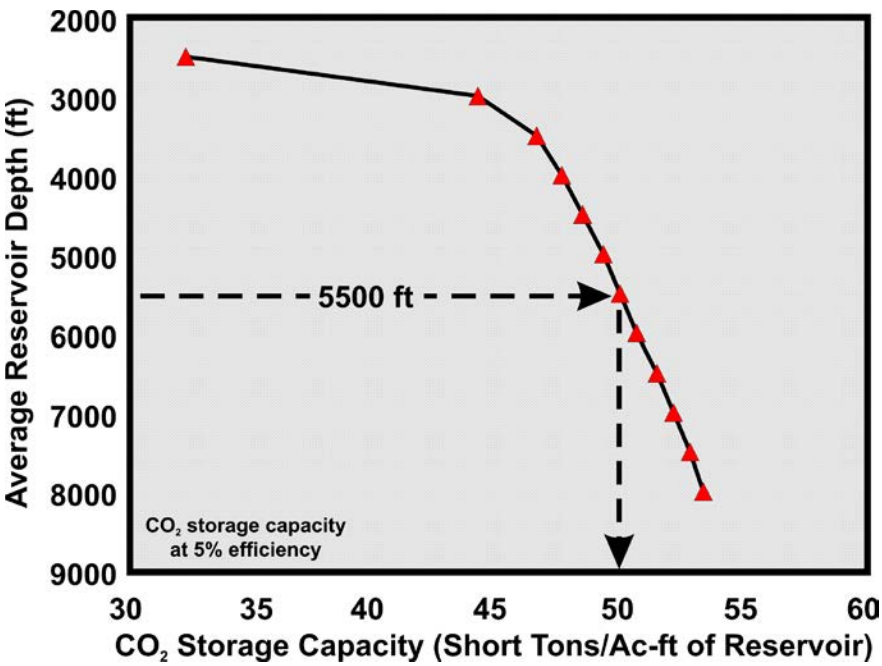


Figure 26. Storage capacity of western Kentucky reservoirs in tons per acre-feet of reservoir assuming a 5-percent storage efficiency. This graph derives from the physical properties of CO_2 as a function of temperature and pressure at western Kentucky reservoir conditions. Western Kentucky reservoirs are normally pressured at the hydrostatic gradient of 0.433 psi/ft of depth. The geothermal gradient in western Kentucky, based on a study of 36 wells (Bowersox, 2008), is approximately 1°F/100 ft of depth.

Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, 2007, 2008), but was not evaluated in this study because of its shallow depth in Hancock County. Thick, impermeable intervals within the Knox may also act as reservoir seals, although there is an increased risk for leakage from fracturing (Finley, 2005).

Eau Claire Formation

The seal for the Mount Simon is the Eau Claire, consisting of interbedded impermeable shales, cemented fine-grained sandstones, and carbonate rocks (Young, 1992a, b; Finley, 2005) (Fig. 3). The Eau Claire is generally thin-bedded, distinct from the underlying, more coarse-grained sandstones of the Mount Simon. Where the Eau Claire is exposed in outcrop in western Wisconsin, it has been subdivided into five laterally persistent facies (Morrison, 1968): basal shale; thinly bedded, clayey, fine-grained sandstone; massive, glauconitic, fine-grained sandstone; thinly bedded, glauconitic, fine-grained sandstone; and thick-bedded to massive, fine-grained sandstone. In the Illinois Basin, the Eau Claire is composed of silty, argillaceous sandstone or sandy dolomite to the north, grading into a siltstone or shale in the central basin (Willman and others, 1975), and becoming a mixture of dolomite and limestone in the southern part of the basin (Finley, 2005). It is thickest in the center of the Illinois Basin and thins toward the basin margins (Young, 1992a). The Eau Claire ranges from 300 ft thick in the northern and western parts of the Illinois Basin to more than 1,000 ft thick in the southern part of the basin. In the DuPont No. 1 WAD well, 644 ft of Eau Claire was penetrated overlying the Mount Simon. Analysis of plugs from a whole core recovered from the DuPont No. 1 WAD well at 4,409–4,460 ft showed porosity ranging from less than 1.0 to 5.4 percent, generally less than 1.0 percent, and vertical permeability in all core plugs less than 0.10 md (the analytical limit of all core plugs from this well).

The well nearest the Marvin Blan No. 1 that penetrated the Eau Claire is the Braden No. 1 well in Breckinridge County, lying about 15 mi southeast of the Marvin Blan No. 1 (Fig. 5). In the Braden No. 1 well, 158 ft of Eau Claire was penetrated at 5,885 ft, nonconformably overlying Precambrian rhyolite, indicative of early uplift of this part of western Kentucky. Likewise, the Eau Claire was very thin in the Marvin Blan No. 1 well, with a 187-ft-thick section unconformably overlying the Precambrian Middle Run at 7,584 ft. Cuttings were generally good through the Eau Claire, although largely composed of dolomite cavings from the fractured basal Knox section. The basal Eau Claire section, 7,554–7,584 ft, consists of 30 ft of white siltstone with traces of glauconitic, fine-grained sandstone. Overlying this section is 61 ft of light brown dolomite at 7,493–7,554 ft. The wellbore washed out to greater than 10.5 in. through the upper 50 ft of this interval, suggesting that the interval is fractured. Overlying the dolomite is 96 ft of mixed light brown dolomite; light brown to white, glauconitic siltstone; and very fine-grained sandstone comprising the interval from the top of the Eau Claire at 7,397 ft to the top of the dolomite section at 7,493 ft.

Knox Group and Basal Wells Creek Formation

Dense dolomite sections in the Knox may provide effective reservoir seals for the CO_2 storage intervals in the formation. Porosity and permeability were measured in whole cores from five intervals in the Knox in the No. 1 WAD well: 1,714–1,807 ft, 2,497–2,530 ft, 2,575–2,577 ft, 2,714–2,727 ft, and 2,804–2,834 ft. Analyses range from less than 3 percent porosity and less than 0.10 md vertical permeability in the dense sections cored that comprise the majority of the Knox section to a maximum of 8.2 percent porosity and 0.34 md permeability. These seal parameters do not suffice to ensure CO_2 storage within the Knox, and the potential for communication between reservoir intervals through the porosity and fracture systems may compromise the integrity of any intra-Knox seals (Finley, 2005). Indeed, pressure communication around straddle packers occurred during injection testing in the Marvin Blan No. 1.

Demonstrating intraformational seals within the Knox is problematic. In the Marvin Blan No. 1 there is only a net 119 ft of strata with less than 2 percent porosity distributed within an interval 3,617 ft thick, as calculated from the compensated-density log. Those core plugs chosen as representative of reservoir seals, analyzed as having permeabilities less than 0.01 md (10 plugs from the Beekmantown and one from the Copper Ridge), had an average porosity of 3.4 percent and average permeability to air of 0.0088 md. These are marginal properties at best to be considered effective seals. Attempts to test injection intervals within the Knox using straddle packers to isolate test intervals proved ineffective because of rapid communication to the wellbore around the packers through the Knox porosity system. Thus, the seal for CO_2 storage in the Knox is in overlying strata.

The basal Wells Creek Formation was cored at 3,760 ft to the top of the Knox at 3,780 ft in core 4. This was to ensure that the St. Peter would be cored, if present. This section consists of gray, bioturbated dolomite about 6 in. thick. A second glauconitic sandstone of comparable thickness, and in a stratigraphic relationship with the Knox correlative to the St. Peter, was found unconformably overlying the Knox in an epikarst. Two core plugs were analyzed from the basal Wells Creek dolomitic section to determine reservoir sealing properties (Fig. 25). Average porosity was 4.1 percent and average permeability was 0.0004 md, suggesting that the interval may provide a modest primary seal for the underlying Knox.

Black River Group

The Black River provides a primary reservoir seal for the St. Peter and deeper reservoirs in Kentucky (Harris, 2007). It was penetrated at 3,124–3,497 ft in the Marvin Blan No. 1, overlain by a thick Maquoketa Shale section. Trenton Group limestones were absent in the Marvin Blan No. 1. The Black River was 373 ft thick in the Knight Brothers No. 1 well, and cuttings from the well described it as interbedded, gray, fossiliferous limestone; light brown dolomite; and cherts. Analysis of a core from the Black River section in the DuPont No. 1 WAD well from 1,697–1,713 ft, showed half of the plugs had vertical permeability less than 0.10 md and associated porosity averaging 4.6 percent. In the Marvin Blan No. 1, the Black River was cored at 3,333–3,395 ft. Core-analysis data are in Appendix 3. Lithology in this core was gray limestone that parted along bioturbated, crinkly bedding planes. X-ray diffraction analysis of one sample showed it to consist of 97 percent calcite, 2 percent quartz, and 1 percent clays (Appendix 3). Measured bulk density of the Black River averaged 2.70 g/cm^3. Ultrasonic wave velocity was measured in two plugs from the Black River. The average compressional wave velocity measured in the plugs was 20,430 ft/s (interval transit time of 49.0 μs/ft), and shear-wave velocity was 10,484 ft/s (interval transit time of 95.4 μs/ft). Two plugs from the Black River were analyzed for their reservoir seal properties (Fig. 25). These plugs had an average porosity of 0.5 percent and permeability less than 0.0002 md. Therefore, it appears that the Black River could effectively serve as a CO_2 storage reservoir seal.

Triaxial compressive rock-strength and ultrasonic velocity tests were made on two plugs from the Black River (Appendix 3). Compressive strength averaged 7,563 psi, sufficient to act as a seal for underlying reservoirs. The borehole section above the casing point at 3,660 ft was drilled with an 11-in. bit, and the entire Black River shows borehole-washout rugosity. Within the section, 193 ft of the borehole is more than 25 percent over gage (more than 13.75 in. diameter) as measured by the borehole caliper log, and 18 ft of the borehole that is more than 50 percent over gage (more than 16.5 in. diameter). This raises the concern of potential fracturing within the section that could compromise its sealing integrity. The thick Black River section along with the overlying, thick Maquoketa Shale section would act as an excellent seal for all underlying strata.

Maquoketa Shale

The Late Ordovician Maquoketa Shale, the lower interval of the Maquoketa Formation, is a low-permeability groundwater-confining unit throughout the Midwest (Young, 1995a, b), and is considered a primary reservoir seal for CO_2 storage in underlying reservoirs (Finley, 2005; U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, 2007, 2008). The Marvin Blan No. 1 well penetrated 337 ft of shale in the Maquoketa at 2,787–3,124 ft. A comparable 345-ft-thick shale section in the Maquoketa was penetrated in the Knight Brothers No. 1 well at 2,466–2,811 ft, also overlying the Black River. In contrast, the Maquoketa Shale section penetrated in the Braden No. 1 well was 214 ft thick, overlying the Trenton, which, in turn, overlies the Black River. The Marvin Blan No. 1 and Knight Brothers No. 1 penetrated the subsurface Sebree Trough, a Midcontinent paleogeographic feature of the Middle to Upper Ordovician section (Kolata and others, 2001; Ettensohn, 2003; McLaughlin and others, 2004), at a location where the Trenton is absent and a thick section of Maquoketa is present. The thick Maquoketa Shale section filling the Sebree Trough plunges southwest across western Kentucky from northwest Breckinridge County into Tennessee south of Trigg County (Kolata and others, 2001). It would be a thick seal for deeper CO_2 storage reservoirs under the central area of the Western Kentucky Coal Field, including Ohio, McLean, Hopkins, and Muhlenberg Counties.

