Geologic Assessment of the Ohio Geological Survey CO_2 No. 1 Well in Tuscarawas County and Surrounding Vicinity

By

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NOTICE

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Cover photo: Thin section photomicrograph of the Beekmantown dolomite at the Ohio Geological Survey CO_2 No. 1 well site at a depth of 7,231 feet (see p. 50).

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UNIT ABBREVIATIONS USED IN THIS REPORT

Area	
square feet	ft^2
square miles	mi^2
Length	
inch	in
foot	ft
mile	mi
kilometer	km
Mass	
gram	g
short ton	ton
metric ton (tonne)	t
million metric ton	Mt
Permeability	
millidarcy	mD
Fluid Properties	
centipoise	cp
hydraulic conductivity	K
transmissivity	T
viscosity	μ
specific weight density	γ
Seismicity	
body wave magnitude	mbLg
peak acceleration	%g
Volume	
gallon	gal
cubic feet	ft^3
thousand cubic feet gas	MCFG
million cubic feet gas	MMCFG
billion cubic feet gas	BCFG
trillion cubic feet gas	TCFG
barrel	bbl
million barrels of oil	MMBO
Water Quality	
parts per million	ppm
Production Rates	
barrels of oil	BO
Chemical Elements	
Lead	Pb
Uranium	U

Geologic Assessment of the Ohio Geological Survey CO_2 No. 1 Well in Tuscarawas County and Surrounding Vicinity

INTRODUCTION

This report represents the first major technical findings released after the drilling of the Ohio Geological Survey CO_2 Number 1 stratigraphic test well in eastern Ohio's Tuscarawas County. The stratigraphic test was conducted to evaluate the CO_2 injectivity and storage capacity of potential reservoirs and the effectiveness of potential confining units in this area of the state. Funding for this project was provided from three sources: (1) $1 million in funds designated from Ohio's general revenue fund via house bill 440 (126th General Assembly), (2) $1.3 million in bond funds from the Ohio Coal Development Office (OCDO) within the Ohio Air Quality Development Authority (OAQDA), and (3) approximately $300,000 from U.S. Department of Energy (DOE) funding to the Midwest Regional Carbon Sequestration Partnership (MRCSP). Battelle Memorial Institute was contracted by the OCDO as project manager for the project because of its prior experience in drilling deep test wells and its leadership position within carbon sequestration research. The Ohio Department of Natural Resources, Division of Geological Survey (or Ohio Geological Survey) represented the state's geologic interest in the project and acted as operator of record for the well permitting process.

The Ohio Geological Survey has been involved in various aspects of characterizing the state for geologic sequestration of CO_2 since 2000. In 2004 the state became interested in submitting a bid for the announced FutureGen competition being funded by private industry and the U.S. DOE and formed the Ohio FutureGen Task Force, of which the Ohio Geological Survey was part. FutureGen was designed to be a 275 megawatt demonstration project for advanced coal-based technologies to generate electricity and also produce hydrogen-to-power fuel cells for transportation and other energy needs. The project was also to require integration of geologic carbon sequestration to remove at least 90 percent of CO_2 emissions of the plant, helping to address the issue of climate change. Through other Ohio Geological Survey projects, and in preparing site-specific information for the FutureGen proposal, it had become apparent that, in many areas of the state, the available geologic data is inadequate to ascertain whether sufficient capacity, injectivity, and safety of Ohio's deep subsurface exists. While existing data do indicate Ohio to have high sequestration potential in some areas, the data is inadequate to prove the existence of key injection horizons (e.g., basal sandstone, Copper Ridge dolomite porosity zones) in much of eastern Ohio, and injectivity tests (which measure the rate at which a formation will accept fluids or gas) are nonexistent for most of the prospective injection horizons.

Wells drilled deep enough to penetrate the entire thickness of sedimentary rocks within the state are relatively rare. Ohio has had in excess of 250,000 wells drilled, yet less than 250 have penetrated the Precambrian basement underlying the sedimentary cover. Most of these Precambrian penetrations are located in western Ohio where the depth through the sedimentary rocks is considerably less than in eastern Ohio (fig. 1). Many of these deep tests are older wells for which the state does not have geophysical logs and/or rock samples. Thus, in large areas of the state, where there are few or no deep wells (or wells with no data), the presence or absence of key rock units is unknown and the properties of most rock units are not known. In short, there are insufficient data to evaluate much of the state for sequestration of CO_2.

Thus, the Ohio legislature passed House Bill 440 in April 2006 directing $1 million dollars from general revenue funds to the purpose of drilling and analysis of a test well. Coincident in time, natural gas and oil prices were rising steadily and demand for drilling supplies and services were in great demand after a long period of low drilling activity. From the time of conception of the project until completion, prices more than doubled. The OCDO and the U.S. DOE obligated funds to enable completion of the project. Ohio's bid for the FutureGen project was unsuccessful (proposals were due in May 2006) in large part because of a lack of deep geologic data.

While Ohio's bid for the FutureGen project was unsuccessful, geologic CO_2 sequestration is still thought to be a major environmental component of many new energy-producing technologies that are now being planned and deployed. Biofuel plants (ethanol and biodiesel), coal-to-liquid synfuel plants, and integrated gasification combined cycle (IGCC) power plants are all examples of energy-producing technologies that are capable of producing large, pure streams of CO_2. While it is presently uncertain if some form of carbon (CO_2) emissions regulations/taxes will be passed within the United States, it is in the state's best interest to understand its geologic infrastructure in regards to sequestration capabilities and developing a long term strategy for carbon management.

The U.S. DOE has formed a nationwide network of seven regional partnerships to help determine the best approaches for capturing and permanently storing gases that can contribute to global climate change. The Regional Carbon Sequestration Partnerships are government-industry efforts tasked with determining the most suitable technologies, regulations, and infrastructure needs for carbon capture, storage, and sequestration in different areas of the country. The Regional Partnerships initiative is being implemented in three phases: Phase I (2003–2005) characterized geologic and terrestrial opportunities (capacities) for carbon sequestration on a regional scale; Phase II (2005–2011) involves small-scale CO_2 injection projects (usually less than 10,000 tons of CO_2 per project), and it has continued to develop additional detail in the characterization of sequestration capacities; Phase III (2008–2017) will conduct large-scale CO_2 injection pilot projects (~1 million tons of CO_2 per project) and further refine details of geologic mapping and strata characterization.

Ohio is part of the Midwest Regional Carbon Sequestration Partnership (**www.mrcsp.org**), which also includes Indiana, Kentucky, Maryland, Michigan, New Jersey, New York, Pennsylvania and West Virginia. Battelle performs as the project leader under this U.S. DOE contract and the Ohio Geological Survey is the geologic task leader for the nine-state consortium. Within the phase II project the partnership drilled a pilot injection well about 50 miles south of Cincinnati along the Ohio River at Duke Energy's East Bend Power Plant to test injection in the Mt. Simon Sandstone, which is also Ohio's largest saline reservoir for CO_2 storage in western Ohio. The MRCSP has also drilled a well for pilot injection of CO_2 at First Energy's Burger Power Plant in southeastern Ohio's Belmont County (Wickstrom and others, 2008). The Burger pilot well was drilled to a depth of 8,384 feet through the Silurian "Clinton" sandstone. At this location, it would require drilling in excess of 13,000 feet to penetrate the entire sedimentary column, a very expensive venture. However, the Burger well is an important test and will add greatly to our geologic knowledge. The partnership also injected over 60,000 tons of carbon dioxide at a site in Otsego County, Michigan.

