

Kentucky Geological Survey
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**Geology of the Kentucky Geological Survey
Marvin Blan No. 1 Well, East-Central Hancock
County, Kentucky**

J. Richard Bowersox and David A. Williams

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Geology of the Kentucky Geological Survey Marvin Blan No. 1 Well, East-Central Hancock County, Kentucky

J. Richard Bowersox and David A. Williams

Abstract

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 CO₂ injection in the Western Kentucky Coal Field, following the mandate and partial funding from Kentucky's House Bill 1, August 2007. Installation of a groundwater monitoring well was required as a condition of obtaining a U.S. Environmental Protection Agency Underground Injection Control Class V Permit prior to drilling the Blan well; however, no groundwater was encountered under the Blan well site. The groundwater monitoring well was immediately plugged and abandoned in accordance with State regulations, and the UIC permit was amended to require monitoring of two domestic water wells and two developed springs within approximately 2 mi of the Blan well site. Drilling of the Blan well commenced in April 2009 and was completed in June 2009.

Testing CO₂ injection and storage was completed in two phases during 2009 and 2010. The Blan well penetrated an unfaulted Early Pennsylvanian through Neoproterozoic stratigraphic section characteristic of western Kentucky north of the Rough Creek Graben. Minor hydrocarbon shows were encountered during drilling. Whole-diameter 4-in. cores were recovered from the Late Devonian New Albany Shale, Late Ordovician Maquoketa Shale and Black River Group, Middle Cambrian–Lower Ordovician Knox Group (Beekmantown Dolomite, Gunter Sandstone, and Copper Ridge Dolomite), and Precambrian Middle Run Sandstone. Electric logs recorded in the Marvin Blan No. 1 can serve as type logs for western Kentucky. Structural dip in the well was found to be homoclinal, dipping approximately 0.5° west above the Knox unconformity, 1° west in the Knox Group and Eau Claire Formation, and about 3.5° north in the Middle Run.

The Knox Group, the target interval of the well, has a complex lithology including 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 in the Beekmantown, Gunter, and Copper Ridge dolomite facies, and fine-grained quartz sand with dolomite cement in the sandstone facies of the Gunter. CO₂ storage capacity of the Knox was evidenced by reservoir properties of porosity and permeability and the injection testing programs.

Reservoir seals were evaluated in the Knox and overlying strata. Within the Knox, permeabilities measured in vertical core plugs from the Beekmantown and Copper

Ridge Dolomites suggest that intraformational seals may be problematic. Three stratigraphic intervals overlying the Knox in the Marvin Blan No. 1 well may provide seals for potential CO₂ storage reservoirs in western Kentucky: the Wells Creek Formation, Black River Group, and Maquoketa Shale. The Wells Creek and Black River had permeabilities suggesting that these intervals may act as secondary sealing strata. The primary reservoir seal for the Knox, however, is the Maquoketa. The Maquoketa is a dark gray, calcareous, silty, fissile shale. Maximum seal capacity calculated from permeabilities measured in vertical core plugs from the Maquoketa exceeded the net reservoir height in the Knox by about two orders of magnitude. Rock strength measured in core plugs from the Maquoketa suggests that any CO₂ migrating from the Knox would likely have sufficient pressure to fracture the Maquoketa.

Phase 1 injection testing used 18,454 bbl of synthetic brine and 323 tons of CO₂ (equivalent to 1,765 bbl of fluid or 5,646 mcf of gaseous CO₂), and phase 2 injection testing used a total of 4,265 bbl of synthetic brine and 367 tons of CO₂ (2,000 bbl of liquid or 6,415 mcf of gaseous CO₂). Calculating the reservoir volume required to store a volume of supercritical CO₂ used data provided by wireline electric logs, analysis of whole and sidewall cores, wireline temperature and pressure surveys, and analysis of formation waters collected prior to injection tests. The most likely storage capacities calculated in the Knox in the Marvin Blan No. 1 ranges from 450 tons per surface acre in the phase 2 Gunter interval to 3,190 tons per surface acre for the entire Knox section. At the completion of testing, the injection zone in the Marvin Blan No. 1 well was permanently abandoned with cement plugs in accordance with Kentucky and U.S. Environmental Protection Agency regulations.

Regional extrapolation of CO₂ storage potential based on the results of a single well test can be problematic unless corroborating evidence can be demonstrated. Core analysis from the Knox is not available from wells in the region surrounding the Marvin Blan No. 1 well, although indirect evidence of porosity and permeability can be demonstrated in the form of active saltwater-disposal and gas-storage wells injecting into the Knox. This preliminary regional evaluation suggests that the Knox reservoir may be found throughout much of western Kentucky. The western Kentucky region suitable for CO₂ storage in the Knox is limited updip, to the east and south, by the depth at which the base of the Maquoketa lies above the depth required to ensure storage of CO₂ storage in its supercritical state and the deepest a commercial well might be drilled for CO₂ storage. The resulting prospective region has an area of approximately 6,000 mi², beyond which it is unlikely that suitable Knox reservoirs may be developed. Faults in the subsurface, which serve as conduits for CO₂ migration and compromise sealing strata, may mitigate the area with Knox reservoirs suitable for CO₂ storage.

The data from the Marvin Blan No. 1 well make an important contribution to understanding the subsurface strata in western Kentucky, and clarify relationships between electric-log responses, lithology, and rock properties, and effectively demonstrate the CO₂ storage potential of the Knox and sealing capacity of the Maquoketa. The results of the injection tests in the Blan well, however, provide a basis for evaluating supercritical CO₂ storage in Cambrian-Ordovician carbonate reservoirs throughout the Midcontinent.

Introduction

The Kentucky Geological Survey's Marvin Blum No. 1 well was drilled in east-central Hancock County, Ky. (Figs. 1–2), about 4 mi southeast of the Ohio River, to demonstrate the feasibility of CO₂ injection and storage in the Western Kentucky Coal Field, following the mandate and partial funding from the Kentucky Legislature's House Bill 1 in August 2007. The well was located on the easternmost margin of the Western Kentucky Coal Field in order to evaluate the CO₂ storage characteristics of the Knox Group, which has a wide distribution in Kentucky. The Marvin Blum No. 1 is one of several CO₂ injection test wells drilled in the Midcontinent (Fig. 1). This site was optimal for testing multiple potential storage reservoirs in the Knox; evaluating the multiple sealing zones in the Knox, Black River Group carbonates, and Maquoketa Shale; minimizing drilling and testing costs; and satisfying the legislative mandate to be located in the Western Kentucky Coal Field. The well was designed to meet U.S. Environmental Protection Agency standards for protecting shallow groundwater aquifers from any contamination during drilling, CO₂ injection testing, or subsequent post-injection migration of CO₂ from the Knox.

Summary of Drilling and Testing

Drilling of the Marvin Blum No. 1 well commenced on April 24, 2009, after 18 mo of planning, drill-site due diligence and construction, and regulatory agency permitting (Bowersox and others, 2009). All depths in this report are measured from the drilling rig kelly bushing (KB; 15 ft above the ground surface) unless otherwise noted. It reached its total depth of 8,126 ft in the Precambrian (Neoproterozoic) Middle Run Sandstone on June 15, 2009. A total of 3,617 ft of the Knox Group section was encountered in the well. The Beekmantown Dolomite, the uppermost formation of the Knox Group in western Kentucky, was penetrated at 3,780 ft, the Gunter Sandstone at 5,090 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 (Table 1). Drilling through the Knox proved to be difficult: Borehole deviation greater than 5° required specialized equipment to return the well to vertical and maintain a vertical borehole, circulation was lost in a fracture at 5,581 ft, and a jammed

core barrel resulted in only 19 ft of core being cut in the Copper Ridge.

Surface conductor pipe was cemented at 52 ft, 13⁵/₈-in. casing was cemented at 441 ft for surface groundwater protection, and 8⁵/₈-in. casing required to isolate the injection-test zones from shallower strata was cemented at 3,660 ft in the Dutchman Limestone, 120 ft above the Knox Group. The hole was left uncased below 3,660 ft to facilitate testing in the Knox. 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 a retrievable bridge plug in casing at 3,625 ft. Two downhole pressure-temperature monitoring gages were set in place below the bridge plug pending subsequent testing. Pressure and temperature data were recorded every minute for slightly more than a year, providing a unique record of subsurface reservoir conditions in the Knox. Operations in the phase 2 testing program commenced with retrieval of the bridge plug and long-term pressure gages in August 2010, followed by mechanical isolation of the Gunter to an interval from 5,038–5,268 ft for injection testing. Following the completion of testing, the injection zone below casing at 3,660 ft in the Marvin Blum No. 1 was abandoned with cement plugs and the well site reclaimed in October 2010. In accordance with U.S. Environmental Protection Agency and State regulations, the Marvin Blum was permanently abandoned in October 2011.

The Marvin Blum No. 1 was drilled through the characteristic Paleozoic section of western Kentucky from Early Pennsylvanian to Middle Cambrian (Swezey, 2009), and reached its total depth in the Neoproterozoic rocks (Fig. 3). This report summarizes the Marvin Blum No. 1 well testing, including the major stratigraphic units penetrated by the well, a table of formation depths, and a correlated electric log.