The Maquoketa Shale section was cored in the Marvin Blan No. 1 at 2,800–2,831 ft. Core descriptions and facies interpretation, laboratory analyses, thin-section photomicrographs, and CT-scan photographs are found in Appendix 4. Two facies were described in the upper 20 ft of the core (the lower 10 ft was not described): a dark gray, calcareous, silty, fissile shale with carbonate-rich concretionary layers 1 to 5 in. thick at 2,803.8–2,821.0 ft, overlain by dark gray, slightly calcareous, silty, fissile shale at 2,800–2,803.8 ft (Appendix 3). CT scans show natural fractures, partings from core recovery and transport to the lab (Figs. 27A–B), calcareous layers (Figs. 27A–C), and organic-rich intervals (Fig. 27C). Laboratory analyses performed on 11 plugs from the Maquoketa at approximately 3-ft intervals from the top to the base of the core included X-ray diffraction, total organic carbon, and routine crushed-core analysis (porosity, permeability, and bulk-density analyses for very low-permeability rocks). Rock mechanical measurements were made on two separate core plugs. X-ray diffraction analysis showed most plugs to be mudstone or clayey mudstone, siltstones with 25 to 75 percent clays, and one marlstone sample (Table 7, Fig. 28). Dominant minerals are illite-chlorite, calcite, and quartz (Table 7). Triaxial compressive strength testing of a representative sample from the Maquoketa yielded a compressive strength of 17,264 psi, exceeding the requirements for an effective reservoir seal.

Measured dry grain density of plugs from the Maquoketa averaged 2.77 g/cm^3, and measured bulk density averaged 2.61 g/cm^3 from the same plugs (Appendix 2). No correlations could be demonstrated between grain density and bulk density measured in core plugs (Fig. 29A), between grain density measured in core plugs and bulk density measured by the density log (Fig. 29B), nor between bulk density measured in core plugs and bulk density measured by the density log (Figs. 29C–D). Porosity calculated from the density log using the grain density measured in Maquoketa core plugs correlates to porosity measured in the core plugs ($r^2 = 0.37$) (Figs. 30A–B), although considerable scatter of the data affected the correlation. The core analysis in itself was internally consistent: Porosity calculated from Maquoketa core plugs using measured sample grain densities and bulk densities was significantly correlated to porosity measured

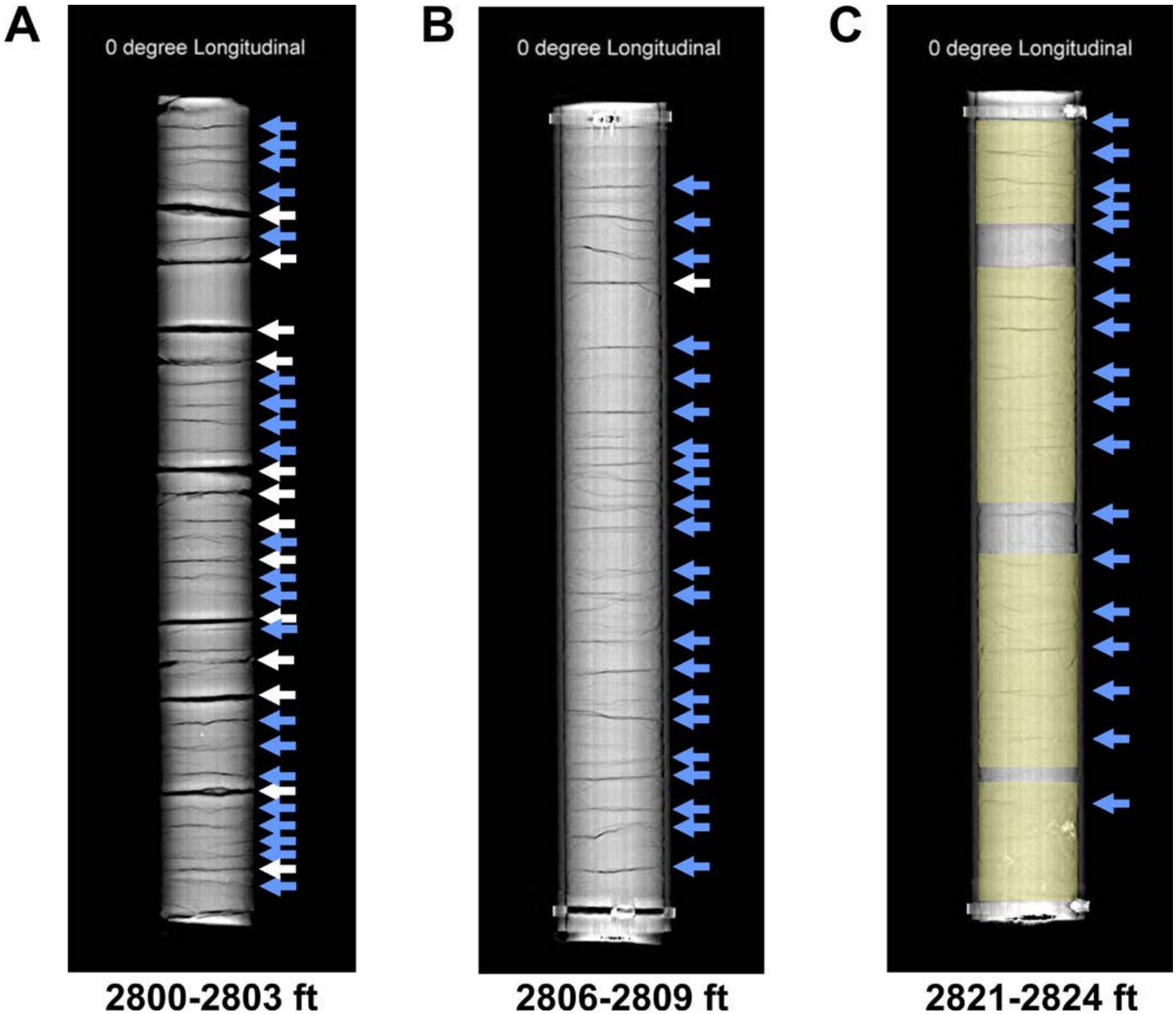


Figure 27. CT scans of cores from the Maquoketa were performed before the cores were removed from their aluminum sleeves. Calcareous layers indicated with blue arrows, partings indicated by white arrows, and intervals with organic material noted are shaded yellow.

in the Maquoketa core plugs ($r^2 = 0.99$) (Fig. 30C). Average dry helium porosity of the Maquoketa plugs was 5.8 percent. No relationship could be demonstrated between Maquoketa porosity and permeability (Figs. 25, 31A), although permeability correlates with gas-filled porosity ($r^2 = 0.41$) (Fig. 31C). Average permeability of the 11 core plugs from the Maquoketa was approximately 0.00002 md, although this likely overstates permeability because of the smaller diameter of the helium atom (1 Å) compared to molecules of water (2.75 Å) or CO_2 (3.23 Å). Thus, in situ permeability to either water or CO_2 is likely to be much less than the permeability measured with helium.

Gas-filled porosity is a measure of the pore volume occupied by methane in carbonaceous shales related to the total organic carbon of the host shale. Commercial shale-gas reservoirs generally can be developed where TOC exceeds 2 to 4 percent, depending on reservoir depth. TOC measured in the Maquoketa plugs was low, averaging 0.57 percent, and no sample exceeded 1 percent TOC (Figs. 32A–B). In the New Albany, TOC is correlated to formation bulk density (Nut-

Table 7. X-ray diffraction analysis of core plugs from the Maquoketa. Mineralogy and texture of the Maquoketa are characteristic of a mudstone (Fig. 28).

Sample Depth (ft)	Clay				Carbonate			Silt			Accessories		Total			
	Chlorite	Kaolin	Illite	Mixed I/S*	Calcite	Fe-Dol	Siderite	Quartz	K-spar	Plag	Pyrite	Apatite	Clay	Carbonate	Silt	Acc. Min
2,800.85	9	1	23	1	22	2	trace	25	2	8	3	4	34	24	35	7
2,803.85	7	1	17	1	37	3	trace	19	4	5	3	3	26	40	28	6
2,806.90	8	1	20	1	19	9	trace	24	3	8	4	3	30	28	35	7
2,809.80	10	2	28	2	8	6	trace	27	3	6	4	4	42	14	36	8
2,812.80	12	2	32	2	7	4	trace	24	3	5	5	4	48	11	32	9
2,815.90	10	1	22	1	23	3	trace	24	3	6	4	3	34	26	33	7
2,818.80	11	2	28	2	8	3	trace	28	3	7	4	4	43	11	38	8
2,821.90	11	2	33	2	7	4	trace	26	3	6	3	3	48	11	35	6
2,824.90	11	2	31	2	8	3	trace	27	3	7	3	3	46	11	37	6
2,827.90	11	2	27	2	8	4	trace	28	3	7	4	4	42	12	38	8
2,830.85	10	2	25	1	11	4	trace	30	3	8	3	3	38	15	41	6
Average	10	2	26	2	14	4	trace	26	3	7	4	3	39	18	35	7

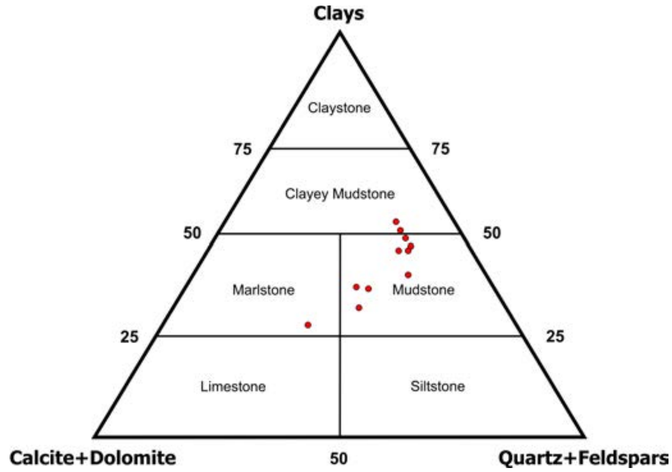


Figure 28. Ternary classification of Maquoketa lithology as used in this study from X-ray diffraction mineralogy analysis.

tall, 2009), and there is a correlation between TOC and bulk density in the Maquoketa plugs as well (Fig. 32). The Maquoketa TOC profile calculated from the density log is shown in Figure 33A. Calculated TOC is affected by borehole rugosity in the 2,850–2,950-ft interval, resulting in TOC spikes greater than 1 percent (Fig. 33A). Maquoketa TOC calculated from the density log correlates well to the measured TOC (Fig. 33B), with an average calculated TOC of 0.58 percent, excluding the rugose interval. No correlation of gas-filled porosity and TOC could be demonstrated in Maquoketa plugs from the Marvin Blan No. 1 (Fig. 33C), however.