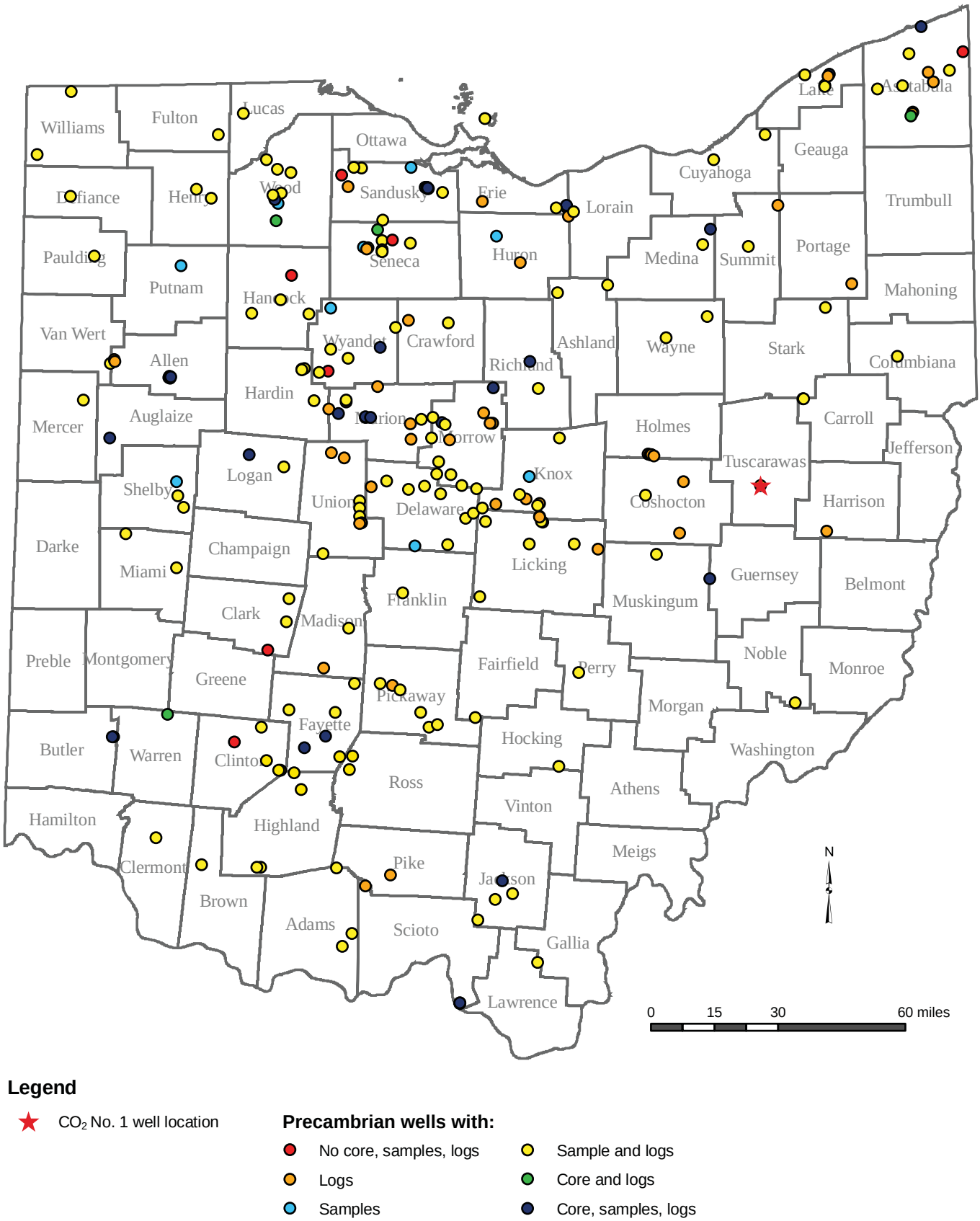

FIGURE 1.—Map showing locations of all Precambrian penetrations in Ohio. Also shown are the types of data for these wells on file at the Ohio Geological Survey.

In 2003, American Electric Power (AEP) and Battelle, with partial funding from the U.S. DOE drilled a deep (9,200-feet)-test well at the Mountaineer Power Plant near New Haven, West Virginia, directly across the Ohio River from Racine, Meigs County, Ohio. This deep test well, which represents another data point useful for defining Ohio sequestration potential, was designed to explore the injection capacity of the Mt. Simon Sandstone and other shallower units. The Mt. Simon, or its equivalent formation, the Cambrian basal sandstone, was found to be almost completely lacking of porosity necessary for CO_2 storage at this site. However, other deep formations—the Rose Run Sandstone and the Copper Ridge Dolomite—were found to have promising storage capacity and injectivity (Greb and others, 2009). Under MRCSP and another U.S. DOE-funded project, Battelle has also worked with oil and gas well operators in the Appalachian Basin to characterize the Cambrian and Ordovician formations in several deep wells.

As mentioned, most of Ohio's deep wells—those that penetrate the entire sedimentary column and into the underlying crystalline Precambrian-age rocks—are located in western Ohio and the far northeastern part of the state. The state's geologic column, or column of sedimentary rocks, thickens to the southeast; however, geologic units are not consistent across the state or, in the case of many geologic units, even within short distances. Thus our existing knowledge of the deepest sedimentary rocks in the state decreases, generally in that direction. In addition to the simple challenge of the locations of deep wells is the data that is gathered when wells are drilled. Many of these deep wells were drilled many decades ago prior to the advent of sophisticated logging technology. Finally, and perhaps most importantly, is the fact that very few of the prior existing deep wells had any sort of pressure measurements or injection testing performed, nor do we have core from these wells on which to perform laboratory-scale analyses. These types of testing are vital in order to know how much rock units can store and at what rate they can accept the fluid.

Through the FutureGen siting process in Ohio, a site was proposed in Tuscarawas County, and this same general location happens to fall in one of the state's largest gaps of deep geologic knowledge (fig. 1). In some directions, one must travel 50 miles or more from this location to find older, deep oil-and-gas wells that had penetrated the entire sedimentary rock column; the closest deep well is 18 miles to the west. The available logs from some of these deep surrounding wells show a fairly good thickness of basal sandstone, which, based on that available data, had left us hopeful that this unit may hold moderate to good potential for CO_2 sequestration in this area of the state. With the results of the CO_2 No. 1 well, we can now correlate back to these surrounding wells and, with some confidence, apply quantitative values of porosity and permeability to the basal sands in these other wells. Other factors influenced the decision to locate a deep test well in this location:

1. Subsurface geology is representative of this eastern-Ohio region and a very complete stratigraphic section exists with potential for multiple sequestration horizons at a depth affordable within the given budget.
2. Thick, impermeable, confining units could be expected to exist above all potential sequestration targets.
3. A number of potential subsurface units for storage are between 2,500 feet (minimum depth for CO_2 to be in supercritical state) and 8,700 feet, the predicted maximum depth of the well.
4. Location is within a quiescent area of no recorded earthquakes and no published regional faults.
5. Limited injectivity data is available in this area, most of which is from Class II (brine injection) wells; brine injection rate data in Ohio is from normal operation of the well, not rate tests or maximum rates.
6. Proximity to oil and gas fields offers future potential for CO_2-assisted enhanced oil recovery opportunities.
7. The site afforded good access with a minimum of site preparation costs.
8. The site is within an area of current oil and gas exploration activity; thus 3-D seismic was available for inspection surrounding the site.

As this general area had previously been considered for the FutureGen project, there was a fairly high level of public interest in the drilling of this test well. A public informational meeting was held May 3, 2007, at the Tuscarawas County campus of Kent State University. Approximately 100 local citizens attended this meeting at which ODNR and Battelle presented information on geologic carbon sequestration and the specifics of how this well was to be drilled and tested.

The primary objectives of this report are to (1) summarize the geology and available data of the CO_2 No. 1 well site and a 10-mile area of review (AOR) surrounding the site and (2) provide a preliminary characterization of the geologic reservoirs and sealing (confining) units found within the CO_2 No. 1 well. This investigation greatly expands the knowledge of Ohio's deep subsurface geology and provides necessary geologic and injection data to further assist in evaluating the state's geologic sequestration potential. Data from this test well will continue to be analyzed and integrated with surrounding geologic data. Additional reports are forthcoming that will include more detailed analyses and detailed models of CO_2 sequestration simulations.

GEOGRAPHIC SITE LOCATION

The Ohio Geological Survey CO_2 No. 1 well is located in southern Tuscarawas County, Ohio, which is in the Gnadenhutten 7.5-minute U.S. Geological Survey quadrangle (fig. 2). The measured location for the well is 4,360 feet from the north line and 70 feet from the east line of the second quarter of Salem Township. In this report, the stratigraphic test is referred to as the CO_2 No. 1 well (American Petroleum Institute Number 3415725334). The AOR as used in this report includes this well and other geologic data within a 10-mile radius of the site.

METHODS

Drilling of the Ohio Geological Survey CO_2 No. 1 well in Tuscarawas County began May 10, 2007, and reached total depth of 8,695 feet in the Precambrian crystalline rocks on June 9, 2007. Logging and coring operations were completed in June 2007. Subsequent injection testing in the Cambrian basal sandstone and the Rose Run sandstone was completed August 6, 2007. A detailed chronology of the drilling and testing of the well is presented as Appendix 1. Following completion of injection testing and plugging of the well below 7,330 feet, the well was turned over to Artex Oil Company and Northwood Energy Corporation, the operators who own the oil-and-gas mineral rights to the site.

Wireline logging was performed by Schlumberger, Inc. and included Gamma Ray, Neutron, and Density (GR/N/D); Laterolog (LL); Nuclear Magnetic Resonance (NMR); Formation MicroImager (Resistivity) Log (FMI); and Sonic(S) tool measurements (see table 1, table of logs run per stage and depths). Perforation (Perf)