Logging and Coring Programs

Three wireline electric-log runs were made during the drilling of the Marvin Blum No. 1: array induction (dual induction), spontaneous potential, gamma ray, and borehole caliper from 442 ft to the surface; array induction, spontaneous potential, gamma ray, spectral gamma ray with lithol-

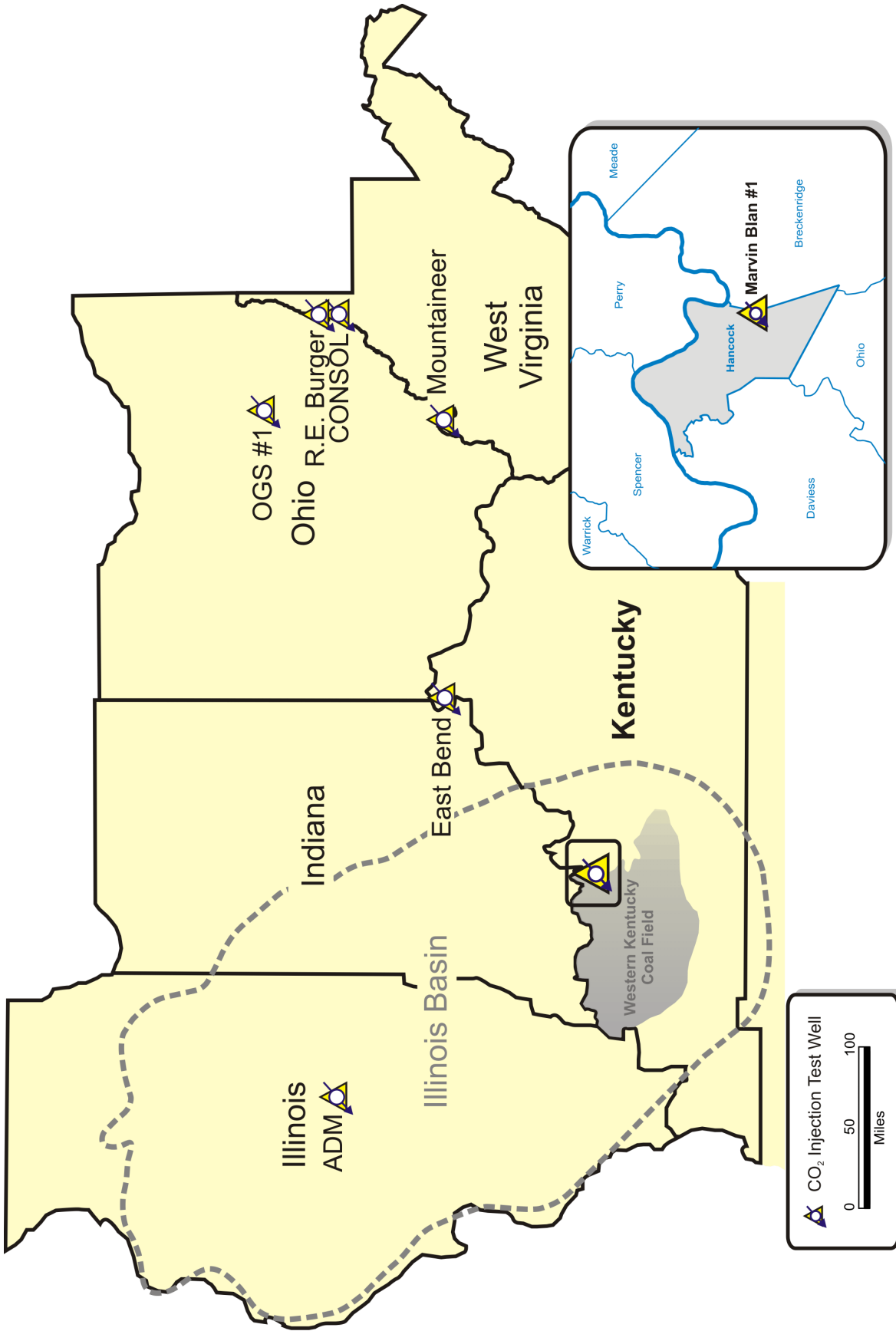
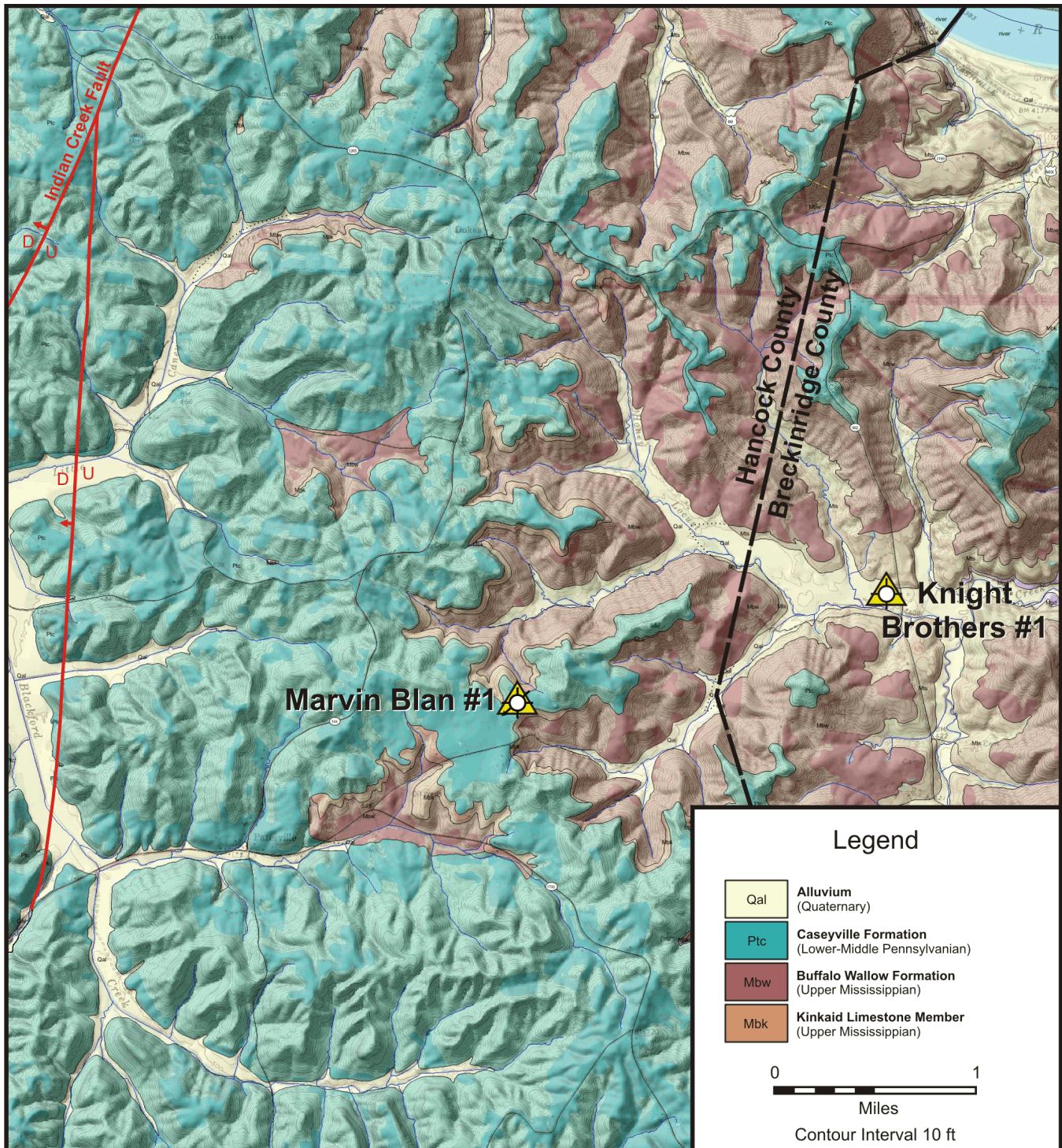


Figure 1. Locations of the Marvin Blan No. 1 and other CO₂ injection test wells in surrounding states.



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

Figure 2. Surface geology of east-central Hancock County, Ky., showing the location of the Marvin Blan No. 1 well and Knight Brothers No. 1 well that drilled into the Copper Ridge Dolomite. Adapted from Bergendahl (1965).

ogy analysis, photoelectric formation density and compensated neutron porosity, dipole sonic with mechanical rock properties analysis, and borehole

caliper from 3,662 ft to casing at 441 ft; and array induction, spontaneous potential, gamma ray, photoelectric density and compensated neutron

Table 1. Depths to the top of important formations in the subsurface for each logging run in the Marvin Blan No. 1 well.					
<i>Logging Run:</i>		<i>Monitoring Well</i>	<i>1</i>	<i>2</i>	<i>3</i>
<i>Date Logged:</i>		<i>9-Apr-09</i>	<i>24-Apr-09</i>	<i>9-May-2009</i>	<i>15-Jun-09</i>
<i>Well Total Depth:</i>		<i>427</i>	<i>442</i>	<i>3,660</i>	<i>8,126</i>
<i>Datum Elevation:</i>		<i>625 GL</i>	<i>635 KB*</i>	<i>635 KB*</i>	<i>635 KB*</i>
<i>Age¹</i>	<i>Formation</i>	<i>Monitoring Well</i>	<i>Logging Run 1</i>	<i>Logging Run 2</i>	<i>Logging Run 3</i>
	Surface	0	NL	NL	
<i>Early Pennsylvanian</i>					
	Caseyville Sandstone	8	26	22	
<i>Late Mississippian</i>					
	Buffalo Wallow Shale	15	32	28	
	Palestine Sandstone	64	56	52	
	Menard Limestone	86	83	79	
	Vienna Limestone	226	241	237	
	Tar Springs Sandstone	absent	absent	absent	
	Glen Dean Limestone	284	301	297	
	Golconda Limestone	373	387	383	
	Jackson Sandstone	NP	NP	459	
	Barlow Limestone			486	
	Cypress Sandstone			501	
	Renault Limestone			599	
<i>Middle Mississippian</i>					
	Ste. Genevieve Limestone			663	
	St. Louis Limestone			858	
	Salem Limestone			1,049	
	Fort Payne Formation			1,417	
<i>Early Mississippian</i>					
	New Providence Shale			1,837	
<i>Late Devonian</i>					
	New Albany Shale			1,857	
	Base of the New Albany Shale			1,973	
<i>Middle Devonian</i>					
	Sellersburg Limestone			1,973	
	Jeffersonville Limestone			2,124	
<i>Early Devonian</i>					
	Clear Creek Limestone			2,292	
<i>Silurian</i>					
	Bailey Limestone			2,438	
	Laurel Dolomite			2,486	
<i>Late Ordovician</i>					
	Maquoketa Group			2,705	
	Maquoketa Shale			2,786	
	Black River Group			3,124	
	Pecatonica Limestone			3,563	NL
<i>Middle Ordovician</i>					
	Joachim Dolomite			3,585	3,585
	Dutchtown Limestone			3,645	3,645

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<i>Age</i> ¹	<i>Formation</i>	<i>Monitoring Well</i>	<i>Logging Run 1</i>	<i>Logging Run 2</i>	<i>Logging Run 3</i>
<i>Early Ordovician</i>					
	Knox Group				3,780
	Beekmantown Dolomite				3,780
	Gunter Sandstone				5,090
	Base of the Gunter Sandstone				5,230
<i>Late Cambrian</i>					
	Copper Ridge Dolomite				5,347
<i>Middle Cambrian</i>					
	Eau Claire Formation				7,397
<i>Precambrian: Neoproterozoic</i>					
	Middle Run Sandstone				7,484
*KB 14.5 ft above GL **KB 5 ft above GL NL=Not logged NP=Not penetrated					
¹ Swezey (2009) and sources cited therein					

porosity, dipole sonic with mechanical rock properties analysis, Compact Formation Micro Imager and analysis, and borehole caliper from 8,126 ft (total depth) to casing at 3,660 ft. Electric logs from the Blan well are available as raster images and digital data files from the Kentucky Geological Survey's online oil and gas records database.