New Albany Shale

The New Albany is considered a significant reservoir seal in the Illinois Basin; however, it generally lies at too shallow a depth to be considered a primary reservoir seal in western Kentucky. The New Albany was penetrated at 1,857–1,973 ft, overlying the Sellersburg Limestone, in the Marvin Blan No. 1 well. Characteristic of the New Albany is its very high gamma-ray log response caused by uranium being adsorbed onto organic matter in the shale. It is described on the mudlog as being dark gray to black, calcareous, having a trace of pyrite, with subplaty to blocky laminations. The New Albany in the Marvin Blan No. 1 has been correlated from the gamma-ray log into three members (Nuttall, 2009): the Grassy Creek Shale, Selmier Shale, and Blocher Shale. Core analysis is in Appendix 2 and a summary report in Appendix 3. Enhanced

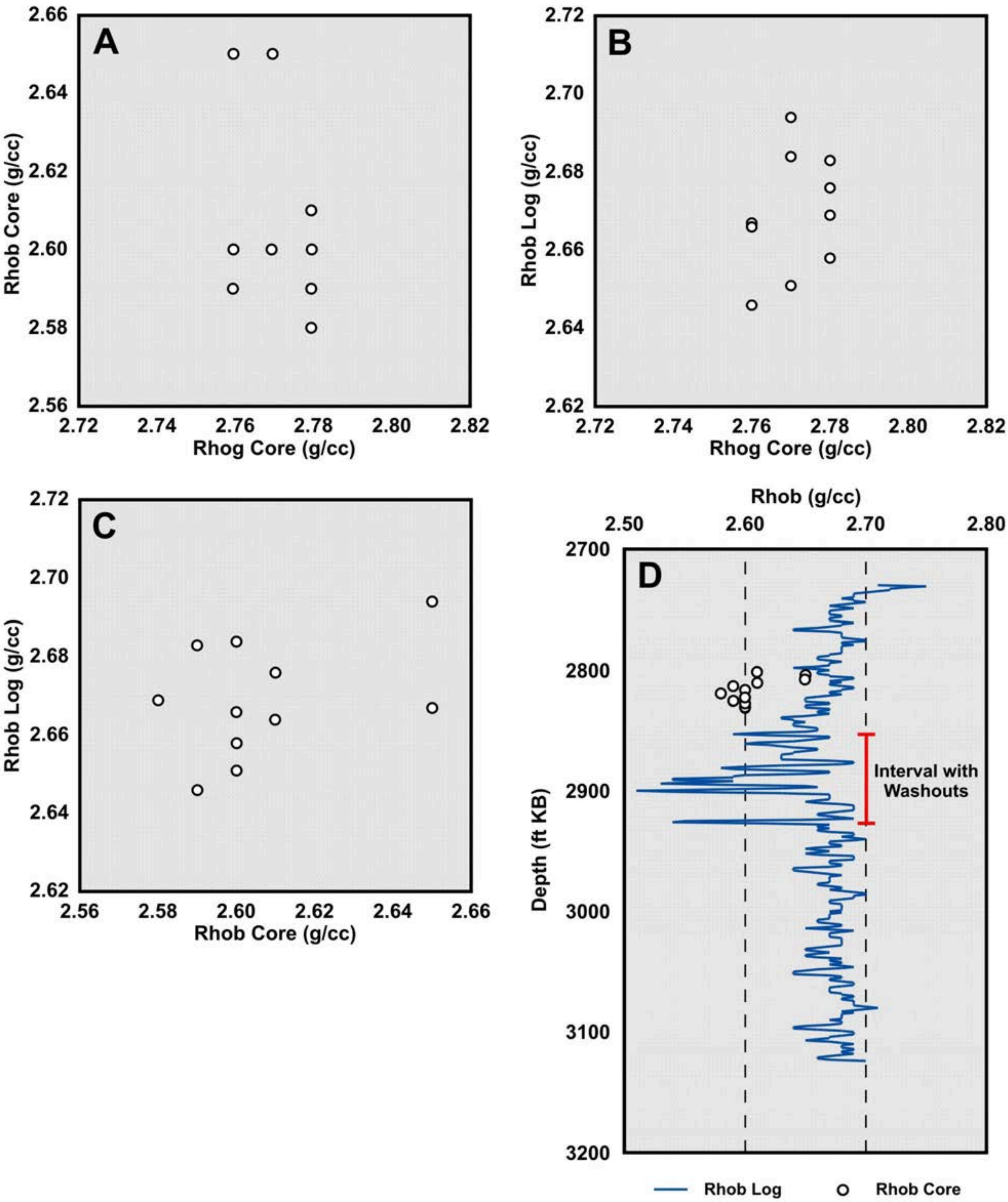


Figure 29. Grain density (ρ_g) and bulk density (ρ_b) of the Maquoketa measured in core plugs and by the compensated-density log. (A–B) Relationships could not be demonstrated between grain density measured in core plugs and bulk density measured in core plugs and bulk density measured in core plugs (A) or by the compensated-density log (B). (C) A relationship could not be demonstrated between bulk density measured in core plugs and bulk density measured by the density log. (D) Bulk density measured in core plugs plotted by drill depth compared to that measured by the compensated-density log. The log interval affected by borehole rugosity (washouts) is noted. Bulk density measured in core plugs averages approximately 0.06 g/cm^3 lower than that recorded by the compensated-density log.

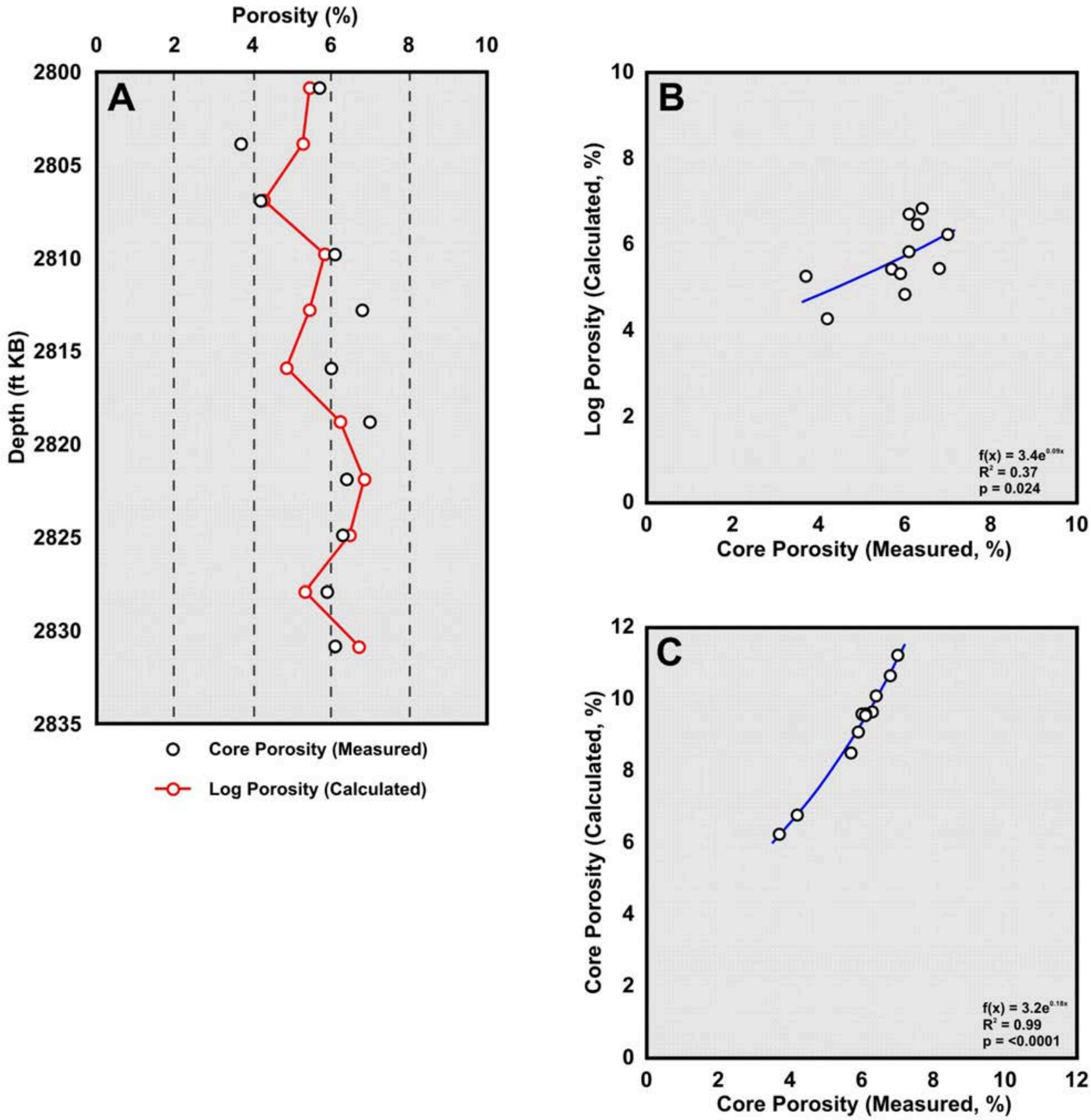


Figure 30. Porosity measured in core plugs from the Maquoketa and calculated from the compensated-density log at the same depths. (A) Porosity was calculated from the compensated-density log using the grain density measured in core plugs from corresponding depths. Average grain density of Maquoketa core plugs was 2.77 g/cm^3. Porosity measured from core plugs plots near the calculated curve. (B) Porosity calculated from the compensated-density log has a moderate correlation to measured porosity, though the correlation is affected by scatter within the data. (C) Porosity calculated from Maquoketa core plugs using the measured grain densities and bulk densities is significantly correlated to porosity measured in the core plugs. Thus, the core-analysis data are internally consistent.