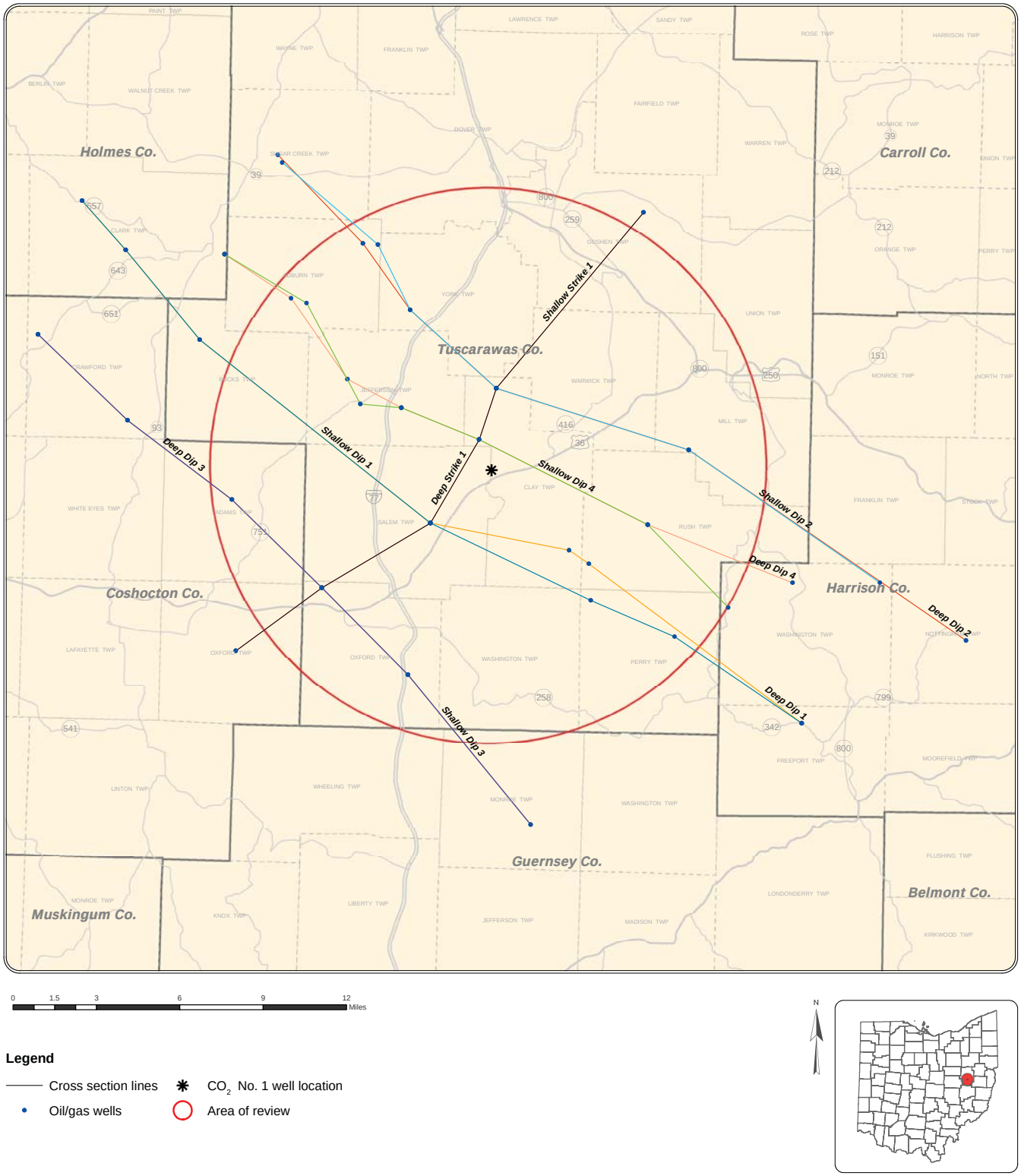

FIGURE 2.—Location of the Ohio Geological Survey CO_2 No. 1 well in Tuscarawas County, Ohio; 10-mile radius = the area of review. Locations of shallow and deep cross sections (figures 4–13) are shown. Inset map illustrates the location within Ohio.

TABLE 1.— *List of wireline logs per run, log curves, log curve description, and logged footage interval in the CO_2 No. 1 well in Tuscarawas County, Ohio*

Log Run	Log Name	Log Curves and Calibration Units		Log Description	Depth (ft)
1	Platform express-lithodensity, compensated neutron, laterolog	GR	.GAPI	:Gamma-Ray {F13.4}	46-122
1	Platform express-lithodensity, compensated neutron, laterolog	NPHI	.CFCF	:Thermal Neutron Porosity (Ratio Method) {F13.4}	46-122
1	Platform express-lithodensity, compensated neutron, laterolog	HCAL	.IN	:HRCC Cal. Caliper {F13.4}	46-122
1	Platform express-lithodensity, compensated neutron, laterolog	HDRA	.G/C3	:HRDD Density Correction {F13.4}	46-122
1	Platform express-lithodensity, compensated neutron, laterolog	PEFZ		:HRDD Standard Resolution Formation Photoelectric Factor {F13.4}	46-122
1	Platform express-lithodensity, compensated neutron, laterolog	RHOZ	.G/C3	:HRDD Standard Resolution Formation Density {F13.4}	46-122
1	Platform express-lithodensity, compensated neutron, laterolog	DPHZ	.CFCF	:HRDD Standard Resolution Density Porosity {F13.4}	46-122
1	Platform express-lithodensity, compensated neutron, laterolog	RXOZ	.OHMM	:MCFL Standard Resolution Invaded Zone Resistivity {F13.4}	46-122
1	Platform express-lithodensity, compensated neutron, laterolog	RLA1	.OHMM	:HRLT Borehole Corrected Resistivity 1 {F13.4}	46-122
1	Platform express-lithodensity, compensated neutron, laterolog	RLA2	.OHMM	:HRLT Borehole Corrected Resistivity 2 {F13.4}	46-122
1	Platform express-lithodensity, compensated neutron, laterolog	RLA3	.OHMM	:HRLT Borehole Corrected Resistivity 3 {F13.4}	46-122
1	Platform express-lithodensity, compensated neutron, laterolog	RLA4	.OHMM	:HRLT Borehole Corrected Resistivity 4 {F13.4}	46-122
1	Platform express-lithodensity, compensated neutron, laterolog	RLA5	.OHMM	:HRLT Borehole Corrected Resistivity 5 {F13.4}	46-122
1	Platform express-lithodensity, compensated neutron, laterolog	RM_HRLT	.OHMM	:HRLT Mud Resistivity {F13.4}	46-122
2	Platform express-lithodensity, compensated neutron, laterolog	TENS	.LBF	:Cable Tension {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	HTEM	.DEGF	:HTC Temperature {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	GR	.GAPI	:Gamma-Ray {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	NPHI	.CFCF	:Thermal Neutron Porosity (Ratio Method) {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	HCAL	.IN	:HRCC Cal. Caliper {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	HDRA	.G/C3	:HRDD Density Correction {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	PEFZ		:HRDD Standard Resolution Formation Photoelectric Factor {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	PEF8		:HRDD High Resolution Formation Photoelectric Factor {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	RHOZ	.G/C3	:HRDD Standard Resolution Formation Density {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	RHO8	.G/C3	:HRDD High Resolution Formation Density {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	DPHZ	.CFCF	:HRDD Standard Resolution Density Porosity {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	DPH8	.CFCF	:HRDD High Resolution Density Porosity {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	HGR	.GAPI	:HiRes Gamma-Ray {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	HRM	.OHMM	:HALS Mud resistivity {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	HLLS	.OHMM	:HALS Laterolog Shallow Resistivity {F13.4}	878-4970
2	Platform express-lithodensity, compensated neutron, laterolog	HLLD	.OHMM	:HALS Laterolog Deep Resistivity {F13.4}	878-4970
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	HRUG	.1/FT	:1 Hole Rugosity	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	TEMP	.DEGF	:2 Temperature	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	HCAL	.IN	:3 Caliper	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	BS	.IN	:4 Bit Size	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	CS	.FT/HR	:5 Cable Speed	6148-8628

Log Run	Log Name	Log Curves and Calibration Units		Log Description	Depth (ft)
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	TENS	.LB	:6 Cable Tension	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	GR_EC	.GAPI	:7 Environmentally Corrected Gamma Ray	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	GR	.GAPI	:8 Gamma Ray	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	RXOZ	.OHMM	:9 MCFL Resistivity	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	RLA1	.OHMM	:10 Laterolog Array 1	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	RLA2	.OHMM	:11 Laterolog Array 2	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	RLA3	.OHMM	:12 Laterolog Array 3	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	RLA4	.OHMM	:13 Laterolog Array 4	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	RLA5	.OHMM	:14 Laterolog Array 5	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	NPHI	.FT3/FT3	:15 Neutron NPHI Porosity	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	TNPH	.FT3/FT3	:16 Neutron TNPH Porosity	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	SPHI	.FT3/FT3	:17 Sonic Porsity	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	PEFZ		:18 Photoelectric Factor	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	HDRA	.G/CC	:19 Density Correction	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	DPHZ	.FT3/FT3	:20 Density Porosity	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	NPHU	.FT3/FT3	:21 Environmentally Corrected Neutron Porosity	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	NPHU_EDIT	.FT3/FT3	:22 Edited Environmentally Corrected Neutron Porosity	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	RHOZ	.G/CC	:23 Bulk Density	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	RHOZ_EDIT	.G/CC	:24 Edited Bulk Density	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	UZ		:25 Volumetric Photoelectric Factor	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	UZ_EDIT		:26 Edited Volumetric Photoelectric Factor	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VCHL	.FT3/FT3	:27 Elan Volume Chlorite	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VILL	.FT3/FT3	:28 Elan Volume Illite	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VQUA	.FT3/FT3	:29 Elan Volume Quartz	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VSM1	.FT3/FT3	:30 Elan Volume Special Mineral 1 Kerogen	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VCLC	.FT3/FT3	:31 Elan Volume Calcite	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VDOL	.FT3/FT3	:32 Elan Volume Dolomite	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VXBW	.FT3/FT3	:33 Elan Clay Bound Water Volume	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VXWA	.FT3/FT3	:34 Elan Flushed Water Volume	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VUWA	.FT3/FT3	:35 Elan Water Volume	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VXIW	.FT3/FT3	:36 Elan Flushed Irreducible Water Volume	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VUIW	.FT3/FT3	:37 Elan Irreducible Water Volume	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VXGA	.FT3/FT3	:38 Elan Flushed Gas Volume	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VUGA	.FT3/FT3	:39 Elan Gas Volume	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VMHY	.FT3/FT3	:40 Elan Moved Hydrocarbon Volume	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	PIGN	.FT3/FT3	:41 Elan Effective Porosity	6148-8628