The gamma-ray log from electric-log run 1 records the top of the Early Pennsylvanian Caseyville Sandstone at 26 ft KB, 11 ft below the surface, whereas the gamma-ray log from electric-log run 2 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, though internally depth-consistent, are recorded 4 ft higher than their apparent true drill depth. The Marvin Blan No. 1 was mud-logged from the surface to its total depth at 8,126 ft with drill cuttings collected in 5-ft intervals. Formation tops and lithologies correlated and recorded on the mud log vary from those correlated from the electric logs by as much as several hundred feet.

Whole-diameter 4-in. cores were cut and recovered from the New Albany and Maquoketa Shales and Black River carbonates to evaluate the sealing capabilities of these intervals. The Beekmantown Dolomite, Gunter Sandstone, and Copper Ridge Dolomite were cored with 4-in. whole-diameter cores to test reservoir properties of porous and permeable intervals, and reservoir seal properties of impermeable intervals within the Knox Group. The Middle Run Sandstone was cored to test whether it has sufficient porosity and permeability to be considered as a potential CO₂ storage reservoir. A total of 395 ft of cores was cut and recovered from the New Albany (1,875–1,905 ft; 30 ft), Maquoketa (2,800–2,831 ft; 31 ft), Black River (3,335–3,396 ft; 61 ft), basal Wells Creek Formation–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). Core depths as drilled may differ from electric-log depths by approximately 0.5 to 1.5 ft. As part of the second phase of testing, 20 rotary sidewall cores were cut and recovered from the Gunter. Cores and drill cuttings from the Marvin Blan No. 1 have been archived for fur-

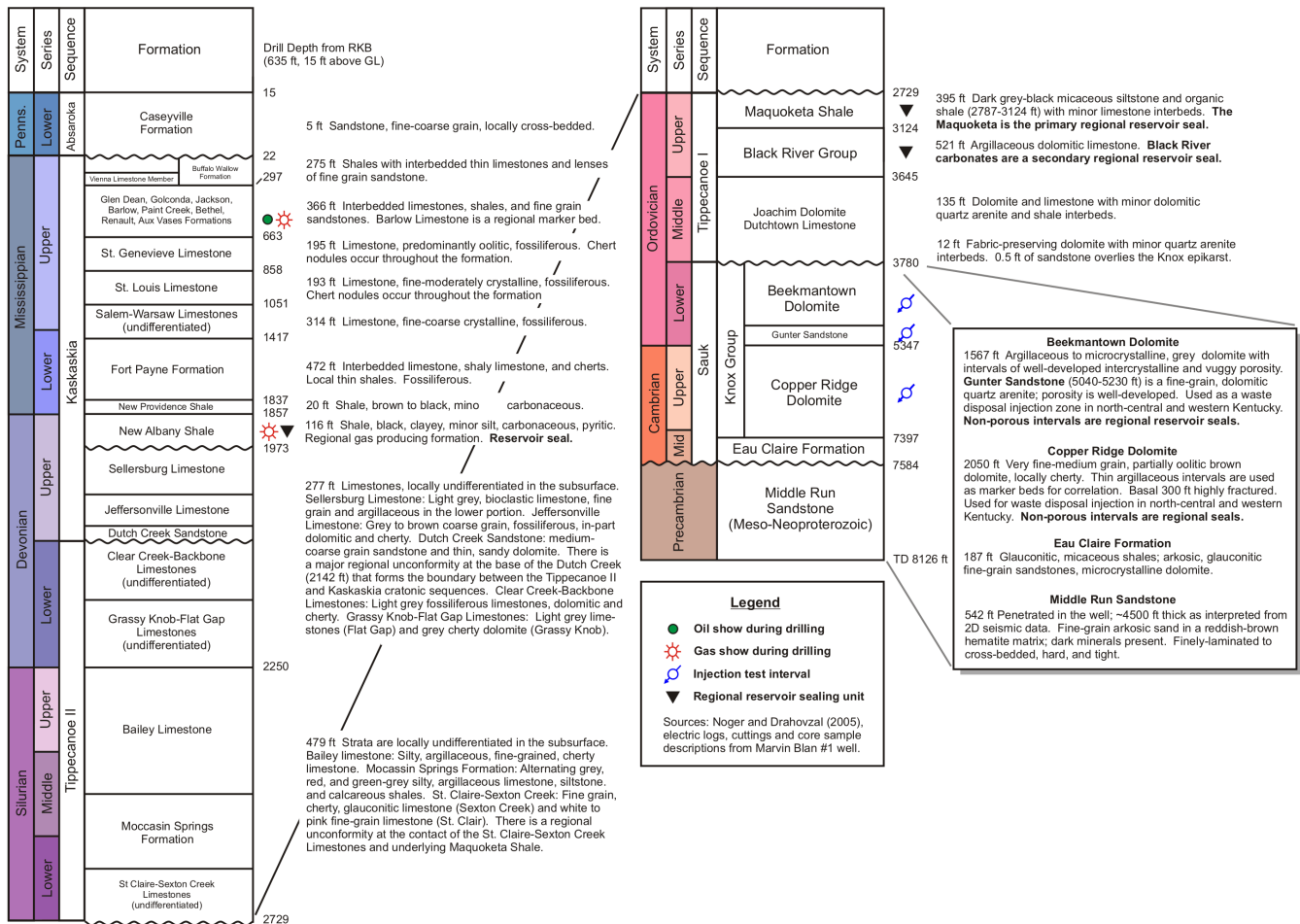


Figure 3. Stratigraphy of the subsurface section penetrated by the Marvin Blan No. 1 well, with lithologic summaries of major intervals, oil and gas shows, injection intervals, and sealing intervals. Adapted from Swezey (2009) and sources cited therein.

ther study at the Kentucky Geological Survey Well Sample and Core Library in Lexington.

Groundwater Monitoring

The Caseyville Sandstone is an important aquifer in Hancock County (Carey and Stickney, 2005). A groundwater monitoring well was required as a condition of the U.S. Environmental Protection Agency Underground Injection Control Class V Permit prior to drilling the Marvin Blan No. 1. The purpose of this well would have been to monitor the groundwater from the Late Mississippian Tar Springs Sandstone (Table 1) for any migration of CO₂ from the deep storage reservoir to the shallow aquifer (Bowersox and Williams, 2008). The monitoring well 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 (Table 1), 4 ft structurally lower than in the Marvin Blan No. 1 when compared to electric-log run 1 (Table 1). Sandstones in the Tar Springs were only approximately 8 ft thick in the Inklebarger Drilling Quinn No. 1 well, 1,860 ft northwest of the monitoring well. The Quinn No. 1 well is 16 ft structurally lower at the top of the Glen Dean Limestone, which underlies the Tar Springs, where present, than in the Marvin Blan No. 1. The Tar Springs was absent in the monitoring well; it 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 immediately plugged and abandoned in accordance with State regulations. Groundwater protection casing was cemented from 441 ft to the surface in the Blan well

(Fig. 4); however, no groundwater was encountered under the well site.

Because no groundwater was encountered under the Blan well site, the Underground Injection Control permit was amended to require monitoring at four sites, including two domestic water wells and two developed springs, within approximately 2 mi of the well site. Water from these sample sites was analyzed for bicarbonate concentration, pH, total dissolved solids, and turbidity. The thick Maquoketa Shale and deeper impermeable strata ensure that CO₂ injected into the Knox does not migrate to the groundwater in the shallow subsurface. Analyses have shown no geochemical evidence of CO₂ leakage from the Knox to any shallow freshwater aquifer.

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 Figures 3 and 4. Because no faults are apparent in the section penetrated by the well, the electric logs from the Blan well stand as type logs for the basal Pennsylvanian through uppermost Precambrian (Neoproterozoic) stratigraphic section in this part of western Kentucky north of the Rough Creek Graben. Strata were deposited in four cratonic sequences (Sloss, 1963) (Fig. 3); the Upper Precambrian–Lower Ordovician Sauk sequence, Lower Ordovician–Upper Ordovician Tippecanoe I subsequence of Noger and Drahovzal (2005), Lower Silurian–Middle Devonian Tippecanoe II subsequence of Noger and Drahovzal (2005), and Middle Devonian–Upper Mississippian Kaskaskia sequence. The Caseyville Sandstone–Buffalo Wallow Shale 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). In general, the stratigraphic succession of these sequences and subsequences consists of a basal transgressive,

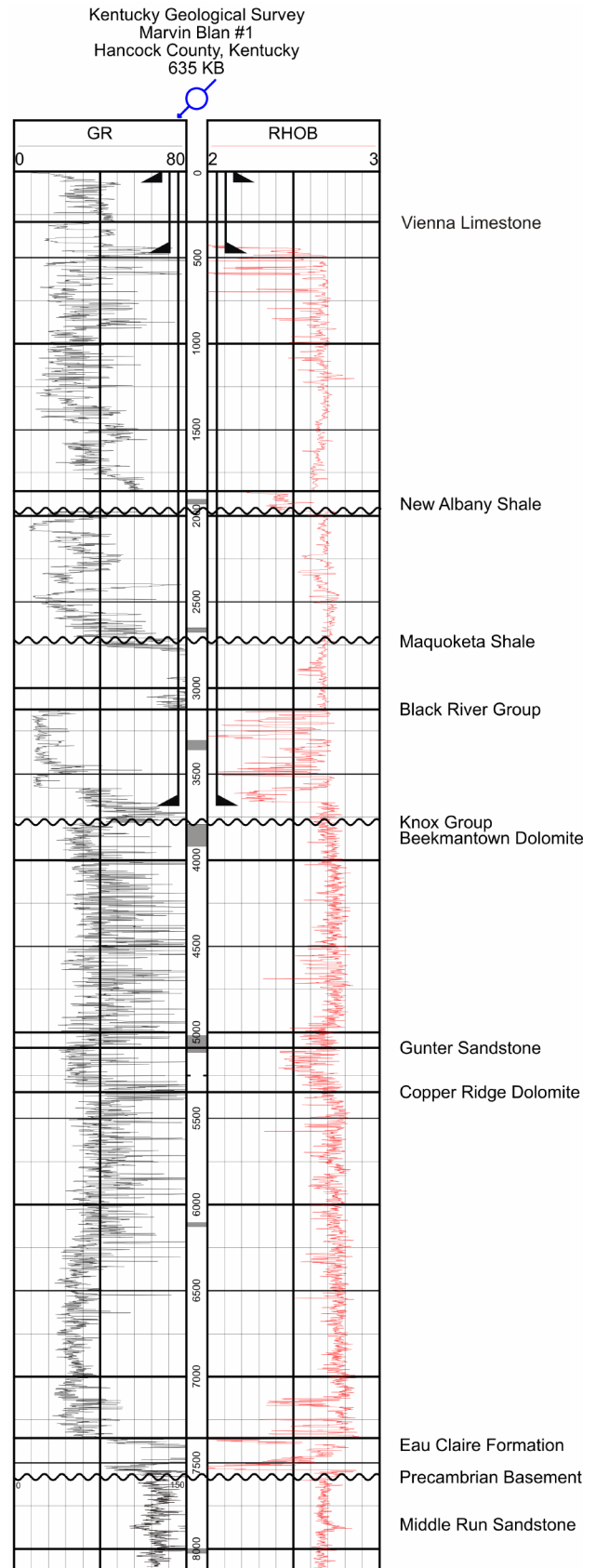


Figure 4. Correlated electric log from the Marvin Blan No. 1 well. The curve on the left in black is the natural gamma ray in API units and the curve on the right in red is the formation bulk density in g/cm³. Cored intervals are shaded gray.

shallow-marine to nonmarine sandstone overlain by deeper-water to basinal shales, limestones, and dolomites with rare, lenticular sandstones. The Tippecanoe II subsequence is incomplete in western Kentucky and is missing the basal sandstone (Fig. 3).