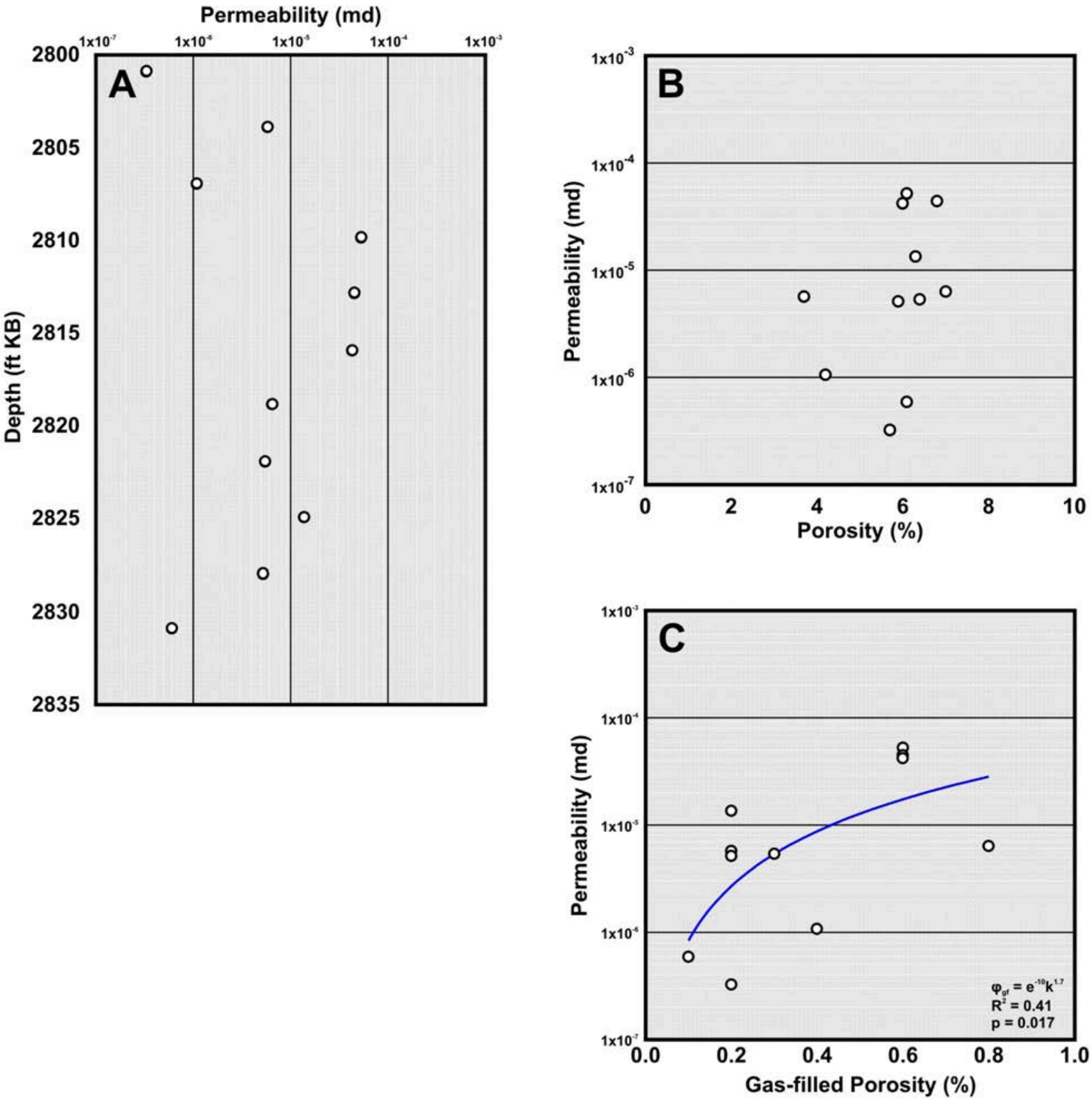


Figure 31. Maquoketa permeability and porosity. (A) Permeability measured in core plugs from the Maquoketa is sufficiently low, less than 10^{-4} md, for the Maquoketa to act as the primary reservoir seal for CO_2 storage in the Knox. (B) No relationship could be demonstrated between permeability and total porosity measured in core plugs from the Maquoketa. (C) Permeability and gas-filled porosity showed a good correlation in core plugs from the Maquoketa, however.

gas recovery and CO_2 storage in the New Albany is the subject of a separate HB-1 research project.

Injection Testing

The testing program commenced on July 25, 2009, and was completed August 22, 2009. All testing was in open hole below the casing at 3,660 ft (Fig. 34). Detailed results of the injection testing program are included in Appendix 5. Two formation-water samples were collected from the Knox Group prior to injection. Initial tests, injecting water mixed with 2 percent potassium chloride brine (Bio-31 brine additive) into short intervals using straddle packers on tubing, had mixed results. The

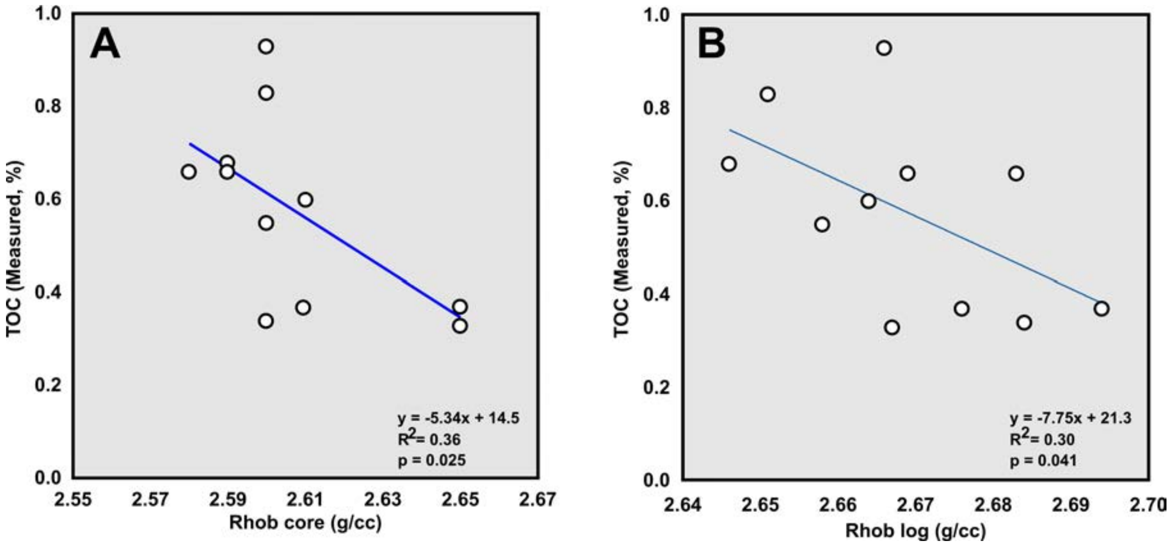


Figure 32. Crossplots of formation bulk density measured in core plugs from the Maquoketa (A) and recorded by the compensated-density log (B) show good correlation with total organic carbon measured in core plugs. Maquoketa TOC was calculated from the compensated-density log (Fig. 33A) using the regression equation shown in Figure 32B.

first injection test using straddle packers was in the basal Copper Ridge fractured interval at 7,180–7,455 ft. This interval broke down during injection at a fracture gradient of 0.9 psi/ft after approximately 1.5 hr pumping at a 2 bbl/min rate. The fracture gradient is comparable to the closure stress gradient of this interval calculated from the dipole sonic log (Appendix 1). Two following tests of the upper Copper Ridge were attempted at 5,515–5,790 ft and 5,433–5,728 ft. Both failed shortly after the pumping began at 2 bbl/min because of communication around the packers through the formation's porosity system. Better injection tests were obtained by injecting into the full wellbore below a single packer. Injection rates up to 14 bbl/min were achieved, with wellhead pressures of 285–550 psi. The Beekmantown, interbedded Gunter Sandstone, and uppermost section of the underlying Copper Ridge were identified as the principal reservoirs in the well. Temperature logs showed 70 percent of the injected brine went into the Beekmantown-Gunter interval. Injection of a 7 lb/bbl borax tracer solution and monitoring with pulsed neutron and spinner logs confirmed these results. A total of 18,454 bbl of brine and borax solution was injected during this testing phase. CO_2 injection was tested on August 19, 2009. A total of 323 tons of CO_2 (1,765 bbl or 5,646 mcfg) was injected at the pumping equipment maximum rate of 4.1 bbl/min. Wellhead pressure was 936 psi, with bottom-hole pressure of 1,754 psi.

Post-injection temperature logging showed the deepest injection point for CO_2 was 5,230 ft, at the base of the Gunter (Fig. 34, Appendices 1, 5). Temperature logs were run after injection verified CO_2 placement (Fig. 34, Appendices 1, 5). This would suggest that only the upper Knox section is prospective for CO_2 storage. By injecting CO_2 through a single tubing string into the open hole below a packer set at the top of the Knox, however, the relative buoyancy of CO_2 versus brine in the borehole limits the maximum injection depth. This is an engineering issue. Injection into the Knox in an uncased wellbore is not optimal, although it was expedient for cost-control purposes for injection testing of the Marvin Blan No. 1. The engineering remedy in a commercial injection well would be to use multiple tubing strings and multiple packers in a cased, perforated wellbore to segregate individual injection intervals within the Knox. Pressures could be balanced between intervals to provide an optimal injection rate without overpressuring the reservoir.

Discussion

The Marvin Blan No. 1 well successfully demonstrated injection of CO_2 into the Knox as well as the presence of sealing intervals in the Black River and Maquoketa. As a conservative base case for