3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	PIGT	.FT3/FT3	:42	Elan Total Porosity	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	SBVC	.FT3/FT3	:43	Elan Bulk Volume Water Irreducible	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	VCL	.FT3/FT3	:44	Elan Total Clay Volume	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	SUWI	.FT3/FT3	:45	Elan Water Saturation	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	WCHL	.LB/LB	:46	Elan Weight Percent Chlorite	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	WILL	.LB/LB	:47	Elan Weight Percent Illite	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	WQUA	.LB/LB	:48	Elan Weight Percent Quartz	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	WSM1	.LB/LB	:49	Elan Weight Percent Special Mineral 1 Kerogen	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	WCLC	.LB/LB	:50	Elan Weight Percent Calcite	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	WDOL	.LB/LB	:51	Elan Weight Percent Dolomite	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	TCMR	.ft3/ft3	:52	Total CMR Porosity	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	BFV	.ft3/ft3	:53	Bound Fluid Volume from CMR	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	CMFF	.ft3/ft3	:54	CMR Free Fluid	6148-8628
3	CMR (Combined Magnetic Resonance) and ELAN (Elemental Analysis)	KTIM	.md	:55	CMR Permeability	6148-8628
3	FracCade (Fracturing Computer Aided)	TYSG	.PS/F	:1	Total Maximum Horizontal Stress Gradient	3090-4930
3	FracCade (Fracturing Computer Aided)	TYSP	.PSI	:2	Total Maximum Horizontal Stress - Sigma Y	3090-4930
3	FracCade (Fracturing Computer Aided)	TXSG	.PS/F	:3	Total Minimum Horizontal Stress Gradient	3090-4930
3	FracCade (Fracturing Computer Aided)	TXSP	.PSI	:4	Total Minimum Horizontal Stress - Sigma X	3090-4930
3	FracCade (Fracturing Computer Aided)	TZSG	.PS/F	:5	Total Vertical Stress Gradient	3090-4930
3	FracCade (Fracturing Computer Aided)	TZSP	.PSI	:6	Total Vertical Stress - Sigma Z	3090-4930
3	FracCade (Fracturing Computer Aided)	PPGI	.PS/F	:7	Pore Pressure Gradient	3090-4930
3	FracCade (Fracturing Computer Aided)	PPRS	.PSI	:8	Pore Pressure	3090-4930
3	FracCade (Fracturing Computer Aided)	ALPH		:9	Alpha (Coefficient in Fracture Pressure Gradient Equation)	3090-4930
3	FracCade (Fracturing Computer Aided)	TSTR	.PSI	:10	Tensile Strength	3090-4930
3	FracCade (Fracturing Computer Aided)	ISHE	.PSI	:11	Initial Shear Strength	3090-4930
3	FracCade (Fracturing Computer Aided)	UCS	.PSI	:12	Uniaxial Compressive Strength	3090-4930
3	FracCade (Fracturing Computer Aided)	FANG	.DEG	:13	Angle relating the increase in shear strength with compressive strength_	3090-4930
3	FracCade (Fracturing Computer Aided)	YME	.6PSI	:14	Young's Modulus (E)	3090-4930
3	FracCade (Fracturing Computer Aided)	SMG	.6PSI	:15	Shear Modulus	3090-4930
3	FracCade (Fracturing Computer Aided)	CB	.RPSI	:16	Bulk Compressibility	3090-4930
3	FracCade (Fracturing Computer Aided)	BMK	.6PSI	:17	Bulk Modulus - K	3090-4930
3	FracCade (Fracturing Computer Aided)	VCL	.V/V	:18	Volume of Clay Type Material Relative to Total Volume	3090-4930
3	FracCade (Fracturing Computer Aided)	PIGN	.V/V	:19	Effective Porosity, VISO, VPAR, and Bound Water Removed	3090-4930
3	FracCade (Fracturing Computer Aided)	PHIT	.V/V	:20	Total Porosity, including that occupied by bound effects	3090-4930
3	FracCade (Fracturing Computer Aided)	KINT	.MD	:21	Intrinsic Permeability	3090-4930
3	FracCade (Fracturing Computer Aided)	SUWI	.V/V	:22	Non-Clay Water Intergranular Water Saturation for Undisturbed Zone	3090-4930

Log Run	Log Name	Log Curves and Calibration Units		Log Description	Depth (ft)
3	FracCade (Fracturing Computer Aided)	AZIY	.DEG	:23 Fast Shear Azimuth	3090-4930
3	FracCade (Fracturing Computer Aided)	AZIM	.DEG	:24 Measured Azimuth	3090-4930
3	FracCade (Fracturing Computer Aided)	DEVI	.DEG	:25 Hole Deviation	3090-4930
3	FracCade (Fracturing Computer Aided)	TVD	.F	:26 True Vertical Depth	3090-4930
3	FracCade (Fracturing Computer Aided)	C2	.IN	:27 Caliper 2	3090-4930
3	FracCade (Fracturing Computer Aided)	C1	.IN	:28 Caliper 1	3090-4930
3	FracCade (Fracturing Computer Aided)	PR		:29 Poisson Shear/Compressional Ratio	3090-4930
3	FracCade (Fracturing Computer Aided)	DTSM	.US/F	:30 Delta-T Shear	3090-4930
3	FracCade (Fracturing Computer Aided)	DTCO	.US/F	:31 Delta-T Compressional	3090-4930
3	FracCade (Fracturing Computer Aided)	NPOR	.V/V	:32 Enhanced Thermal Neutron Porosity in Selected Lithology	3090-4930
3	FracCade (Fracturing Computer Aided)	RHOB	.G/C3	:33 Bulk Density	3090-4930
3	FracCade (Fracturing Computer Aided)	RHOB_WT	.G/C3	:34 Density of Wet Rock	3090-4930
3	FracCade (Fracturing Computer Aided)	AT90	.OHMM	:35 AIT Two Foot Resistivity A90	3090-4930
3	FracCade (Fracturing Computer Aided)	GR	.GAPI	:36 Gamma Ray	3090-4930
3	Sonic	VPVS		:1 Compressional to Shear Velocity Ratio	3070-4930
3	Sonic	SPHI	.V/V	:2 Sonic Porosity	3070-4930
3	Sonic	RHOB	.G/C3	:3 Bulk Density	3070-4930
3	Sonic	GR	.GAPI	:4 Gamma Ray	3070-4930
3	Sonic	DTSM	.US/F	:5 Delta-T Shear	3070-4930
3	Sonic	DT	.US/F	:6 Delta-T (also called Slowness or Interval Transit Time)	3070-4930
3	Sonic	CHRP		:7 Label Peak Coherence, Receiver Array, Compressional - Monopole P&S	3070-4930
3	Sonic	CHR1		:8 Label Peak Coherence, Receiver Array - Lower Dipole	3070-4930
3	Sonic	CALI	.IN	:9 Caliper	3070-4930
3	Directional	DEVI	.DEG	:Hole Deviation {F13.4}	4950-8700
3	Directional	ED	.F	:East Departure {F13.4}	4950-8700
3	Directional	GR	.GAPI	:Gamma Ray {F13.4}	4950-8700
3	Directional	HAZI	.DEG	:Hole Azimuth {F13.4}	4950-8700
3	Directional	ICV	.F3	:Integrated Cement Volume {F13.4}	4950-8700
3	Directional	IHV	.F3	:Integrated Hole Volume {F13.4}	4950-8700
3	Directional	ND	.F	:North Departure {F13.4}	4950-8700
3	Directional	TVDE	.F	:True Vertical Depth {F13.4}	4950-8700
3	Platform express-lithodensity, compensated neutron, laterolog	DPHZ	.CFCF	:HRDD Standard Resolution Density Porosity {F13.4}	4950-8700
3	Platform express-lithodensity, compensated neutron, laterolog	GR	.GAPI	:Gamma-Ray {F13.4}	4852-8718
3	Platform express-lithodensity, compensated neutron, laterolog	HCAL	.IN	:HRCC Cal. Caliper {F13.4}	4852-8718
3	Platform express-lithodensity, compensated neutron, laterolog	HDRA	.G/C3	:HRDD Density Correction {F13.4}	4852-8718