Structural Geology of Hancock County

Generalized subsurface structure contours on top of the Knox and a subsurface correlation cross section are shown in Figures 5 and 6. In western Kentucky and the Hancock County region, strata dip homoclinally approximately 0.5° west above the Knox unconformity and 1° west below the Knox unconformity in the Knox and Eau Claire. Dip in the Middle Run is about 3.5° north. The surface fault nearest the Marvin Blan No. 1 is a strand of the northeast-trending Indian Creek Fault Zone, lying approximately 2.2 mi west of the well (Figs. 2, 5). The Rough Creek Graben, a major east-west-trending structural feature in western Kentucky, lies approximately 18 mi south of the Marvin Blan No. 1 (Fig. 5). No subsurface faulted sections were encountered in the Blan well, although fractures with small offsets were interpreted from the Compact Formation Micro Imager log.

Surficial Geology of the Well Site

Two formations are present at the surface in the vicinity of the Marvin Blan No. 1 well site in east-central Hancock County (Bergendahl, 1965; Greb and others, 1992): the Early Pennsylvanian Caseyville Sandstone and the shale facies of the Late Mississippian Buffalo Wallow Shale and its Kincaid Limestone Member (Figs. 2–3). Approximately 100 ft of fluvial sandstone of the Caseyville is 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 the Caseyville lies directly on the Buffalo Wallow at the surface (Fig. 2). Valley bottoms are filled by Quaternary alluvium with a maximum thickness of approximately 25 ft (Fig. 2). The original soil profile is estimated to have been approximately 12 ft thick prior to site preparation, and the soil profile penetrated on the well pad during installation of the cellar and

conductor pipe was estimated to be 10 ft thick. A 6-ft section of Caseyville overlying 24 ft of Buffalo Wallow was penetrated in the Marvin Blan No. 1 well.

A maximum of approximately 130 ft of Buffalo Wallow shales, thin limestones, and lenticular sands is exposed in the valleys surrounding the well site (Fig. 2). The Kincaid is karstic, with sinkholes 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 by the University of Kentucky's Department of Earth and Environmental Sciences as part of the well-site due diligence prior to drilling (Bowersox and Williams, 2008). 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 of the Marvin Blan No. 1

The intermediate subsurface section, the section from the casing point at 441 ft to the casing point at 3,660 ft, includes Middle Mississippian–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 strata below the top of the Laurel Dolomite at 2,486 ft include the primary seals for the underlying Knox CO₂ 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 (Table 1). This section extends from the basal Dutchtown Limestone to the Middle Run, largely consisting of the Knox, and includes the underlying Eau Claire Formation. At total depth, the Marvin Blan No. 1 had encountered 542 ft of Middle Run, a brick-red, fine-grained, crossbedded, lithic sandstone unconformably below the Eau Claire at 7,584 ft. The Middle Run was cored at 8,000–8,030 ft to determine its reservoir properties for potential CO₂ storage, but it proved unsuitable because of very low porosity and permeability (Bowersox and others, 2010).

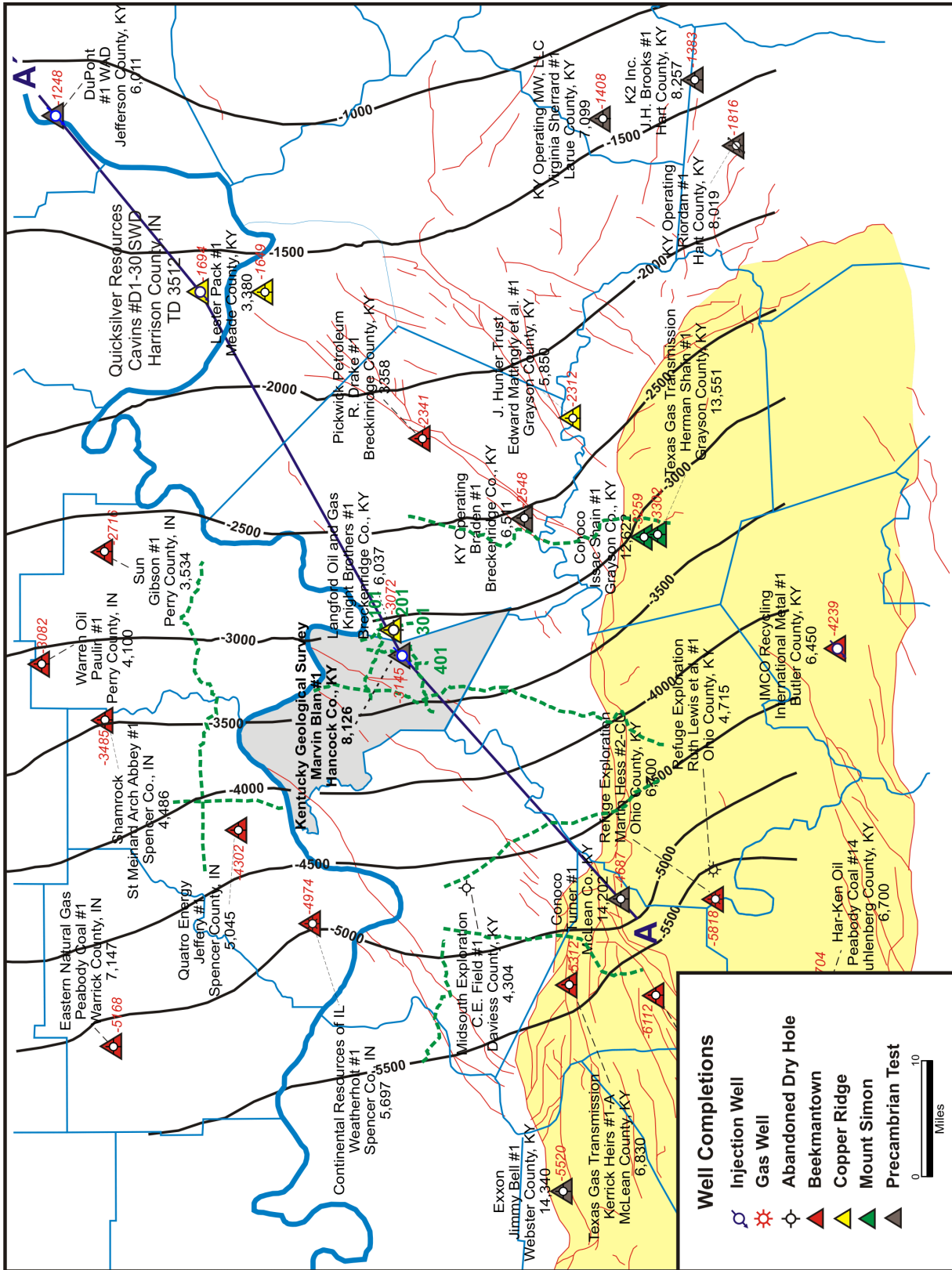


Figure 5. Generalized structure contours on top of the Knox Group in western Kentucky. The contour interval is 500 ft. Subsea elevation in feet at the top of the Knox is indicated in red to the right of the well symbol. The Ohio River is indicated by the heavy blue line and 2-D reflection-seismic lines are indicated by green dashed lines. The Rough Creek Graben is shaded yellow. Cross section A-A' (Fig. 6) extends from the Conoco Mark Turner No. 1 well in McLean County to the DuPont WAD No. 1 in Jefferson County.