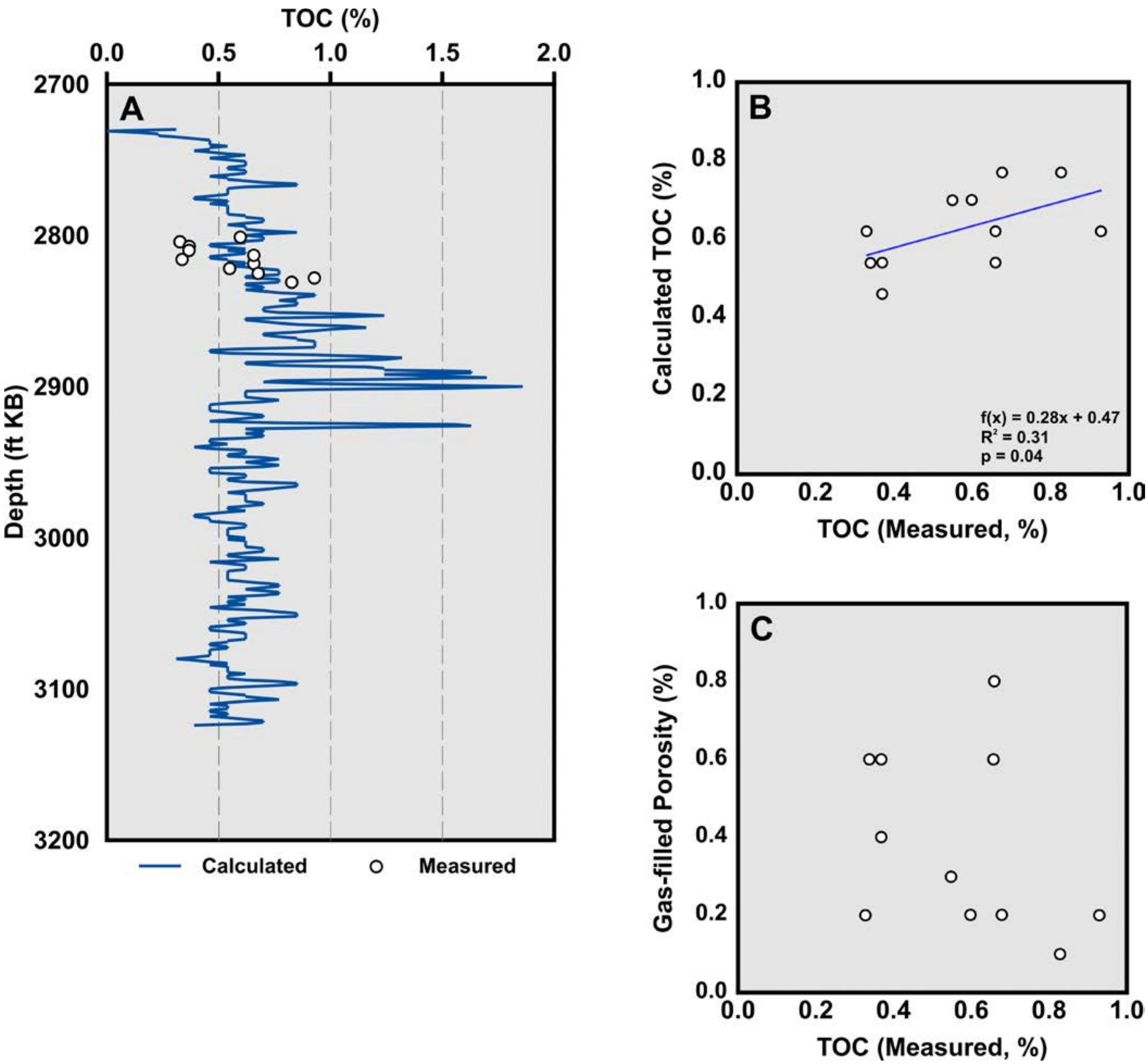


Figure 33. Total organic carbon measured in core plugs from the Maquoketa and calculated from the compensated-density log. (A) Calculated and measured TOC plotted by depth. Calculated TOC is inaccurate (too high) in the interval with borehole washouts. (B) Crossplot of measured and calculated TOC shows good correlation. (C) No relationship could be demonstrated between measured gas-filled porosity and TOC. The Maquoketa in the Marvin Blan No. 1 well lacks enough TOC to be a hydrocarbon source rock.

potential CO_2 storage, using a 5-percent minimum porosity cutoff, total pore volume in the Marvin Blan No. 1 well was estimated at 172 porosity-ft (Fig. 14). This equates to a storage capacity of 8,600 tons of CO_2 per surface acre of reservoir, or an area of 116 surface acres required to store 1 million tons of CO_2. Thus, approximately 3,500 surface acres of Knox reservoir comparable to the Marvin Blan No. 1 well would be required to store the 30 million tons of CO_2 produced during the operational life of a coal-fired electric power plant. The injection profiles recorded in the Marvin Blan No. 1 showed the deepest effective injection depth with full-wellbore injection to be approximately 5,800 ft; 80 percent of the injected fluid entered the Knox above the Copper Ridge (Fig. 34, Appendix 5).

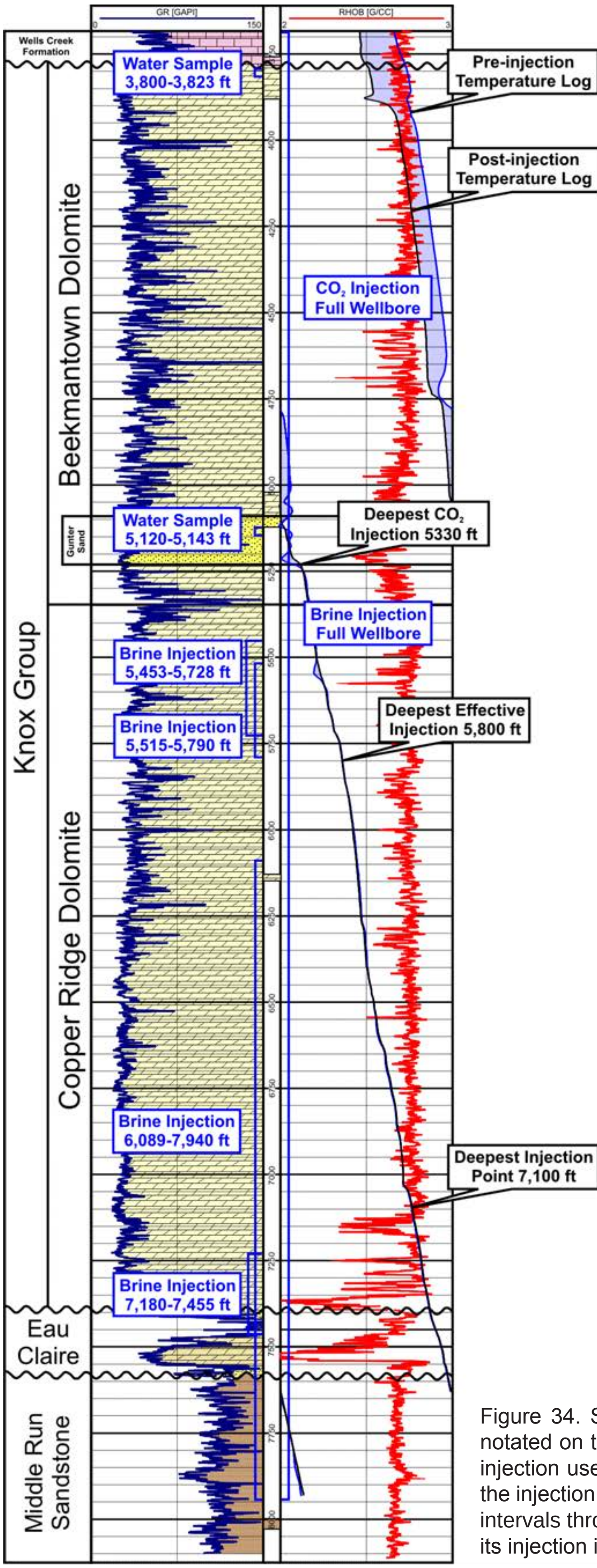


Figure 34. Summary of injection testing in the Marvin Blan No. 1 well annotated on the gamma ray–density–temperature log. Initial tests to establish injection used 18,454 bbl of 2 percent potassium chloride brine, followed by the injection of 323 tons of CO_2. Although brine injection was demonstrated in intervals throughout the Knox section, buoyancy of the CO_2 effectively limited its injection in the full wellbore to the upper 2,000 ft of the reservoir.

Thus, assuming an effective reservoir section of 3,870–5,800 ft, including the Beekmantown, Gunter, and uppermost 450 ft of the Copper Ridge, and 5 percent porosity cutoff, the available pore volume is reduced to 108 porosity-ft, or 63 percent of the total pore volume. This reduced pore volume would proportionally increase the required area to store 30 million tons of CO_2 to about 5,540 acres, and the number of injection wells from 11 to 16. If only the section above the Copper Ridge is prospective CO_2 storage reservoir, as suggested by injection test, pore volume is further reduced to 82 porosity-ft (Table 3), less than half of the total pore volume encountered in the Marvin Blan No. 1. Fracture porosity in the basal Copper Ridge does not contribute much to the total reservoir volume in the well (Fig. 15, Table 4), although the greater permeability found in test 1 may permit access to a larger area for CO_2 storage.

Regional CO_2 Storage Potential in the Knox

Regional extrapolation based on the results of a single well test can be problematic unless corroborating evidence can be demonstrated. For evaluating the regional potential for CO_2 storage in Kentucky Knox reservoirs, evidence is sparse but not lacking. Core analysis is not available from any of the wells penetrating the Knox in the region surrounding the Marvin Blan No. 1 well. Indirect evidence of porosity and permeability can be demonstrated in the form of active saltwater-disposal and gas-storage wells injecting into the Knox, however. There is only one active EPA UIC Class I injection well in Kentucky, the IMCO Recycling International Metal No. 1 well in Butler County, and two abandoned UIC Class I wells, the DuPont WAD No. 1 and WAD No. 2 wells in Jefferson County (Figs. 1, 5). All three wells were completed for injection into the Knox. Elsewhere in the Midwest, two UIC Class I wells completed in the Knox are active in east-central Illinois and one in northeastern Ohio (Fig. 1). The Knox is also

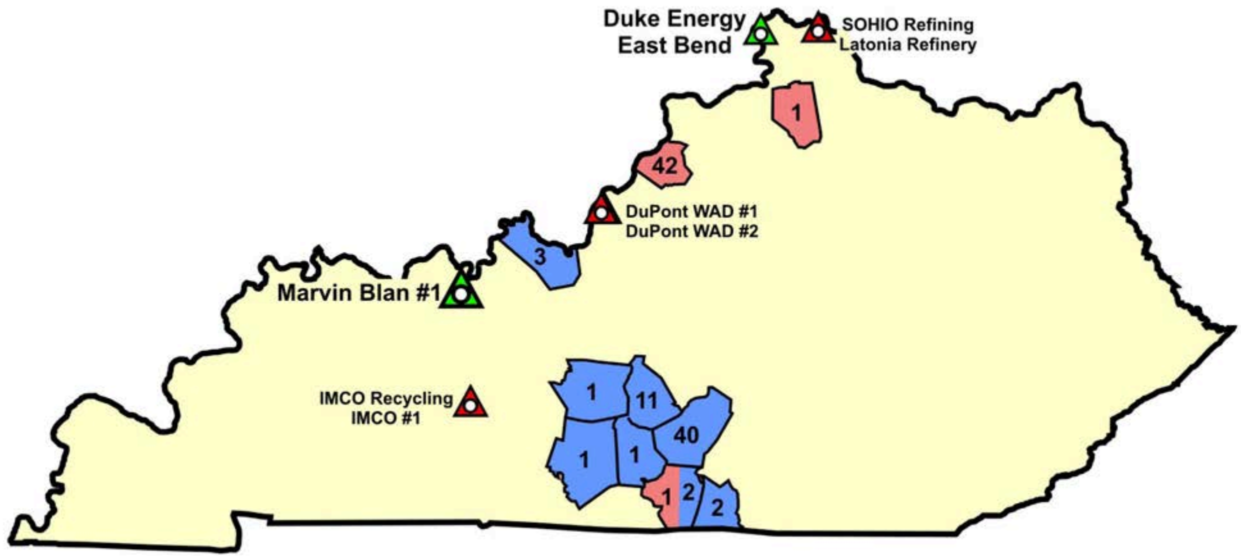


Figure 35. Distribution by county of injection wells developed in the Knox dolomites in Kentucky. Counties with saltwater injection wells are colored blue, and counties with gas-storage wells are colored red. Class I injection wells are noted with red triangles, and CO_2 injection tests are noted with green triangles.

used extensively for oil-field saltwater disposal and utility natural-gas storage. For example, there are 63 saltwater-disposal wells and 44 gas-storage wells in Kentucky completed in the Knox (Fig. 35). About 95 percent of the saltwater-disposal wells are located in Adair and adjacent counties, 80 mi southeast of the Marvin Blan No. 1 well, and all but two of the gas-storage wells are in Louisville Gas and Electric's gas-storage field in Oldham County, 80 mi northeast of the Marvin Blan No. 1. Outside of Kentucky, there are six active saltwater-disposal wells completed in the Knox in Harrison County, Ind., about 40 mi northeast of the Marvin Blan No. 1 well, and throughout southern Indiana there are an additional nine active saltwater-disposal wells and seven active gas-storage wells completed in the Knox (listed in the Indiana Geological Survey petroleum database). The distribution of active saltwater and gas-storage wells in Kentucky and southern Indiana suggests porous and permeable Knox is present in Kentucky west of the Cincinnati Arch.