3	Platform express-lithodensity, compensated neutron, laterolog	NPHI	.CFCF	:Thermal Neutron Porosity (Ratio Method) {F13.4}	4852-8718
3	Platform express-lithodensity, compensated neutron, laterolog	PEFZ		:HRDD Standard Resolution Formation Photoelectric Factor {F13.4}	4852-8718
3	Platform express-lithodensity, compensated neutron, laterolog	RHOZ	.G/C3	:HRDD Standard Resolution Formation Density {F13.4}	4852-8718
3	Platform express-lithodensity, compensated neutron, laterolog	RLA1	.OHMM	:HRLT Borehole Corrected Resistivity 1 {F13.4}	4852-8718
3	Platform express-lithodensity, compensated neutron, laterolog	RLA2	.OHMM	:HRLT Borehole Corrected Resistivity 2 {F13.4}	4852-8718
3	Platform express-lithodensity, compensated neutron, laterolog	RLA3	.OHMM	:HRLT Borehole Corrected Resistivity 3 {F13.4}	4852-8718
3	Platform express-lithodensity, compensated neutron, laterolog	RLA4	.OHMM	:HRLT Borehole Corrected Resistivity 4 {F13.4}	4852-8718
3	Platform express-lithodensity, compensated neutron, laterolog	RLA5	.OHMM	:HRLT Borehole Corrected Resistivity 5 {F13.4}	4852-8718
3	Platform express-lithodensity, compensated neutron, laterolog	RM_HRLT	.OHMM	:HRLT Mud Resistivity {F13.4}	4852-8718
3	Platform express-lithodensity, compensated neutron, laterolog	RXOZ	.OHMM	:MCFL Standard Resolution Invaded Zone Resistivity {F13.4}	4852-8718
3	FMI (Formation Microscanner Image)				6936, 7234, 7376, 7386, 7391, 7434, 7440, 7480, 7495, 7505, 8528, 8554, 8560, 8582, 8603, 8610
3	PressureXpress				
	Mudlog				40-8695

and Cement Bond (CB) logs were run to identify correct injection zones and confirm the integrity of the cement behind casing. The Schlumberger PressureXpress also was run to provide high-quality pressure and fluid mobility measurements in potential CO_2 sequestration zones of interest. In addition, 82 sidewall cores were taken in selected reservoirs and confining units to assist in the evaluation of CO_2 sequestration potential. Sidewall cores were sent to Weatherford Labs (formerly OMNI Labs) to obtain quantitative measurements of porosity and permeability, total organic content (TOC), thermal maturity, and rock mechanics. Weatherford Labs also examined reservoir quality of selected cores with thin section petrography, Scanning Electron Microscopy (SEM), and X-ray diffraction techniques. A report of all analyses by Weatherford Labs is presented as Appendix 2.

All data, including logs, samples, cores, and reports, concerning the drilling or analysis of this well are available for inspection at the offices of the Ohio Geological Survey, and much of the data is available for viewing and downloading from its website (**www.OhioGeology.com**). Prior to a final decision to drill at this location, a geological characterization was conducted for a 10-mile radius AOR that includes portions of Tuscarawas, Coshocton, Harrison, and Guernsey counties[1] (fig. 2). Within the current report, data collected from the CO_2 No. 1 well has been integrated with pre-existing geologic data within the AOR. Additionally, because of a paucity of deep wells penetrating Cambrian-age strata, some well data were used from as far as 18 miles from the site. Some of this data was previously collected and compiled for the FutureGen work from public records on file at the Ohio Geological Survey. This data includes available published studies, geologic maps, oil-and-gas-well locations and related data, interpreted formation depths, formation thicknesses, well-construction details, formation pressure, permeability, porosity, location and availability of core samples, location and availability of brine/formation-fluid samples, and mineralogy of potential injection zones. Digital data were assembled from sources at the Ohio Geological Survey. Wells in the text and figures may be referred to by both lease name and the American Petroleum Institute's well-identification number (APINO). Stratigraphic nomenclature used in this report is that currently accepted by the Ohio Geological Survey and can be found in Larsen (1998), Riley and others (1993), Wickstrom and others (2005) and Baranoski (unpub. data, 2011). Figure 3 is a stratigraphic chart for strata underlying the Tuscarawas County vicinity.

A network of four dip-oriented and one strike-oriented cross-sections were constructed across the vicinity of the proposed Tuscarawas County site (fig. 2) and are presented (figs. 4–13). The cross sections illustrate the regional stratigraphy, including potential injection zones and confining units. Two sets of cross sections were used for correlation (shallow and deep sections), with stratigraphic data on the top of the Onondaga Limestone and "Gull River" limestone, respectively.

Maps of selected geologic horizons are presented to illustrate variations across this AOR. Mapped properties presented include structure (depth relative to sea level), interval thickness, average and net porosity, and net sandstone. Some of the formation tops used in this report were previously interpreted by consulting geologist Steven Zody for the FutureGen project. The CO_2 No.

[1] See "Geologic Framework of the Proposed Tuscarawas County, Ohio FutureGen Site," proposal prepared for the U.S. Department of Energy in response to the FutureGen request for proposal under award number DE-FC-26-06NT42073, on file at the ODNR Division of Geological Survey.

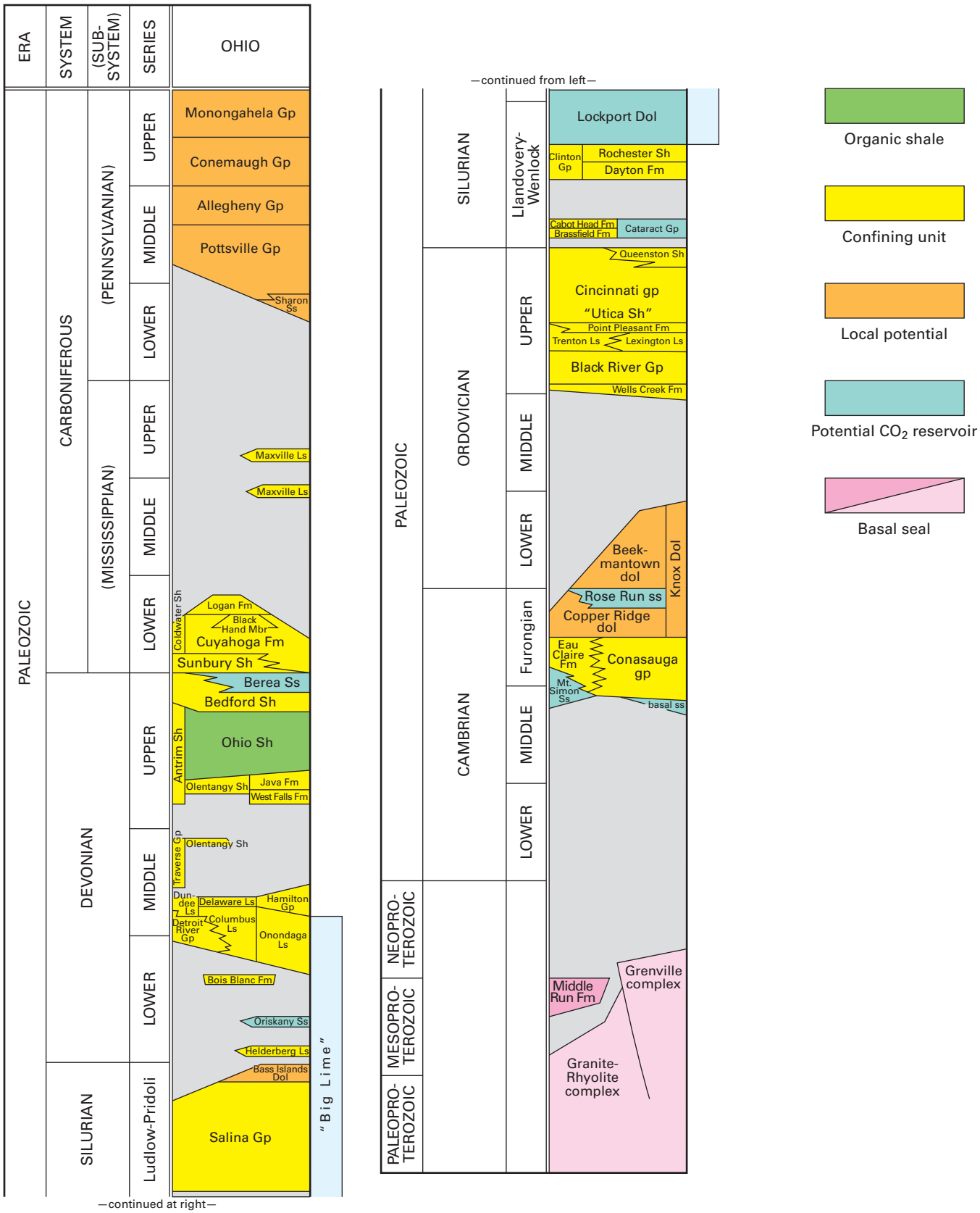

FIGURE 3.—Stratigraphic chart illustrating geologic units found beneath the Ohio Geological Survey CO_2 No. 1 well site in Tuscarawas County, Ohio, color-coded to illustrate potential injection zones, confining units, organic shales, and basal seal (modified from Wickstrom and others, 2005).