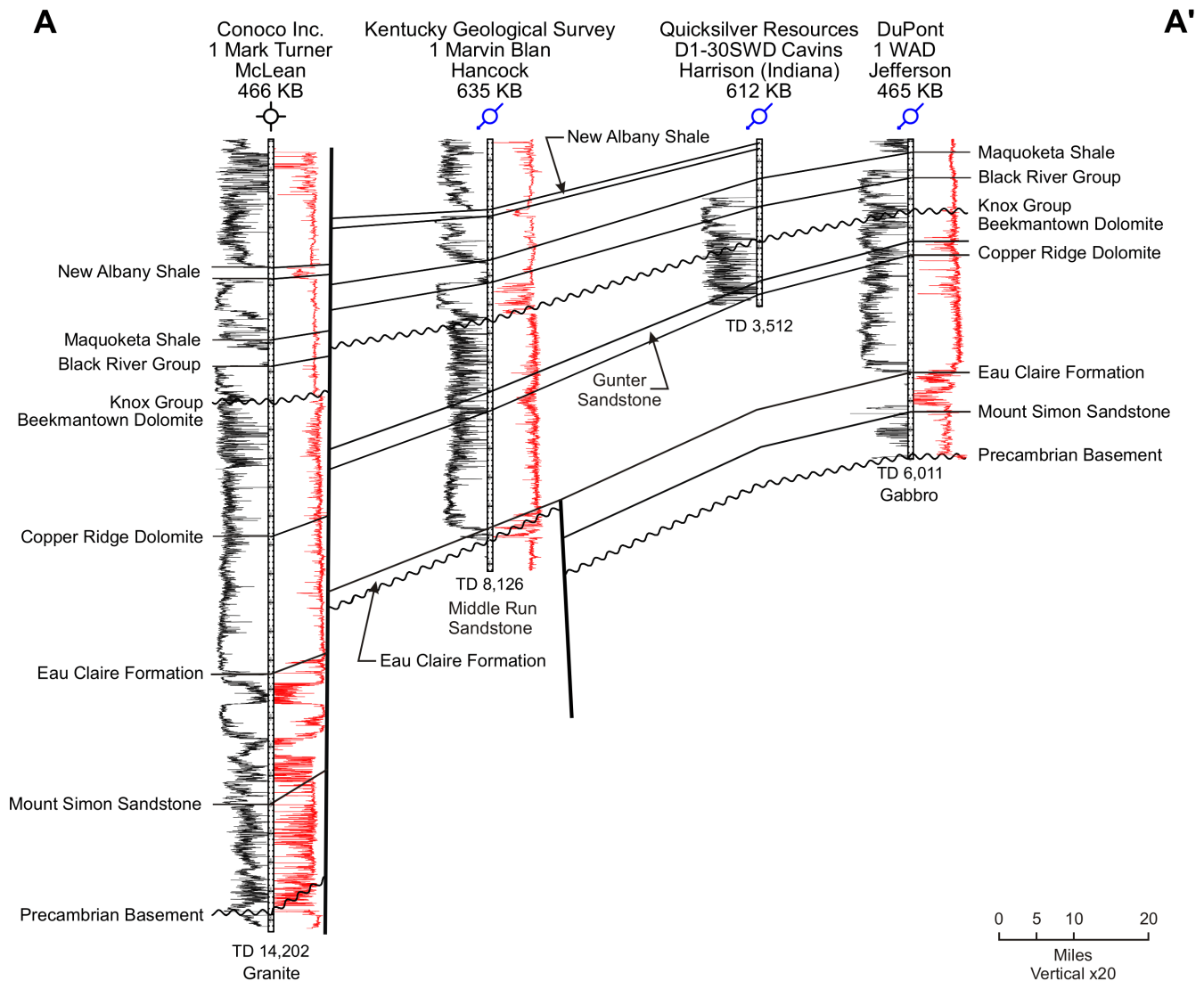


Figure 6. Generalized subsurface cross section correlating major formation tops. Well-log curves for all wells are the same as shown in Figure 4.

Hydrocarbon Shows During Drilling

Oil and gas in Hancock County has been produced, or hydrocarbon shows noted, in the shallow Late Mississippian sandstones and limestones, and in the Late Devonian naturally fractured New Albany Shale (Fig. 3). The Knox has not produced oil or gas in Hancock County or any surrounding counties, although elsewhere in Kentucky oil and gas are produced and gas stored in Knox reservoirs (Gooding, 1992). Hydrocarbon shows were logged in several intervals during drilling of the Marvin Blan No. 1: a gas show in the Late Mississippian Barlow Limestone at 496–500 ft, four slight

gas shows in the 500–600 ft interval, an oil and gas show in the Middle Mississippian 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 Shale at 1,857–1,973 ft. No H_2S was encountered during drilling. No recent commercial production has been developed in the area surrounding the Marvin Blan No. 1 well, although shallow oil production, less than 500 ft deep, was established before 1960 about 1 mi southwest of the well site, and five noncommercial wells were drilled and completed in the New Albany in 2006 at Victoria Crossroads, about 3 mi south of the Marvin Blan No. 1.

Knox Lithology and Reservoir Properties

The Beekmantown Dolomite was penetrated at 3,780–5,090 ft in the Marvin Blan No. 1 well (Figs. 3–4, 6), a gross interval of 1,310 ft. A total of 172 ft of whole-diameter 4-in. core was cut and recovered from the Beekmantown. The 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, however. 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 5,090–5,347 ft, a gross interval of 257 ft (Figs. 3–4, 6). 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 35 percent of the section. A whole-diameter 4-in. core recovered from the uppermost 32 ft of the Gunter showed the mixed lithology of this formation. Planar bedding and herringbone crossbeds were observed in the sandstone beds, indicating shallow-nearshore marine deposition. Dolomite interbeds were characterized by vuggy porosity developed in fabric-destructive dolomites, solution-enhanced fractures, and pervasive stylolites. Analysis of a formation-water sample recovered from the upper Gunter at 5,120–5,144 ft yielded 97,192 ppm of total dissolved solids, 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, overlying a thin, 187-ft section of Eau Claire (Figs. 3–4, 6). 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 dolograins, 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. An attempt to collect a formation-water sample from the Copper Ridge was unsuccessful.

Permeability and Porosity in the Knox

The Knox porosity system is a complex of (1) primary dolomite intercrystalline porosity and relic primary porosity associated with stromatolites, (2) vugs, fractures, and solution-enhanced fractures, (3) siliceous fabrics of microporous chert and moldic and interparticle pores associated with silicified peloidal grainstones, and (4) intergranular porosity in sandstone facies, primarily in the Gunter, enhanced by dissolution of the dolomite matrix (Figs. 7–8). Horizontal porosity and permeability were measured under ambient conditions in 34 horizontal core plugs selected from whole cores to represent the range of lithologies in the Knox, and in the 20 rotary sidewall cores from the Gunter. Porosity ranged from 0.3 percent in the densest dolomite intervals in the Beekmantown to 23.3 percent in the Gunter Sandstone, and permeability ranged from 0.0003 to 580 md. Porosity and permeability measured in core plugs and sidewall cores from the Gunter range from 0.7 to 7.2 percent porosity and 0.0003 to 1.17 md permeability in samples from the dolomite facies to 1.1 to 23.3 percent porosity and 0.17 to 1,570 md permeability in samples from the sandstone facies.

Reservoir Sealing Zones

Equally important for the evaluation of CO₂ storage potential in western Kentucky is the presence of adequate sealing intervals overlying any

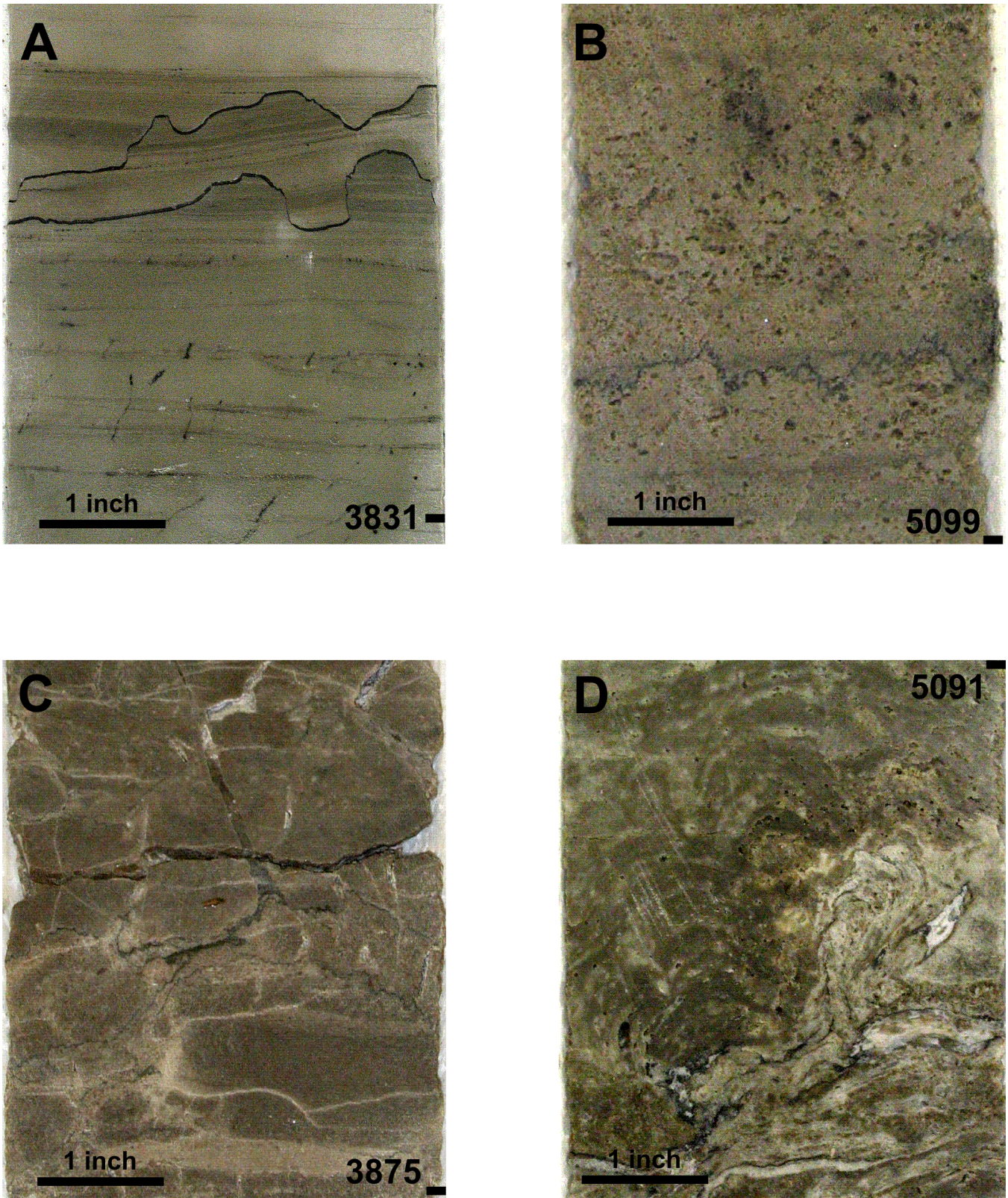


Figure 7. Typical reservoir fabrics from dolomite facies in the Beekmantown. (A) Intercrystalline porosity in relict microbial mat facies with an inverted, stylitized rip-up clast, 3,830.5–3,831.0 ft. (B) Stylitized vugular porosity developed in lagoonal facies, 5,098.5–5,099.0 ft. (C) Shoreface collapse 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.