A preliminary, conservative evaluation of prospective Knox reservoirs in western Kentucky was completed for those wells penetrating the Copper Ridge (Fig. 5) and having a density log for calculating porosity. Nine wells, extending from the WAD No. 1 well on the west flank of the Cincinnati Arch to the Jimmy Bell No. 1 in the north-central Rough Creek Graben, were selected for further evaluation; of these, six penetrated the entire Knox section. It was not possible, however, to evaluate porosity in heavily fractured Knox sections where the density log was affected by borehole rugosity and recorded anomalously low formation bulk density. On average, 10 percent of the Knox section in the nine wells was not included in this evaluation. Therefore, average pore volume at a 5-percent porosity cutoff was conservatively estimated to be 57 porosity-ft in the nine wells penetrating the Beekmantown (Table 8A), 46 porosity-ft in the six wells penetrating the Copper Ridge (Table 8B), and 113 porosity-ft for the entire Knox section (Table 8C). Pore volume is reduced in wells east of the Marvin Blan No. 1 (Fig. 5) because erosional truncation of the Beekmantown on the western flank of the Cincinnati Arch thins the section. Wells west of the Marvin Blan No. 1 (Fig. 5) have Beekmantown sections with pore volumes comparable to the 72 porosity-ft in the Marvin Blan No. 1 well (Table 8A), but lose pore volume in the Copper Ridge compared to the 90 porosity-ft in the Marvin Blan No. 1 (Table 8B) because of compaction at their greater depths (Fig. 7).

The western Kentucky region suitable for CO_2 storage in the Knox is limited updip to the east, by the point at which the base of the deepest sealing interval falls above the depth required to ensure

Table 8. Preliminary evaluation of prospective Knox reservoirs in western Kentucky, extending from the WAD No. 1 well on the western flank of the Cincinnati Arch to the Jimmy Bell No. 1 in the north-central Rough Creek Graben, was completed for those wells penetrating the Copper Ridge (Fig. 5) and having a density log for calculating porosity. The Marvin Blan No. 1 well was included for comparison. On average, approximately 10 percent of the Knox section in the nine wells was excluded from this evaluation because of borehole rugosity effects on the density log in heavily fractured sections.

A		Beekmantown-Gunter			
Well	**County**	**Porosity (%)**	**Gross Interval (ft)**	**Net Interval (ft)**	**Porosity-Feet**
WAD No. 1	Jefferson	9.1	700	651	59
Cavins No. D1-30 SWD	Harrison, Ind.	7.5	937	405	30
Braden No. 1	Breckinridge	7.4	1,627	663	49
Marvin Blan No. 1	Hancock	7.9	1,567	1,028	82
Edward Mattingly No. 1	Grayson	8.6	1,499	613	53
Herman Shain No. 1	Grayson	7.6	1,814	1,164	89
J.H. Brooks No. 1	Hart	7.9	1,295	927	73
Truman D. Riordan No. 1	Hart	7.1	1,452	649	46
Mark Turner No. 1	McLean	7.7	1,775	1,037	80
Jimmy Bell No. 1	Webster	7.1	4,319	1,884	134
	Average	7.9	1,699	762	60

B		Copper Ridge			
Well	**County**	**Porosity (%)**	**Gross Interval (ft)**	**Net Interval (ft)**	**Porosity-Feet**
WAD No. 1	Jefferson	8.2	2,096	916	75
Cavins No. D1-30 SWD	Harrison, Ind.				
Braden No. 1	Breckinridge				
Marvin Blan No. 1	Hancock	7.4	2,050	1,218	90
Edward Mattingly No. 1	Grayson				
Herman Shain No. 1	Grayson	6.7	2,602	635	43
J.H. Brooks No. 1	Hart	7.2	2,335	418	30
Truman D. Riordan No. 1	Hart	7.8	2,603	480	37
Mark Turner No. 1	McLean	6.8	2,649	1,059	72
Jimmy Bell No. 1	Webster	7.5	3,182	1,253	94
	Average	7.5	2,502	733	55

C		Total Knox			
Well	**County**	**Porosity (%)**	**Gross Interval (ft)**	**Net Interval (ft)**	**Porosity-Feet**
WAD No. 1	Jefferson	8.6	2,796	1,566	134
Cavins No. D1-30 SWD	Harrison, Ind.				
Braden No. 1	Breckinridge				
Marvin Blan No. 1	Hancock	7.7	3,617	2,248	172
Edward Mattingly No. 1	Grayson				
Herman Shain No. 1	Grayson	7.3	4,416	1,799	132
J.H. Brooks No. 1	Hart	7.7	3,630	1,344	103
Truman D. Riordan No. 1	Hart	7.4	4,055	1,129	84
Mark Turner No. 1	McLean	7.2	4,424	2,096	152
Jimmy Bell No. 1	Webster	7.3	7,501	3,137	228
	Average	7.7	4,348	1,617	125

storage of CO_2 in its supercritical state at approximately 2,500 ft below the surface. If the deepest sealing interval is to be the Black River, whose base lies approximately 200 ft above the top of the Knox, then the updip limit for CO_2 storage falls where the Knox is shallower than 2,700 ft. Thus, for western Kentucky, the updip regional limit of potential CO_2 storage approximates the –2,000-ft subsea structural contour on top of the Knox in eastern Breckinridge County and counties along structural strike to the east and south (Fig. 6). If the base of the Maquoketa is to define the eastern limit of CO_2 storage, about 650 ft above the top of the Knox, the prospective region is then limited to where the Knox is below about –2,650-ft subsea elevation (Fig. 6) in western Breckinridge County and counties along structural strike to the south and southwest (Fig. 36).

Defining the western extent of the prospective Knox CO_2 storage reservoir is both geologically and economically problematic: Is sufficient reservoir present, and does it lie at a depth where it can be economically exploited? The preliminary regional evaluation suggests that the Knox reservoir may be found throughout much of western Kentucky. For the purposes of determining the western extent of the Knox reservoir, two cases were considered (Table 9A–C): first, a Marvin Blan No. 1–like well completed in the upper Knox with a total depth 450 ft below the top of the Copper Ridge in order to encounter the largest section likely to have porosity and permeability sufficient to store CO_2 (Table 9A, case 1), and second, a well with any total depth required to store 1 million tons of CO_2 under a 200-acre tract (Table 9C, case 2); this is the approximate area required by a Marvin Blan No. 1–like well to store 1 million tons of CO_2 in the Beekmantown-Gunter and upper Copper Ridge, and, coincidentally, the approximate area of the Blan property. The associated issue is developing a well that is both deep enough to penetrate sufficient reservoir strata, but not so deep that the cost of drilling, completion, and operating the well is prohibitive. Increasing well depth increases these costs, but allows the storage of larger CO_2 volumes because of the greater density of supercritical CO_2 as reservoir pressure and temperature increase (Fig. 26). For the purposes of this evaluation, the deepest a commercial well may be drilled for CO_2 storage in the Knox is 9,000 ft.

In the Marvin Blan No. 1 well, the upper Knox section through the upper 450 ft of the Copper Ridge was approximately 2,000 ft thick. With an average surface elevation of 500 ft in western Kentucky, this suggests a westerly limit of potential Knox reservoir strata approximating the –6,500 ft subsea structural contour on top of the Copper Ridge (Fig. 7) to reach a drill depth of 9,000 ft. There are only four deep wells lying west of the Marvin Blan No. 1 well that penetrate the Copper Ridge, however: the Conoco Mark Turner No. 1 in McLean County, the Exxon Jimmy Bell No. 1 and Choice Duncan No. 1 in Webster County (Fig. 5), and the Sun Oil Stephens No. 1 well in Caldwell County. These wells lie in the Rough Creek Graben and have Knox sections that are not necessarily comparable to each other or what may be found to the north or south, outside of the Rough Creek Graben, because of structural and stratigraphic differences. The Stephens No. 1 well, which reached a total depth of 12,965 ft in the Eau Claire, was not logged across the base of the Copper Ridge because of junk left in the borehole below 11,950 ft. The total Knox section in this well is estimated to be 6,090 ft thick, but because of the effects of borehole rugosity, electric-log quality was inadequate for evaluating porosity and potential CO_2 storage. The upper Knox section in the Stephens No. 1 well falls within the prospective depth limit of 9,000 ft, however, suggesting the potential for CO_2 storage in northern Caldwell County and in counties along structural strike to the west (Fig. 36). Electric logs from the Choice Duncan No. 1 well record a Knox section 4,714 ft thick, but again the electric-log quality is inadequate for evaluating porosity because of the effects of borehole rugosity. The limited section of upper Knox lying above 9,000 ft in the Choice Duncan No. 1, a gross interval of 1,204 ft, suggests that the area downdip of this well, north of Webster County, will encounter the Knox at depths exceeding the 9,000-ft limit of this evaluation (Fig. 36).