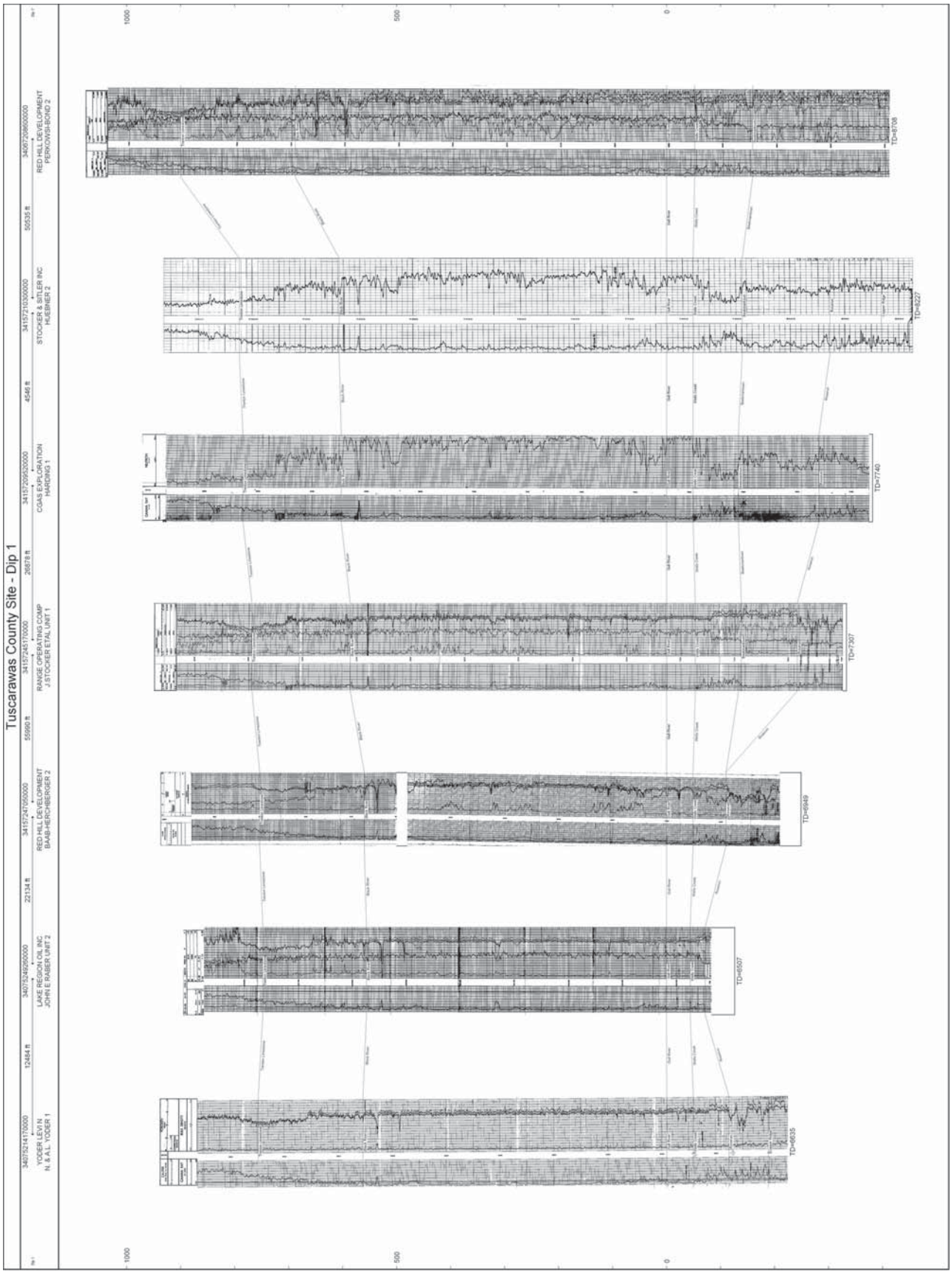

FIGURE 4.—Stratigraphic cross section Dip 1 for the Ohio Geological Survey CO_2 No. 1 test well in Tuscarawas County, Ohio, illustrating the Cambrian-Ordovician Knox Dolomite to Ordovician Trenton Limestone interval. Datum is the top of the "Gull River" limestone.

CLICK FOR LARGER IMAGE

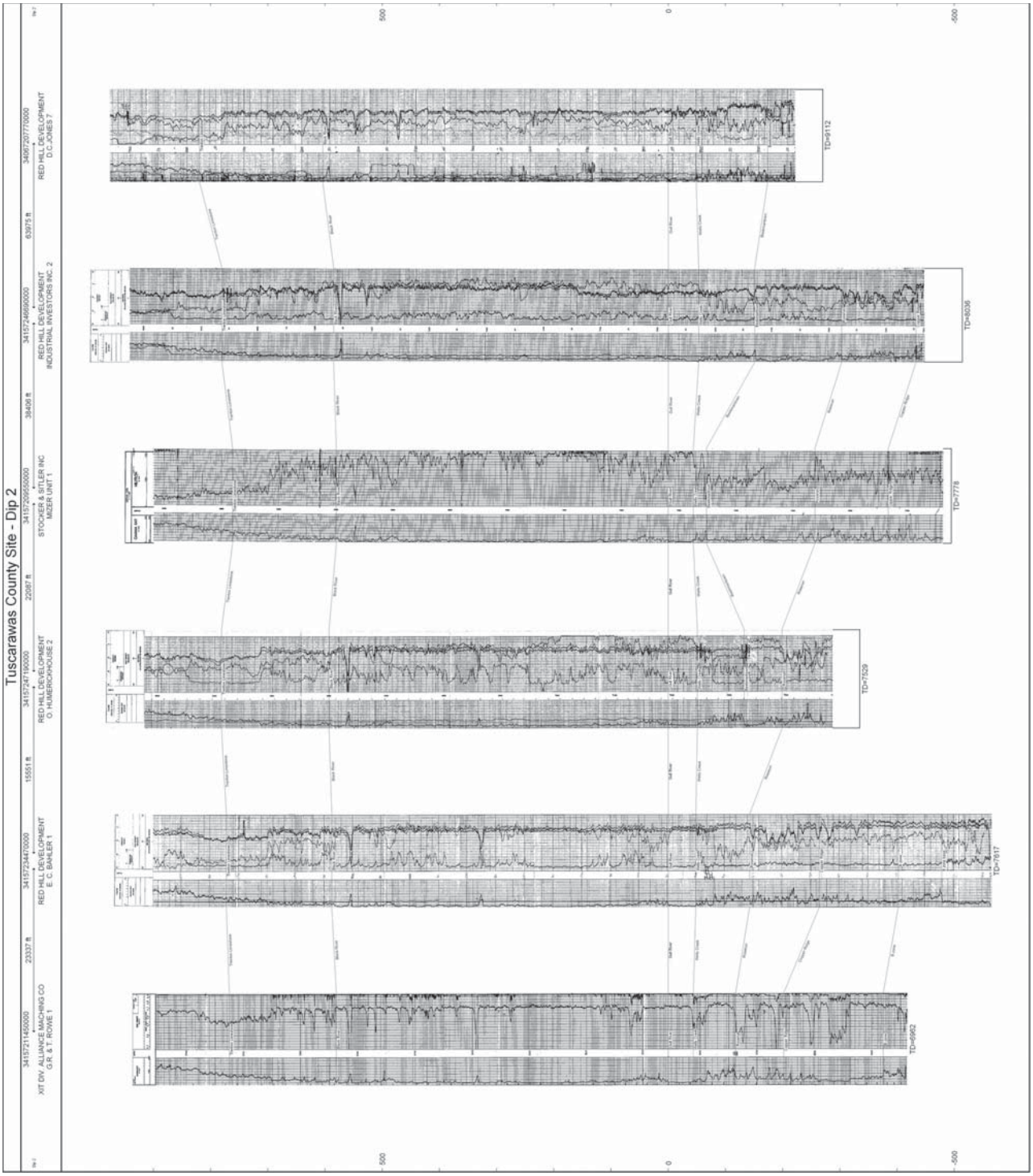

FIGURE 5.—Stratigraphic cross section Dip 2 for the Ohio Geological Survey CO_2 No. 1 test well in Tuscarawas County, Ohio, illustrating the Cambrian-Ordovician Knox Dolomite to Ordovician Trenton Limestone interval. Datum is the top of the "Gull River" limestone.

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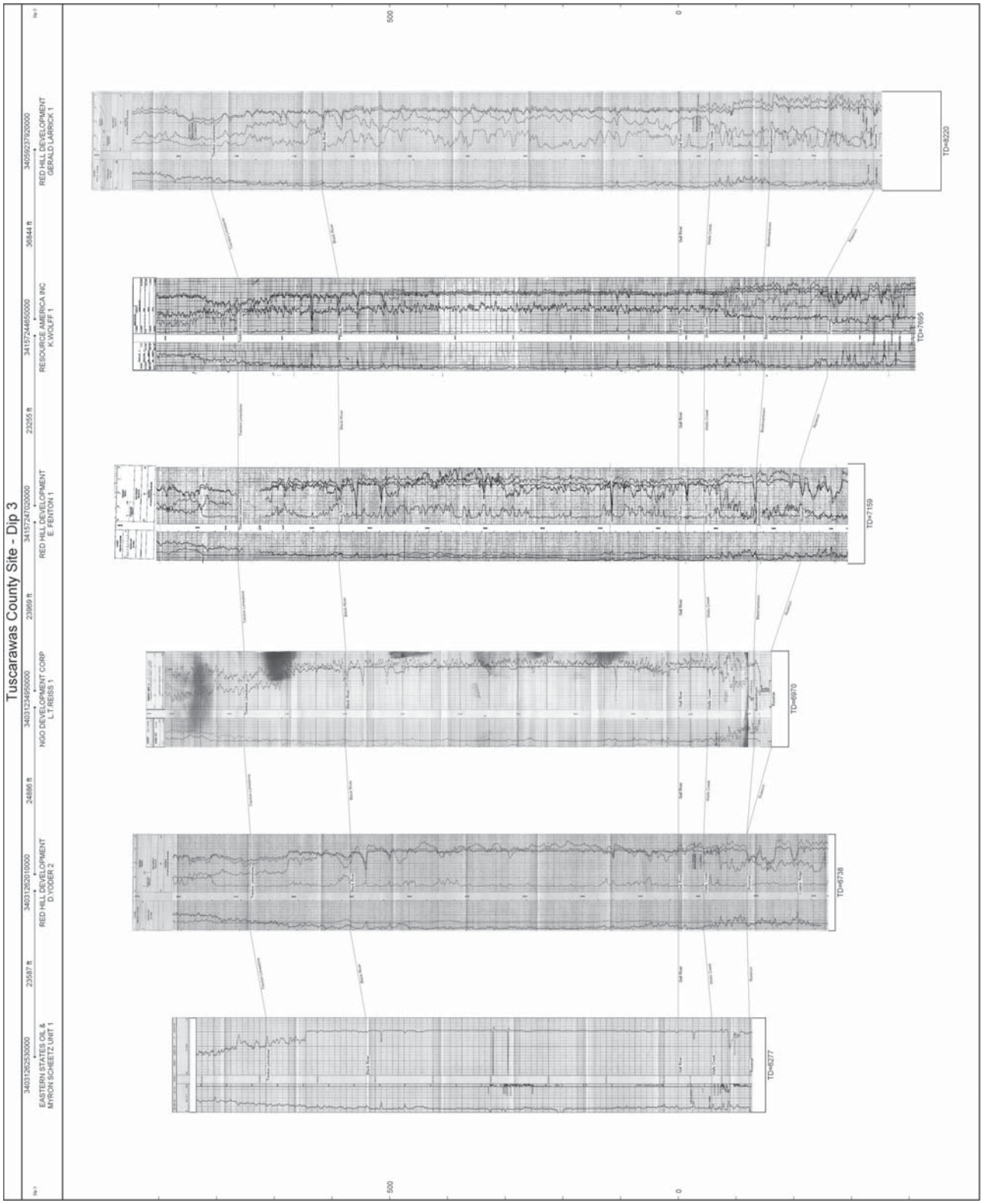