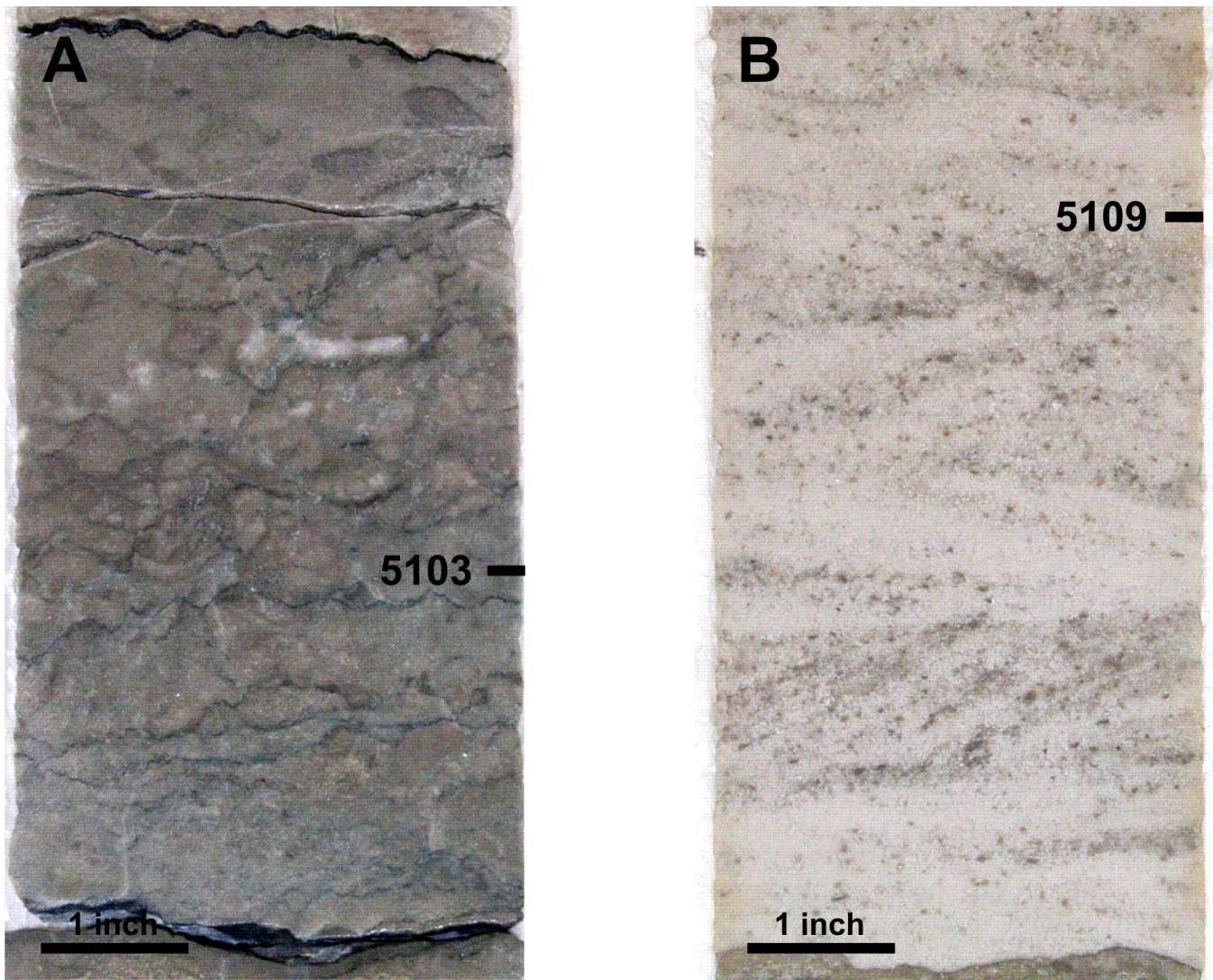


Figure 8. Facies developed in the Gunter. (A) Heavily stylitized, pervasively bioturbated collapse breccia in a Gunter Dolomite lagoonal facies. Gunter Dolomite facies are generally low porosity (less than 4 percent porosity). (B) Crossbeds indicative of beach and intertidal deposition in a Gunter sand facies. Sand facies are high porosity, averaging 8.7 percent porosity.

potential CO₂ storage reservoir. Effective reservoir pressure seals require permeability of 10⁻⁶ to 10⁻⁸ md (Deming, 1994). Primary sealing strata tested in the Marvin Blain No. 1 were the Black River carbonates and Maquoketa shales and their stratigraphic equivalents overlying the Knox (Harris, 2007); see Swezey (2009) for details of the correlations. Thick, impermeable intervals within the Knox may also act as reservoir seals, although there is an increased risk for leakage from the natural fracture system in the Knox (Finley, 2005; this study). The New Albany (Figs. 3-4) may act as a secondary seal for CO₂ storage in deeper saline reservoirs (Finley, 2005; U.S. 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. Two samples from the Black River carbonates were analyzed for their reservoir seal properties, but the porosity and permeability were not low enough to serve adequately as a primary CO₂ 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.

Vertical core plugs chosen as representative of intraformational reservoir seals within the Knox had porosity of 1.3 to 9.8 percent and perme-

ability to air of 0.0009 to 0.063 md. Thus, the low-permeability intervals in the Knox are unlikely to serve as sealing zones for long-term CO₂ storage. 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 and cored at 3,333–3,395 ft. Lithology in this core was gray limestone that parted along bioturbated, crinkly bedding planes. The entire Black River section shows borehole rugosity on the caliper log, suggesting pervasive fracture development. A vertical core plug from the Black River at 3,363.3 ft was analyzed for reservoir sealing properties. Its porosity was 0.4 percent and permeability was 0.0009 md, insufficient to act as a primary reservoir sealing zone but enough to serve as a first-line secondary seal above the Knox.

The lower section of the Late Ordovician Maquoketa Shale is a low-permeability groundwater-confining unit throughout the Midwest (Young, 1992a, b), and is considered a primary reservoir seal for CO₂ 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 penetrated 337 ft of Maquoketa Shale overlying the Black River from 2,787–3,124 ft. In contrast, KY Operating Co. Braden No. 1 well, located 16 mi to the southeast in Breckinridge County (Fig. 5), encountered a 214-ft-thick section of Maquoketa Shale overlying the Trenton Limestone (which normally overlies the Black River, but is absent in the Marvin Blan No. 1). This is because the Blan wellbore penetrated the subsurface Sebree Trough, a Midcontinent paleogeographic feature of the Middle to Late Ordovician section (Kolata and others, 2001; Ettensohn, 2003; McLaughlin and others, 2004). 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). In the Sebree Trough, the Trenton is absent where a thick section of Maquoketa was deposited (Kolata and others, 2001; Ettensohn, 2003; McLaughlin and others, 2004).

The Maquoketa Shale section was cored in the Marvin Blan No. 1 at 2,800–2,831 ft. Analyses of this core included descriptions and facies interpretation, laboratory analyses, thin-section photomicrographs, and CT-scan photographs.

Two facies were observed in the core: a dark gray, calcareous, silty, fissile shale with carbonate-rich concretionary layers 1 to 5 in. thick, and a dark gray, slightly calcareous, silty, fissile shale (Fig. 9). Laboratory analyses performed on 11 vertical plugs from the Maquoketa, taken at approximately 3-ft intervals from the top to the base of the core, included routine crushed-core analysis (porosity, permeability, and bulk-density analyses for very low-permeability rocks), X-ray diffraction analysis, and measurement of total organic carbon in the rock. X-ray diffraction analysis showed most plugs to be mudstone or clayey mudstone with 25 to 75 percent clays. Dominant minerals are illite-chlorite, calcite, and quartz. Rock-mechanical measurements made on two separate core plugs yielded a compressive strength of 17,264 psi. Total organic carbon measured in the Maquoketa plugs was very low, averaging 0.57 percent, and no sample exceeding 1 percent; the Maquoketa was found to be submature for hydrocarbon generation. Porosity of the 11 vertical core plugs was 3.7 to 7.0 percent and permeability was 5.28×10^{-5} to 3.29×10^{-7} md. Thus, the low permeability of the Maquoketa Shale facies would be sufficient to ensure long-term CO₂ storage in the deeper Knox reservoir.

Injection Testing in the Knox

Injection testing was completed in two phases: Phase 1 (summer 2009) tested the entire Knox section in the open borehole at 3,780–7,397 ft below casing at 3,660 ft, whereas phase 2 (summer 2010) tested a mechanically isolated section of the Gunter at 5,038–5,268 ft. During phase 1 testing, several intervals in the Knox Group were identified as potential CO₂ storage reservoirs by injection tests with synthetic brine, followed by CO₂ injection. After CO₂ injection, additional water was injected prior to temporary well abandonment. Total brine injected during phase 1 testing was 18,454 bbl, and total CO₂ injected was 323 tons (equivalent to 1,765 bbl of fluid or 5,646 mcf of gaseous CO₂). The wellbore was then temporarily abandoned with a retrievable bridge plug in casing at 3,625 ft. Operations in the phase 2 testing program commenced with retrieval of the bridge plug and long-term pressure gages, followed by mechanical isolation of the Gunter for injection testing. Phase 2 injection