The upper Knox section in the Mark Turner No. 1 well is approximately 2,500 ft thick with its base at 7,526 ft, thus falling within the 9,000-ft depth constraint, but requiring more than 200 acres to store 1 million tons of CO_2 (Table 9A, case 1). Increasing the evaluation depth in this well to 8,300 ft meets the requirement of 200 acres to store 1 million tons of CO_2 while staying within a total depth

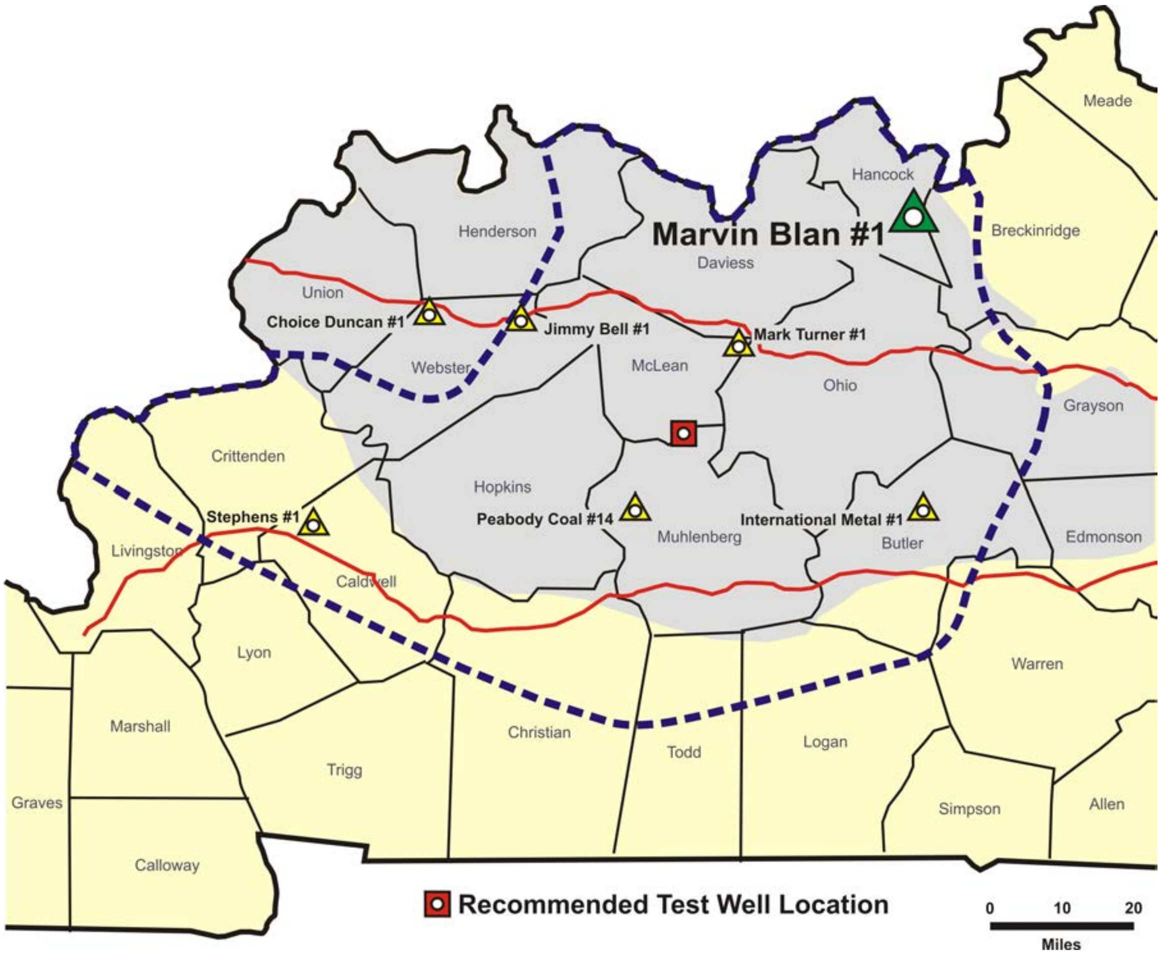


Figure 36. The prospective region for CO_2 storage in the Knox in western Kentucky is outlined by the blue dashed line. The Western Kentucky Coal Field is shaded gray and the Rough Creek Graben is outlined by the red lines. Wells of interest discussed in the text are noted with yellow triangles. To the east and south, the base of the Maquoketa lies above 2,500 ft and to the northwest, the top of the Knox lies below about 7,000 ft. Although the prospective region covers approximately 6,400 mi^2, faults in the prospective region, particularly in the Rough Creek Graben, may reduce the prospective area by limiting the locations of injection wells and well fields.

of 9,000 ft (Table 9C, case 2). The Jimmy Bell No. 1 has a Knox section considerably thicker than the other three deep wells, likely because of its location on the northern margin of the Rough Creek Graben, and the Beekmantown-Gunter section alone appears to have greater pore volume than the Beekmantown–upper Copper Ridge section in the Marvin Blan No. 1 well (Table 9A). When the upper 450 ft of Copper Ridge is included with the Beekmantown-Gunter interval in the Jimmy Bell No. 1, the Knox section in the well has a pore volume equal to the total pore volume of the Marvin Blan No. 1. Total depth of this interval in the Jimmy Bell No. 1 would be 10,719 ft, however, likely too deep to be economically drilled and completed (Table 9A, case 1). At a 9,000-ft cutoff depth (average reservoir depth of 6,975 ft), pore volume in the Jimmy Bell No. 1 is reduced to 94 porosity-ft but meets the requirement of 200 acres to store 1 million tons of CO_2 (Table 9C, case 2). This suggests that the western limit to the prospective region of CO_2 storage in the Knox is approximately along structural strike with the Jimmy Bell No. 1 well (Fig. 36). Total prospective area outlined in Figure 36 approximates that of the Western Kentucky Coal Field, or about 6,400 mi^2 (4.1 million acres). Using the evaluation criteria of a maximum total depth of 9,000 ft, and a maximum area per injection well of 200 acres per million tons of CO_2, estimated total pore volume available for CO_2 storage in the prospective area is 410 million acre-ft, or an estimated total storage capacity of about 20.5 billion tons of

CO_2. Mitigating this estimate are faults in the subsurface, which may have the potential for leakage and allowing CO_2 migration out of the storage reservoirs. Therefore, evaluation of faults in the prospective area will be necessary to determine whether they may act as seals for CO_2 storage or leakage pathways, and their impact on overlying reservoir sealing intervals.

The prospective region outlined in Figure 36 provides limits beyond which it is unlikely that suitable Knox reservoirs may be developed, but the uncertainty of the evaluation is great. The Har-Ken Oil Peabody Coal No. 14 well in northwestern Muhlenberg County (Fig. 36) penetrated 551 ft of Knox at 6,149–6,700 ft, total well depth, but electric-log quality is inadequate to evaluate even this limited section. The International Metal No. 1 well in Butler County, near the east-central margin of the prospective area (Fig. 36), is an active UIC Class I injection well, and penetrated 1,760 ft of Knox at 4,609–6,450 ft, total well depth. Injection in this well is intermittent, low volumes of fluid. Both well depth and injection volumes in the International Metal No. 1 well are insufficient to evaluate the Knox reservoir for commercial-scale CO_2 injection.

Table 9. Evaluation of the prospective area for CO_2 injection into the Knox in western Kentucky (Fig. 36). (A) A Marvin Blan No. 1–like well completed in the Beekmantown-Gunter and upper 450 ft of the Copper Ridge sections in order to encounter the largest section likely to have porosity and permeability sufficient to store CO_2 of any total depth (case 1), and a similar well with a maximum total depth of 9,000 ft (case 2). (B) Potential CO_2 storage volumes for the well cases in (A) based on their average depth, derived from Figure 26. (C) CO_2 storage areas required for the two well cases.

A		Pore Volume (φ_h, acre-feet)	
Well	**Top Knox (ft)**	**Case 1**	**Case 2**
Marvin Blan No. 1	3,780	108[a]	102[1]
Mark Turner No. 1	5,031	88[b]	96[2]
Jimmy Bell No. 1	5,950	171[c]	94[3]

B		CO_2 Storage (tons/acre-feet)	
Well	**Top Knox (ft)**	**Case 1**	**Case 2**
Marvin Blan No. 1	3,780	49	49
Mark Turner No. 1	5,031	51	52
Jimmy Bell No. 1	5,950	54	53

C		CO_2 Storage (acres/million tons)	
Marvin Blan No. 1	3,780	189	201
Mark Turner No. 1	5,031	223	202
Jimmy Bell No. 1	5,950	109	202

[a]Total depth 5,797 ft
[b]Total depth 7,526 ft
[c]Total depth 10,719 ft
[1]Total depth 5,700 ft
[2]Total depth 8,300 ft
[3]Total depth 9,000 ft

Adequacy of Western Kentucky Sealing Strata to Ensure Long-Term CO_2 Storage

Effective reservoir seals must have both porosity and permeability sufficiently low in order to prevent vertical migration of stored CO_2 from the storage reservoir. In order to evaluate the adequacy of potential sealing strata in the Marvin Blan No. 1 well for long-term CO_2 storage, strata encountered in the well were compared to the Farnham Dome CO_2 gas field in northeastern Utah. The Southwest Regional Partnership has evaluated the Farnham Dome CO_2 gas field as an analog for reservoir seals for geologic sequestration of CO_2 in a deep saline reservoir (Allis and others, 2001; White and others, 2002, 2004; Morgan and others, 2005; McPherson, 2006). The Farnham Dome, lying on the Colorado Plateau in northeastern Utah, provides a natural analog for CO_2 storage in a deep saline reservoir. Farnham Dome Field, a northwest-trending anticline approximately 3.5 mi long and 3 mi wide, was discovered in 1924 and first produced CO_2 in 1931. The discovery well produced at an initial rate of 1,200 mcfg CO_2 per day from 12 ft of perforations in the Navajo Sandstone at 3,100 ft (Morgan and Chidsey, 1991). One well produced CO_2 at 16,506 mcfg per day rate (Morgan and Chidsey, 1991), suggesting high reservoir pressure. Gas composition in Farnham Dome is 98.9 percent CO_2 (Morgan and Chidsey, 1991), although the source of the CO_2 has not been determined (White and others, 2004). Farnham Dome produced a total of 4.8 Bcfg of CO_2 from six wells before the field ceased production in 1972 for lack of a market (Morgan and Chidsey, 1991; Allis and others, 2001). CO_2 production has also been tested from the Sinbad Limestone Member of the Moenkopi Formation, Kaibab Limestone, and White Rim

Sandstone at Farnham Dome (White and others, 2004). CO_2 resources in Farnham Dome are estimated to be at least 1.5 Tcfg of CO_2 in an area of 3,700 acres (White and others, 2004).

The Navajo CO_2 reservoir lies at an average depth of 2,950 ft and is 260–350 ft thick with 40 net ft of pay zone and a 350-ft gas column (Morgan and Chidsey, 1991; Allis and others, 2001; White and others, 2004). Average porosity of the Navajo pay zone is 12 percent and permeability is estimated to be greater than 100 md (Morgan and Chidsey, 1991; Allis and others, 2001; White and others, 2004). Initial reservoir pressure is estimated to have been 1,008 psi at a reservoir temperature of 125°F (Morgan and Chidsey, 1991). Assuming even a normally pressured reservoir in the Navajo at Farnham Dome, CO_2 in the reservoir would have been in a supercritical state. Soil CO_2 flux over the Farnham Dome is uniformly low, consistent with shallow biogenic CO_2, and there is no evidence of leakage from the Navajo and deeper reservoirs (White and others, 2004). The seal over the Navajo, the stratigraphically highest reservoir, is the Carmel Formation (White and others, 2004). Mercury injection porosimetry measurements suggest any sealing formations of the Colorado Plateau are capable of supporting CO_2 column heights of at least 350 ft (White and others, 2004). Modeling of the Navajo reservoir suggests that CO_2 has been in place for about 10 million yr (White and others, 2004), and may have migrated into the reservoir as early as 58 million yr ago (Morgan and others, 2005). Numerical modeling of the Farnham Dome reservoir found that seal permeability of 0.01 md is required to store CO_2 for a period of at least 1,000 yr (White and others, 2002, 2003). CO_2 has a lower interfacial surface tension than methane; therefore, fine-grained lithologies are essential for good seals (Christopher and Iliffe, 2006). Thus, the question becomes: Are the sealing strata in western Kentucky adequate to ensure long-term CO_2 storage?