FIGURE 6.—Stratigraphic cross section Dip 3 for the Ohio Geological Survey CO_2 No. 1 test well in Tuscarawas County, Ohio, illustrating the Cambrian-Ordovician Knox Dolomite to Ordovician Trenton Limestone interval. Datum is the top of the "Gull River" limestone.

CLICK FOR LARGER IMAGE

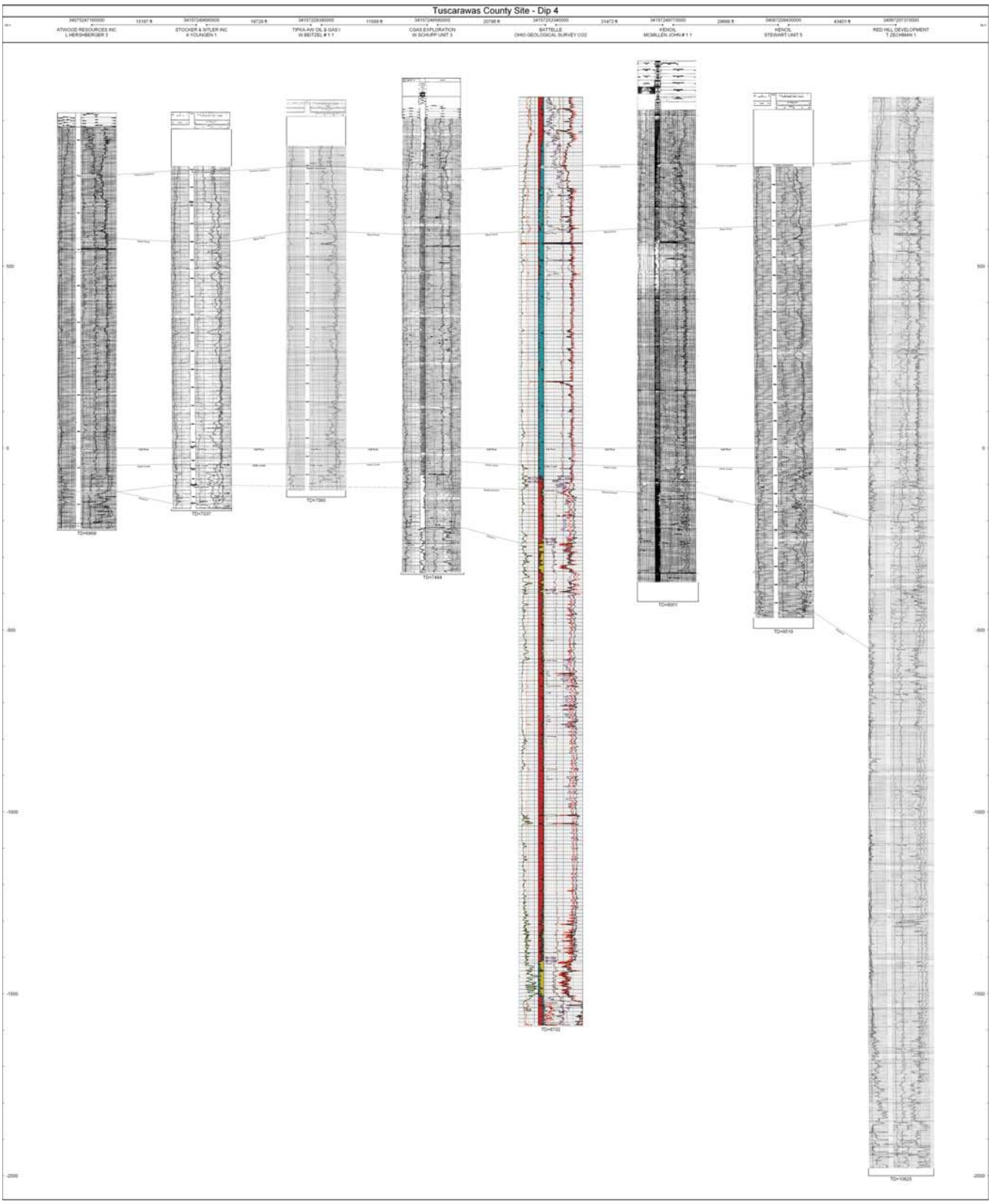


FIGURE 7.—Stratigraphic cross section Dip 4 for the Ohio Geological Survey CO_2 No. 1 test well in Tuscarawas County, Ohio, illustrating the Precambrian to Ordovician Trenton Limestone interval. Datum is the top of the "Gull River" limestone.

CLICK FOR LARGER IMAGE

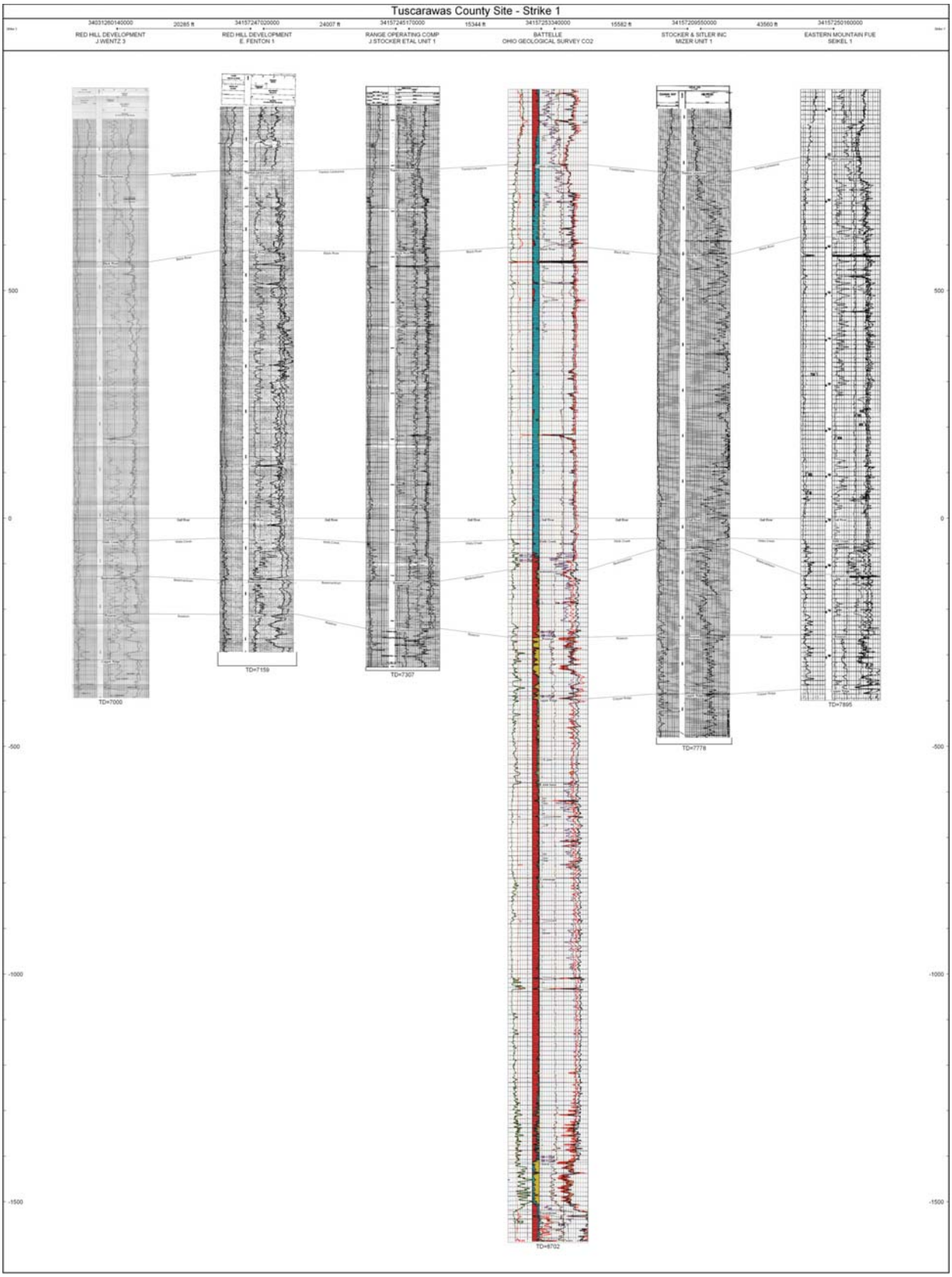


FIGURE 8.—Stratigraphic cross section Strike 1 for the Ohio Geological Survey CO_2 No. 1 test well in Tuscarawas County, Ohio, illustrating the Precambrian to Ordovician Trenton Limestone interval. Datum is the top of the "Gull River" limestone.