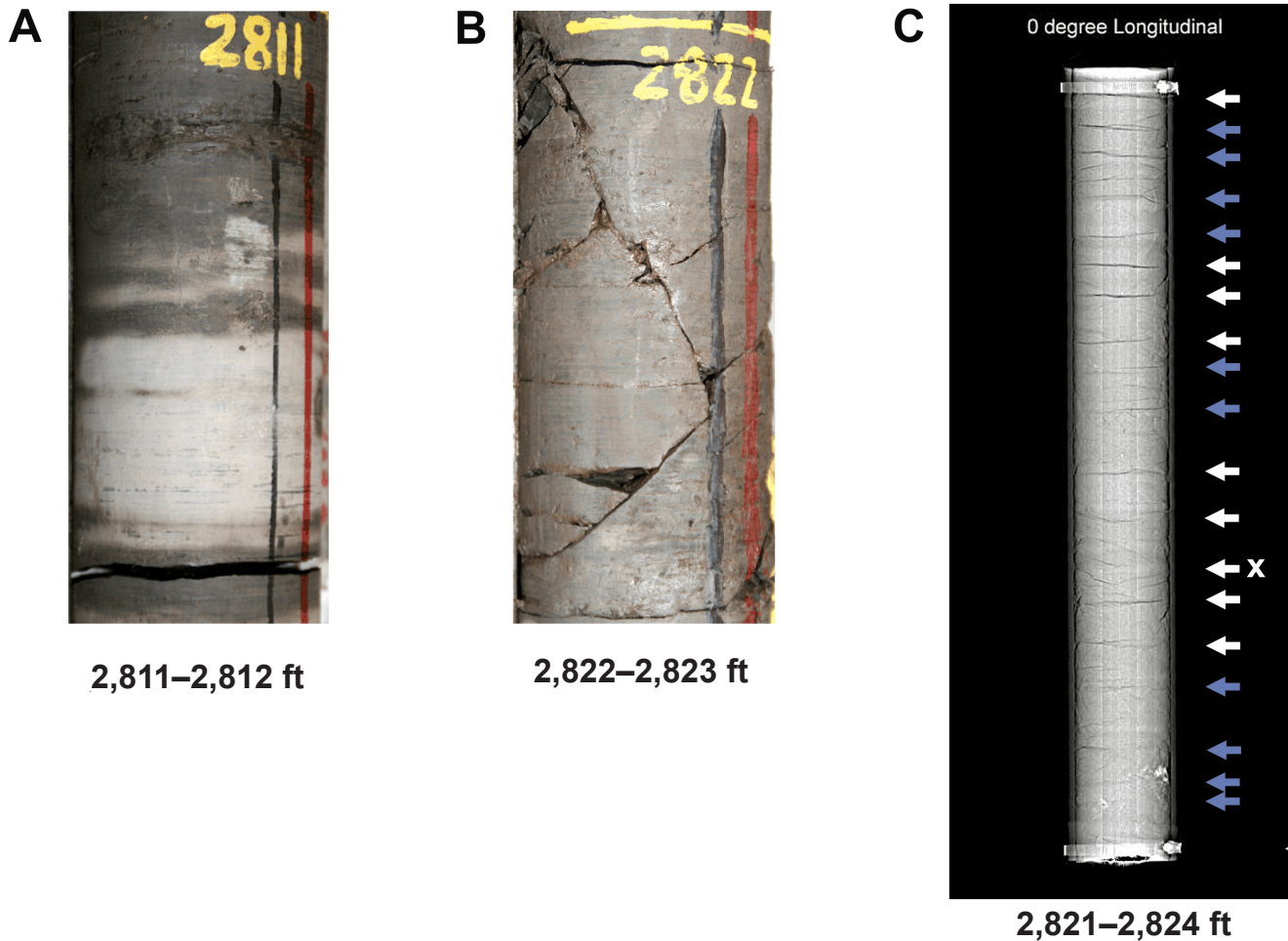


Figure 9. Cores from the Maquoketa Shale. (A) Core from 2,811–2,812 ft shows laminae in the Maquoketa. Calcareous layers are not visible in the whole-diameter core. The parting was a product of core handling during shipping to the laboratory. Photo by ConocoPhillips Co.; used with permission (B) Core from 2,822–2,823 ft shows natural fractures in the Maquoketa. Photo by ConocoPhillips Co.; used with permission. (C) CT scans of Maquoketa cores were performed before the cores were removed from their aluminum sleeves. Calcareous layers indicated with blue arrows and partings indicated with white arrows. Natural fractures shown in (B) are noted at “x.”

testing focused on the Gunter, the highest porosity and permeability section within the Knox at 5,038–5,268 ft. This interval was mechanically isolated to ensure a good packer seal during injection testing and thus mitigate wellbore pressure communication issues encountered during phase 1 testing. The interval was isolated by setting a cement plug at 5,268–5,545 ft and cementing 5½-in. casing in the open wellbore at 4,821–5,038 ft. The injection program was similar to the phase 1 injection program, with water being injected before and after CO₂ injection. A total of 4,265 bbl of synthetic brine and 367 tons of CO₂ (2,000 bbl of liquid or 6,415 mcf of gaseous CO₂) was injected during phase 2 testing. Following the completion of testing, the injection zone in the Marvin Blan No. 1 well was perma-

nently abandoned with cement plugs in accordance with Kentucky and EPA regulations, and the well site was reclaimed.

Calculation of Knox Reservoir CO₂ Storage Volume

Five types of data are needed to calculate the reservoir volume required to store a volume of supercritical CO₂: porosity, reservoir height, temperature, pressure, and formation-water salinity. These data were acquired by petrophysical and laboratory analysis of wireline electric logs, whole cores and sidewall cores, wireline temperature and pressure surveys, and formation waters recovered prior to injection tests. Porosity was calculated

from the formation-density log after testing the quality of its record through crossplots and comparison to laboratory analysis of whole core and sidewall core. Porosity calculated from the density log correlated well with porosity measured in the cores (Figs. 10–11). Scatter in the core porosity values (Figs. 10–12) reflects the choice of whole-core plugs and sidewall-core sample depths to measure specific reservoir properties of the Knox Group from an otherwise heterogeneous lithologic sequence. Two formation-water samples were collected from the Marvin Blain No. 1: one from the Gunter Sandstone, and the second at the top of the Beekmantown Dolomite near the unconformity with overlying Middle Ordovician strata.

The phase 1 effective test interval in the Knox Group at 3,780–5,750 ft had a mean porosity of 9.6 percent at the industry-standard 7 percent porosity cut-off (Medina and others, 2011), mean permeability of 9.3 md, and net reservoir height of 791 ft (Fig. 12). Effective reservoir pore volume for this interval is about 76 acre-ft per surface acre. The phase 2 test interval in the Gunter Sandstone at 5,038–5,268 ft, included in the phase 1 test interval, had a mean porosity of 11.0 percent at the 7 percent porosity cutoff, mean permeability of 12.5 md, and a net reservoir height of 165 ft. Phase 2 reservoir pore volume is about 18 acre-ft per surface acre, contributing about 24 percent of the total Knox pore volume tested during the phase 1 program. Reservoir temperature and pressure in the Knox Group at the phase 1 average reservoir depth of 4,764 ft was 103°F and 2,050 psi, and 105°F and 2,228 psi at the average phase 2 reservoir depth of 5,154 ft. For this evaluation, reservoir water salinity is assumed to be 100,000 ppm sodium chloride, approximately the salinity of water recovered from

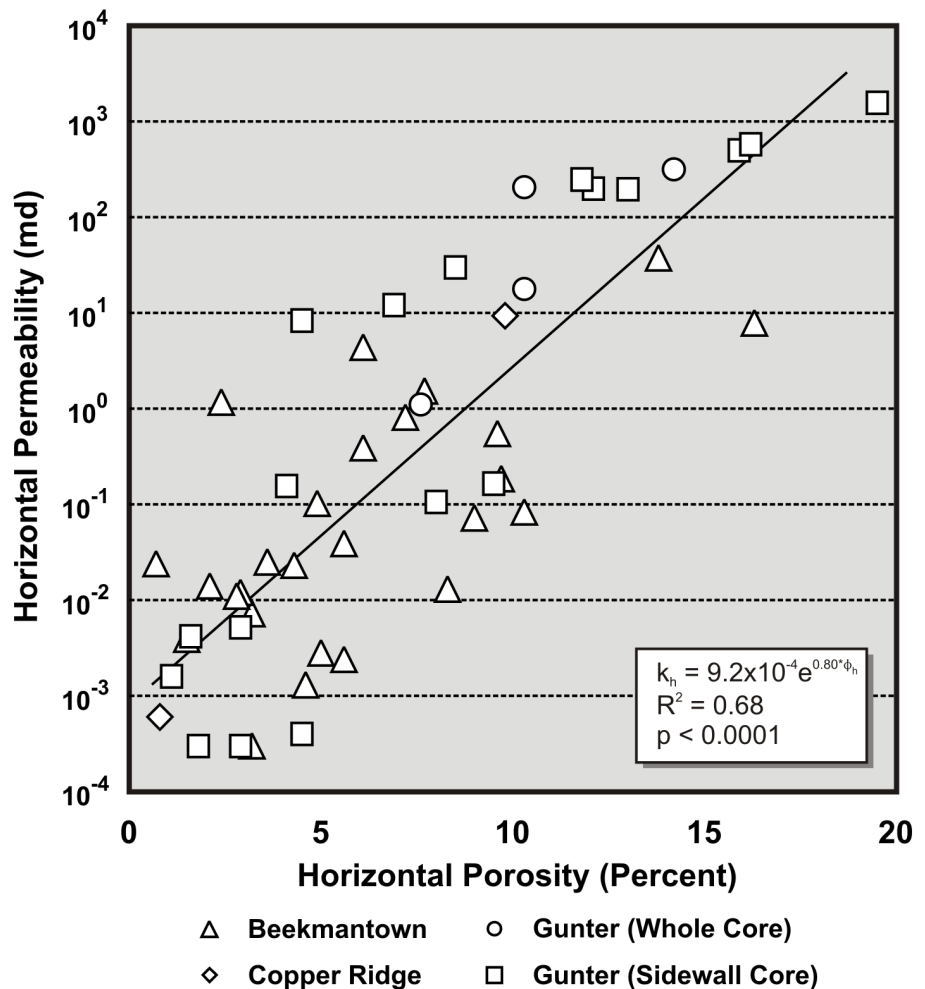


Figure 10. Porosity and permeability measured in horizontal core plugs and sidewall cores from the Knox.

the Gunter Sandstone. Density of CO₂ under average reservoir conditions (DeSimone, 2002) for the phase 1 test is 0.76 g/cm³, and 0.79 g/cm³ under phase 2 reservoir conditions.

CO₂ storage volume in the Knox was calculated using efficiencies for dolomite and clastic reservoirs from U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory (2010), weighted for the relative contributions of the dolomite sections and Gunter Sandstone to the total reservoir volume. The P₅₀ (most likely) efficiency factor for the Knox Group is 19.3 percent, with a range of 14.0 percent (P₁₀) to 25.5 percent (P₉₀). Efficiency factors for clastic reservoirs comparable to the Gunter Sandstone are 7.4 percent (P₁₀) to 24.0 percent (P₉₀), with a most likely efficiency factor of 14.0 percent (U.S. Department of Energy, Office of Fossil Energy, National

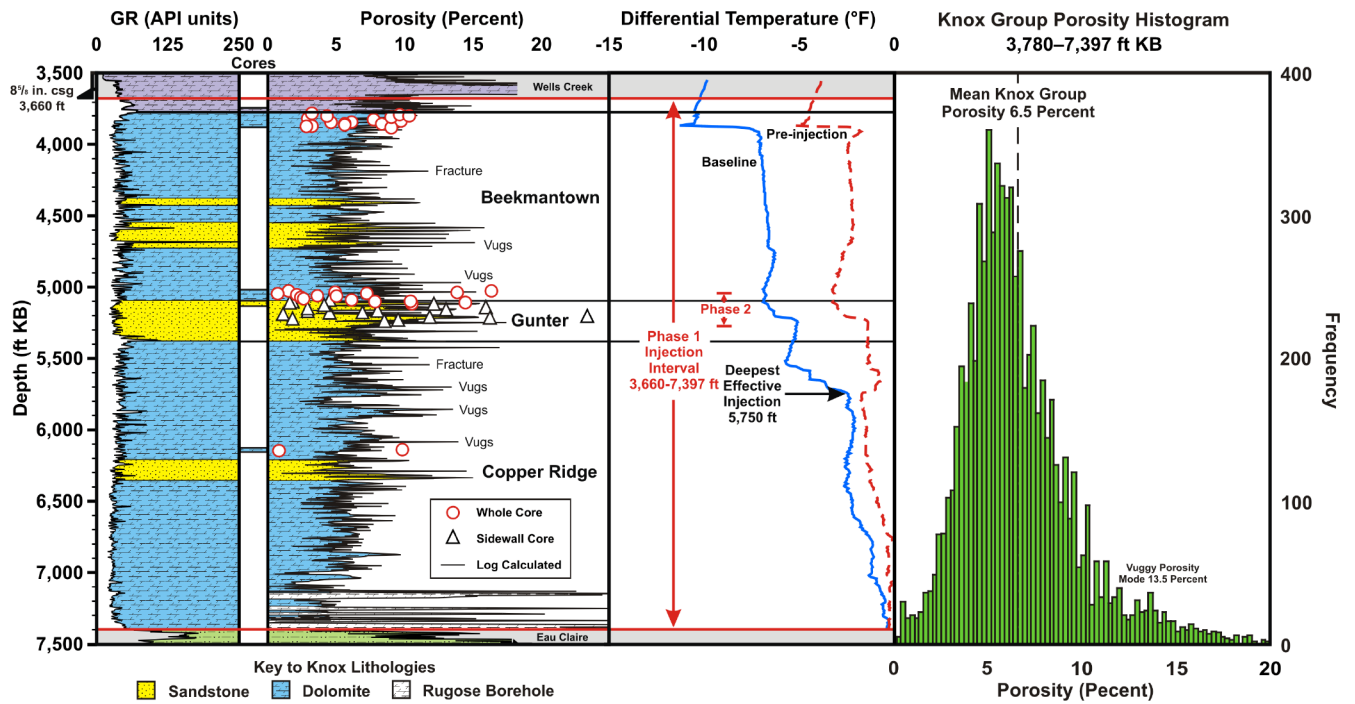


Figure 11. Reservoir characteristics of the Knox and results of the phase 1 injection testing.