Three stratigraphic intervals overlying the Knox in the Marvin Blan No. 1 well may provide seals for potential CO_2 storage reservoirs in western Kentucky. Permeabilities measured in these strata range from a high of 0.0004 md in the basal Wells Creek to approximately 0.00002 md in the Maquoketa. Permeabilities measured in Colorado Plateau sealing strata range from 0.0002 md to 2×10^{-8} md (White and others, 2004). Thus, permeabilities measured in sealing strata in the Marvin Blan No. 1 well fall within the range of reservoir seals in the Farnham Dome Field. The numerical model of the Farnham Dome Field showed that only 0.01 md permeability was required to store the 350-ft CO_2 column at its reservoir pressure for at least 1,000 yr (White and others, 2002, 2003) at its initial reservoir pressure of 1,008 psi (Morgan and Chidsey, 1991), equivalent to a pressure gradient of 0.77 psi/ft. Fracture pressure of the Knox was measured in the Marvin Blan No. 1 well as 0.9 psi/ft; thus, the relatively high seal permeability of 0.01 md modeled for the Farnham Dome Field should be able to store CO_2 injected at pressures greater than 85 percent of the Knox fracture gradient. The 350-ft CO_2 column in the Farnham Dome Field is approximately twice the net height of a CO_2 column in a Marvin Blan No. 1–type well with 172 net ft of reservoir at a 5-percent porosity cutoff distributed over an approximately 3,600-ft section. When permeabilities of the Black River and Maquoketa in the Marvin Blan No. 1 well are considered, with rock strengths of 7,563 psi in the Black River and 17,264 psi in the Maquoketa, the requirements for an effective reservoir seal for CO_2 storage in western Kentucky are well exceeded.

Additional Research, 2010-11

This evaluation leaves three questions without unequivocal answers: (1) How far can the data and conclusions drawn from the Marvin Blan No. 1 well be extrapolated to estimate regional storage volumes? (2) What are the structural issues of faulting and fracturing that might compromise the integrity of both the CO_2 storage reservoir and the seal? (3) What will the maximum sustainable rate of CO_2 injection be? There are sparse regional geologic data to provide a definitive volumetric estimate of CO_2 storage capacity in western Kentucky Knox reservoirs. Also, this evaluation only addresses the issues of reservoir and seal integrity as they affect the Marvin Blan No. 1 well. As part of the regional effort to evaluate CO_2 storage in Midwestern reservoirs during 2010 and 2011, the Kentucky Geological Survey will model the Knox reservoir in western Kentucky, incorporating 2-D reflection-seismic data, available electric logs, and geologic data from cores and cuttings. Fault distributions, both at the surface and in the subsurface, and their potential to compromise seals and allow CO_2 leakage from storage reservoirs to shallower intervals, aquifers, and the surface, will be evaluated. In addition to analysis of 2-D reflection-seismic and well data, this study will require field investigation of surface faults and incorporation of reservoir-fluid geochemistry to determine subsurface reservoir continuity or compartmentalization. Geochemical modeling will characterize interactions between CO_2, reservoir fluids, and reservoir and sealing strata. The question of maximum sustainable injection rates will be addressed, in part, by the recovery and analysis of data from the pressure gage left in the Marvin Blan No. 1 prior to its temporary abandonment in August 2009, and an additional injection program to be performed in the well before it is permanently abandoned. The only sure way the maximum sustainable CO_2 injection rate will be determined, however, is by commercial-scale injection in a pilot CO_2 storage project.

Recommendations for Future Work

At the completion of the 2010-11 research program, the Knox stratigraphy, reservoir characteristics, and potential seals in the Rough Creek Graben will still be unknown. Because the Rough Creek Graben includes approximately half of the Western Kentucky Coal Field (Fig. 36), the lack of Knox data adds some risk to implementing industrial-scale CO_2 storage in the region. Risks include the depth and thickness of the Knox, reservoir pore volume, adequacy of seals, and presence of fractures and faulting. In order to mitigate these risks, a well should be drilled to a total depth sufficient to penetrate the entire Knox section, approximately 9,000 ft, at a location along the McLean-Muhlenberg County line (Fig. 36). The purpose of this well would be to evaluate pore volume in the Knox and reservoir seals in overlying strata in the central part of the Western Kentucky Coal Field. A stratigraphic test well would be the least-expensive way to accomplish this research and, depending on well design, could also be used for injection testing.

Conclusions

Western Kentucky holds the potential for CO_2 storage in the deep saline reservoirs in the Knox dolomite section, sealed by impermeable strata of the Black River carbonates and Maquoketa shales.

1. Assuming a 5-percent porosity cutoff for reservoir strata, average reservoir porosity was calculated to be 7.7 percent, and reservoir pore volume was conservatively estimated to be 172 porosity-ft. About 50 percent of the Knox reservoir was found within the upper 1,600 ft of the section.
2. Permeabilities measured in core plugs ranged from 0.0003 md in a dense dolomite to 206 md in a vuggy dolomite-facies sample from the Gunter. In general, core plugs from Knox dolomite-facies reservoirs fall between 0.001 md and 10 md horizontal permeability to air, with Gunter core plugs having horizontal permeabilities to air greater than 10 md. Permeability within the Knox calculated from pressure data collected during the injection testing program range from 1.8 md in the basal Copper Ridge to 36.8 md in the open wellbore below casing.
3. Sealing strata require permeabilities of less than 0.001 md. Average permeability of two core plugs from the Black River was less than 0.0002 md, and the 11 core plugs from the Maquoketa averaged 1.63×10^{-5} md. Both units could serve as effective reservoir seals, although the incidence of borehole rugosity through the Black River suggests the presence of fracturing that could compromise its sealing integrity. Rock strengths measured in core plugs from the Black River and Maquoketa were more than sufficient for the units to serve as reservoir seals.
4. The potential for CO_2 storage in Knox reservoirs was demonstrated by the subsurface geologic data from the Marvin Blan No. 1 well and injection testing with 18,454 bbl of potassium chloride brine and borax solution and 323 tons of CO_2. Depending upon connected permeability, a well similar to the Marvin Blan No. 1 should conservatively be able to store ap-

proximately 8,600 tons of CO_2 per acre-foot of reservoir. This equates to a surface area of 116 acres to store 1 million tons of CO_2, or approximately 3,500 acres to store the estimated 30 million tons of CO_2 produced during the operational life of a coal-fired power plant. A commercial-scale CO_2 storage project of that size would require seven to 10 injection wells.

5. The prospective region for CO_2 storage in the Knox is limited to the east and south by the shallowest depth at which the base of the Maquoketa may be encountered (2,500 ft), and to the northwest by the depth at which the base of the reservoir exceeds 9,000 ft and the area to store 1 million tons of CO_2 exceeds 200 acres. The prospective region for CO_2 storage in the Knox includes the central area of the Western Kentucky Coal Field and an adjacent area to the south, south of the Rough Creek Graben. Total prospective area approximates that of the Western Kentucky Coal Field, or about 6,400 mi^2. Estimated total pore volume available for CO_2 storage in the prospective area is 410 million acre-ft, or an estimated total storage capacity of about 20,500 million tons of CO_2.
6. Research during 2010-11 will focus on modeling potential CO_2 storage reservoir distribution within the Knox using regional 2-D reflection-seismic data, electric logs, and geologic data. The effects of faulting on reservoir and reservoir-seal integrity will be evaluated through interpretation of 2-D reflection-seismic data, electric logs, geologic and geochemical data, and field investigations. Interactions between CO_2, reservoir fluids, and reservoir and sealing strata will be evaluated through geochemical modeling.
7. The maximum sustainable rate of CO_2 injection into a Knox reservoir needs to be determined by a commercial-scale pilot injection project.
8. It is recommended that a test well be drilled to a total depth sufficient to penetrate the entire Knox section at a location along the McLean-Muhlenberg County line to evaluate pore volume and injectivity in the Knox in the central part of the Western Kentucky Coal Field.

Acknowledgments

This research was supported by a grant from the Commonwealth of Kentucky with additional contributions by the Energy and Environment Cabinet, the University of Kentucky, and a consortium of industry and government partners, including:

- Western Kentucky Carbon Storage Foundation Inc., Louisville, Ky.
- ConocoPhillips Co., Houston, Texas
- Peabody Energy, St. Louis, Mo.
- E.ON U.S., Louisville, Ky.
- Tennessee Valley Authority, Knoxville, Tenn.
- Illinois Department of Commerce and Economic Opportunity, Office of Coal Development, Springfield, Ill.
- U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, Morgantown, W.Va.
- GEO Consultants LLC, Paducah, Ky.
- Schlumberger Carbon Services, Houston, Texas
- Smith Management Co., Lexington, Ky.
- Wyatt, Tarrant & Combs LLP, Lexington, Ky.

Drill-site access was graciously granted by Marvin and Brenda Blan, Hawesville, Ky., and by R&B Resources LLC, Gaylord, Mich., without whose cooperation this project would not have been possible. Co-principal investigator Dave Williams, manager of the Kentucky Geological Survey's Henderson office, was the representative in Hancock County with local government officials, negotiated agreements and coordinated drill-site access with the Blans, and made public-outreach presentations explaining the project. In short, Dave Williams made the project happen. Mike Lynch deftly coordinated public-outreach efforts, an essential part of this project. Dave Harris, Energy and Minerals Section head, handled budgeting and financial issues. Jim Cobb, director of the Kentucky Geological Survey, provided the overarching management of the project.

There were many contributors to this report, whose reports are found in Appendices 3–6: Jim Cobb, Dave Harris, Dave Williams, Brandon Nuttall, Marty Parris, Kathy Takacs, Jim Drahovzal, and Mike Lynch of the Kentucky Geological Survey; Michelle Pittenger, David Pena, Ray Reid, and Chip Feazel of ConocoPhillips; Jeffrey Dravis, consultant to ConocoPhillips; Phil Papadeas and Bill Armstrong, Sandia Technologies; and Bob Butsch of Schlumberger Carbon Services. My apologies to anyone who may have been missed. My thanks to Dave Williams and Meg Smath, Kentucky Geological Survey; Doug Schetzel, E.ON U.S.; Diana Tickner, Peabody Energy; and Michelle Pittenger, whose comments and edits contributed to the quality of this report.

Project-management services were provided by Sandia Technologies LLC, Houston, Texas. Seismic-data acquisition and processing were performed by WesternGeco LLC, Houston, Texas. Electric-log surveys were performed by Weatherford U.S., Houston, Texas, and mudlogging by Geosearch Logging Inc., Edmond, Okla. Core analyses were performed by Weatherford Laboratories, Houston, Texas. Water analyses were performed by the Kentucky Geological Survey, Lexington; ConocoPhillips Co., Houston; Accutest Laboratories, Dayton, N.J.; and Isotech Laboratories, Champaign, Ill. Gas analyses were performed by Isotech Laboratories. CO_2 injection was performed by Praxair Inc., Danbury, Conn.

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