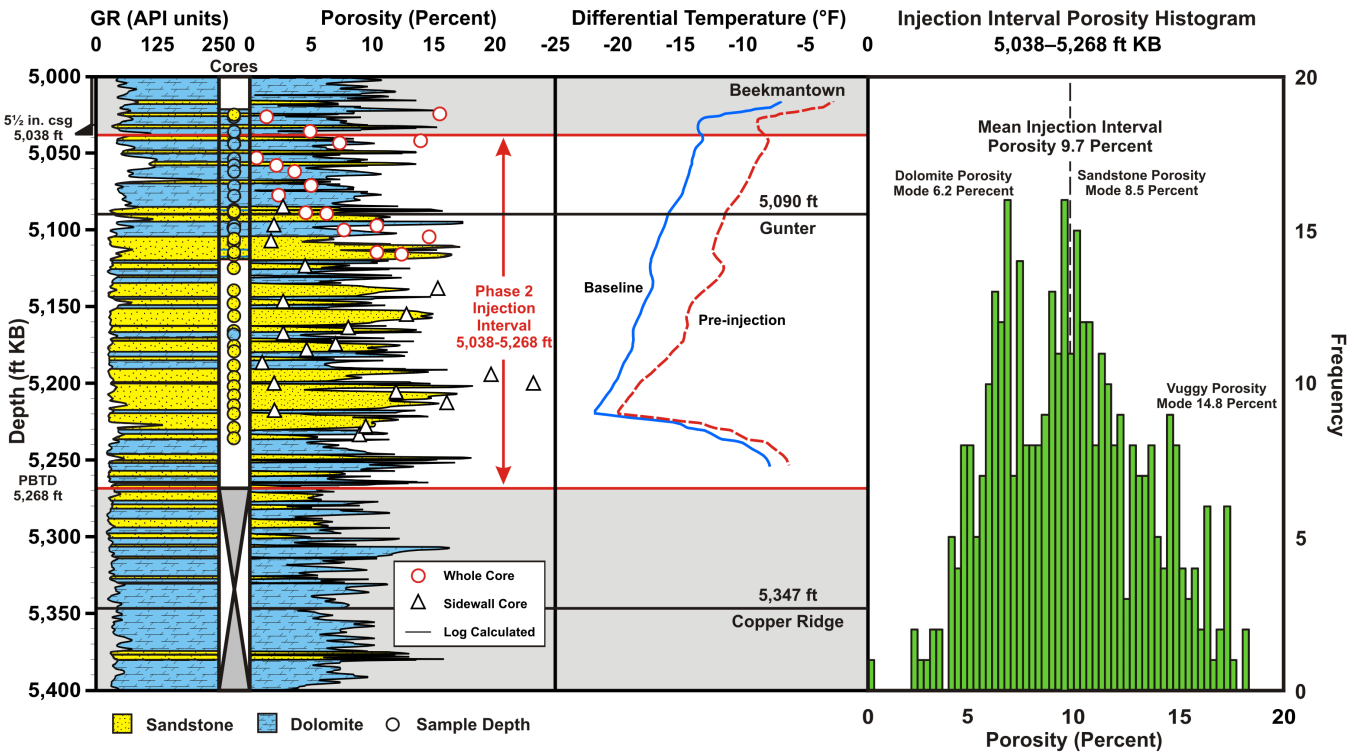


Figure 12. Reservoir characteristics of the Gunter and phase 2 injection interval and results of the phase 2 injection testing.

Energy Technology Laboratory, 2010). Thus, calculated storage reservoir pore volume for the Knox Group in the phase 1 test interval at 3,780–5,750 ft, including the Gunter Sandstone, ranges from about 10.7 acre-ft per surface acre (P_{10}) to 19.4 acre-ft per surface acre (P_{90}), with a most likely storage reservoir pore volume of 14.7 acre-ft per surface acre. By itself, storage reservoir pore volume in the Gunter Sandstone in the phase 2 test interval ranges from about 14 acre-ft per surface acre (P_{10}) to 4.4 acre-ft per surface acre (P_{90}), with a most likely volume of 2.6 acre-ft per surface acre. Supercritical CO_2 storage reservoir pore volume is about 1,760 to 3,204 tons per surface acre in the phase 1 Knox Group section encountered in the Marvin Blain No. 1 well, with a most likely storage reservoir pore volume of 2,425 tons of supercritical CO_2 per surface acre. With the higher density of supercritical CO_2 at phase 2 reservoir conditions in the Gunter Sandstone, estimated storage reservoir pore volume is 235 to 770 tons of supercritical CO_2 per surface acre, with a most likely storage reservoir pore volume of about 450 tons of supercritical CO_2 per surface acre. Thus, the most likely surface area required to store 1 million tons of supercritical CO_2 in a Knox section comparable to the phase 1 test interval is 412 acres, about 0.65 mi^2 , and 2,220 acres, or about 3.5 mi^2 for a Gunter section comparable to the phase 2 test section.

A most likely case assuming the entire Knox section encountered in the Marvin Blain No. 1 well is available for supercritical CO_2 storage, excluding the fractured intervals near the base of the Copper Ridge section, cannot be made by simply adding the individual storage-volume cases for the Beekmantown Dolomite, Gunter Sandstone, and Copper Ridge Dolomite because of the difference in the supercritical CO_2 density at the average reservoir conditions of temperature and pressure in the Knox Group section as a whole. Pore volume is additive, however; thus, the total Knox Group storage reservoir pore volume is 18.4 acre-ft per surface acre. At an average reservoir depth of 5,590 ft, the temperature is 108°F, pressure is 2,437 psi, and the density of supercritical CO_2 (DeSimone, 2002) is 0.78 g/cm^3 . Weighted P_{50} storage efficiency in this case, in which the Gunter Sandstone contributes about 16 percent of the total storage reservoir pore volume, is 19.9 percent. Thus, if the entire Knox

section encountered in the Marvin Blain No. 1 well is considered, excluding fractured intervals near the base of the Copper Ridge Dolomite, supercritical CO_2 storage capacity is about 3,190 tons per surface acre, and the surface area required to store 1 million tons of supercritical CO_2 is thus reduced to about 284 acres (0.44 mi^2).

Discussion

Analysis of data from electric logs, cores, and injection tests in the Marvin Blain No. 1 well effectively demonstrated the capability of the Knox Group to store supercritical CO_2 and of the CO_2 to be confined in the subsurface below sealing zones. Evidence is sparse but not lacking for evaluating the regional potential for CO_2 storage in Kentucky Knox reservoirs. The distribution of active saltwater-disposal and gas-storage wells in Kentucky and southern Indiana suggests porous and permeable Knox is present in Kentucky west of the Cincinnati Arch. For example, 63 saltwater-disposal wells and 44 gas-storage wells in Kentucky are completed in the Knox Group. About 95 percent of the saltwater-disposal wells are located in Adair and adjacent counties, 80 mi southeast of the Marvin Blain 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 Blain No. 1. Outside of Kentucky, six active saltwater-disposal wells are completed in the Knox in Harrison County, Ind., about 40 mi northeast of the Blain well, and an additional nine active saltwater-disposal wells and seven active gas-storage wells throughout southern Indiana are completed in the Knox (according to a search of the Indiana Geological Survey Petroleum Database Management System).

Effective reservoir seals should have less than 10^{-6} md permeability (Deming, 1994). Within the Knox, permeabilities measured in vertical core plugs from the Beekmantown and Copper Ridge suggest that intraformational seals are insufficient to confine supercritical CO_2 . During the first phase of injection testing in 2009, attempts to isolate test intervals proved ineffective because of rapid pressure communication through the Knox to the wellbore annulus. Thus, the seal for CO_2 storage in the Knox has to be in overlying strata. Two stratigraphic intervals overlying the Knox in the Mar-

vin Blan No. 1 well may provide seals for potential CO₂ storage reservoirs in western Kentucky: the Black River Group and the Maquoketa Shale. The Black River has permeabilities of approximately 10⁻³ md, suggesting that this interval may act as secondary sealing strata but not a primary seal for long-term confinement of supercritical CO₂ in the Knox Group storage reservoir. Therefore, the primary reservoir seal for the Knox is the Maquoketa. The Marvin Blan No. 1 penetrated the subsurface Sebree Trough at a location where the Trenton is absent and a thick section of the Maquoketa is present. The Maquoketa would be a thick seal for deeper CO₂ storage reservoirs under the central area of the Western Kentucky Coal Field in Ohio, McLean, Hopkins, and Muhlenberg Counties. Maximum seal capacity calculated from permeabilities measured in vertical core plugs from the Maquoketa, as well as its rock strength, suggests that the Maquoketa meets the requirements to be an effective, long-term reservoir seal for CO₂ storage in western Kentucky Knox reservoirs.

Conclusions

The Marvin Blan No. 1 well penetrated a complete section of basal Pennsylvanian through Neoproterozoic strata, and thus the wireline electric logs from the well can serve as type logs for this section in western Kentucky north of the Rough Creek Graben. The data from the well make important contributions to an understanding of the subsurface stratigraphic section of western Kentucky, and help clarify the relationships between electric-log responses, lithology, and rock properties. Electric-log, core, and injection data from two tests demonstrated that the Knox could serve as a reservoir for subsurface storage of CO₂, and that the Maquoketa could act as the primary reservoir sealing zone.

Acknowledgments

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