CLICK FOR LARGER IMAGE

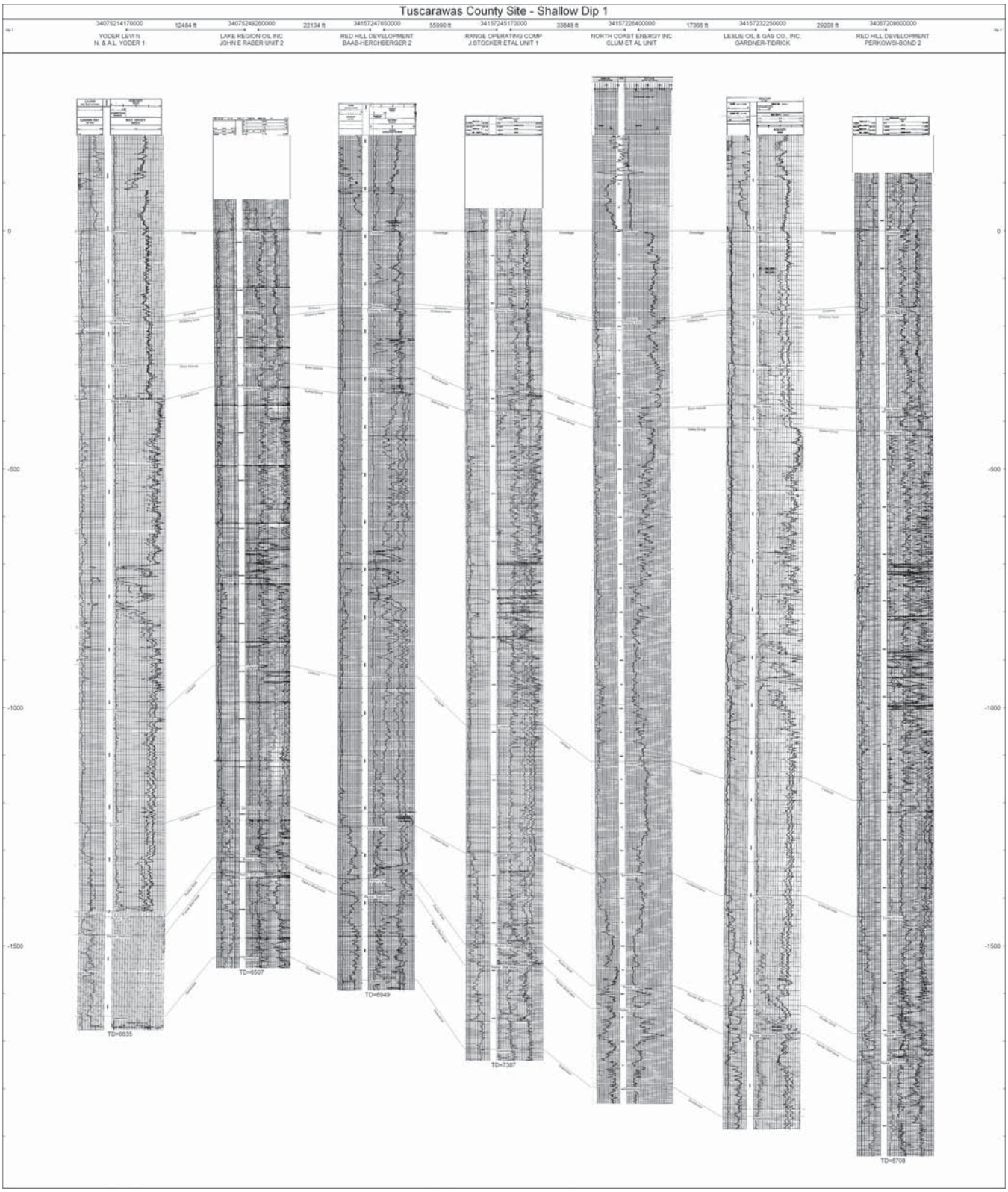


FIGURE 9.—Stratigraphic cross section Shallow Dip 1 for the Ohio Geological Survey CO_2 No. 1 test well in Tuscarawas County, Ohio, illustrating the Silurian-Devonian Queenston Shale to Onondaga Limestone interval. Datum is the top of the Onondaga Limestone.

CLICK FOR LARGER IMAGE

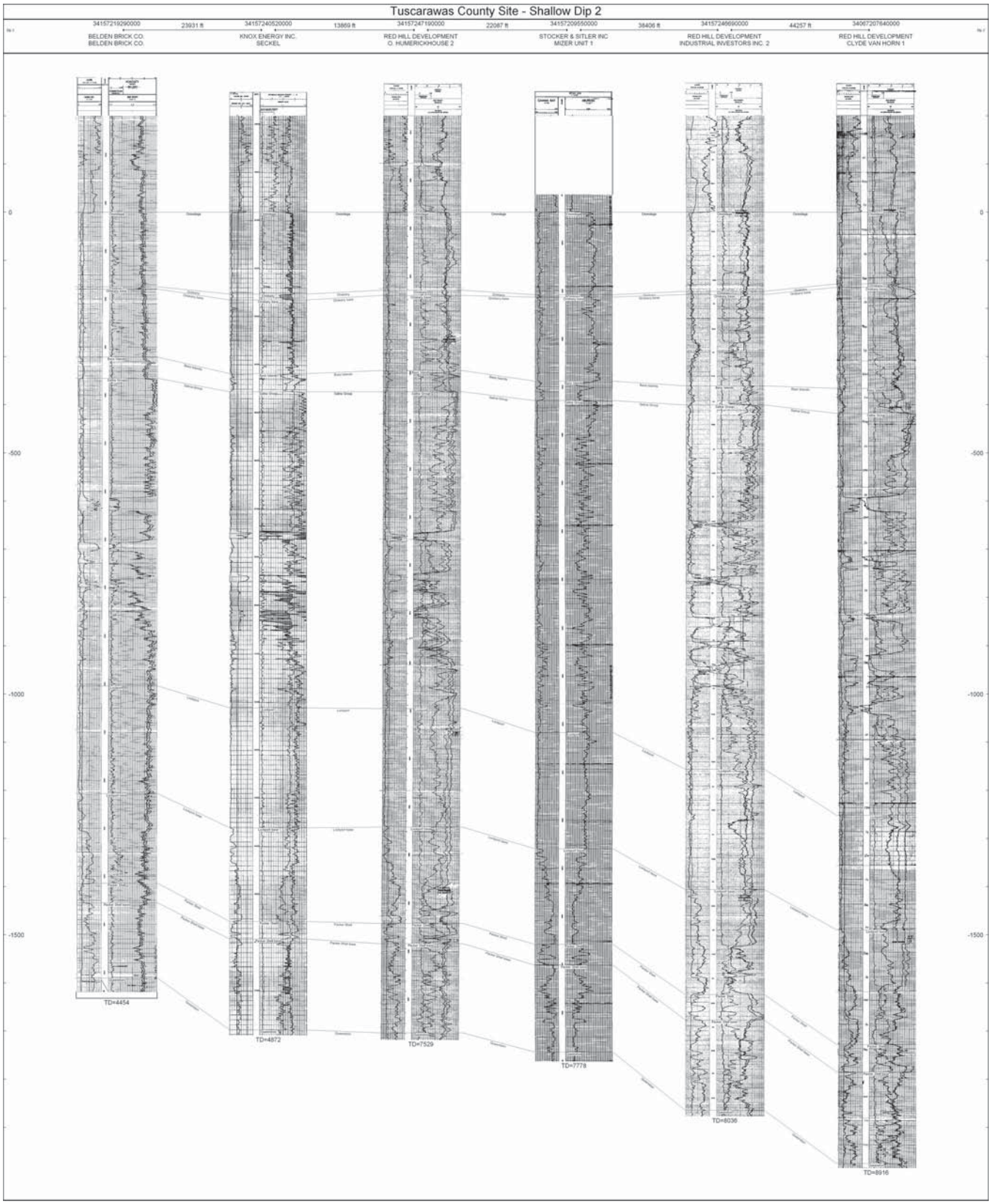


FIGURE 10.—Stratigraphic cross section Shallow Dip 2 for the Ohio Geological Survey CO_2 No. 1 test well in Tuscarawas County, Ohio, illustrating the Silurian-Devonian Queenston Shale to Onondaga Limestone interval. Datum is the top of the Onondaga Limestone.

CLICK FOR LARGER IMAGE

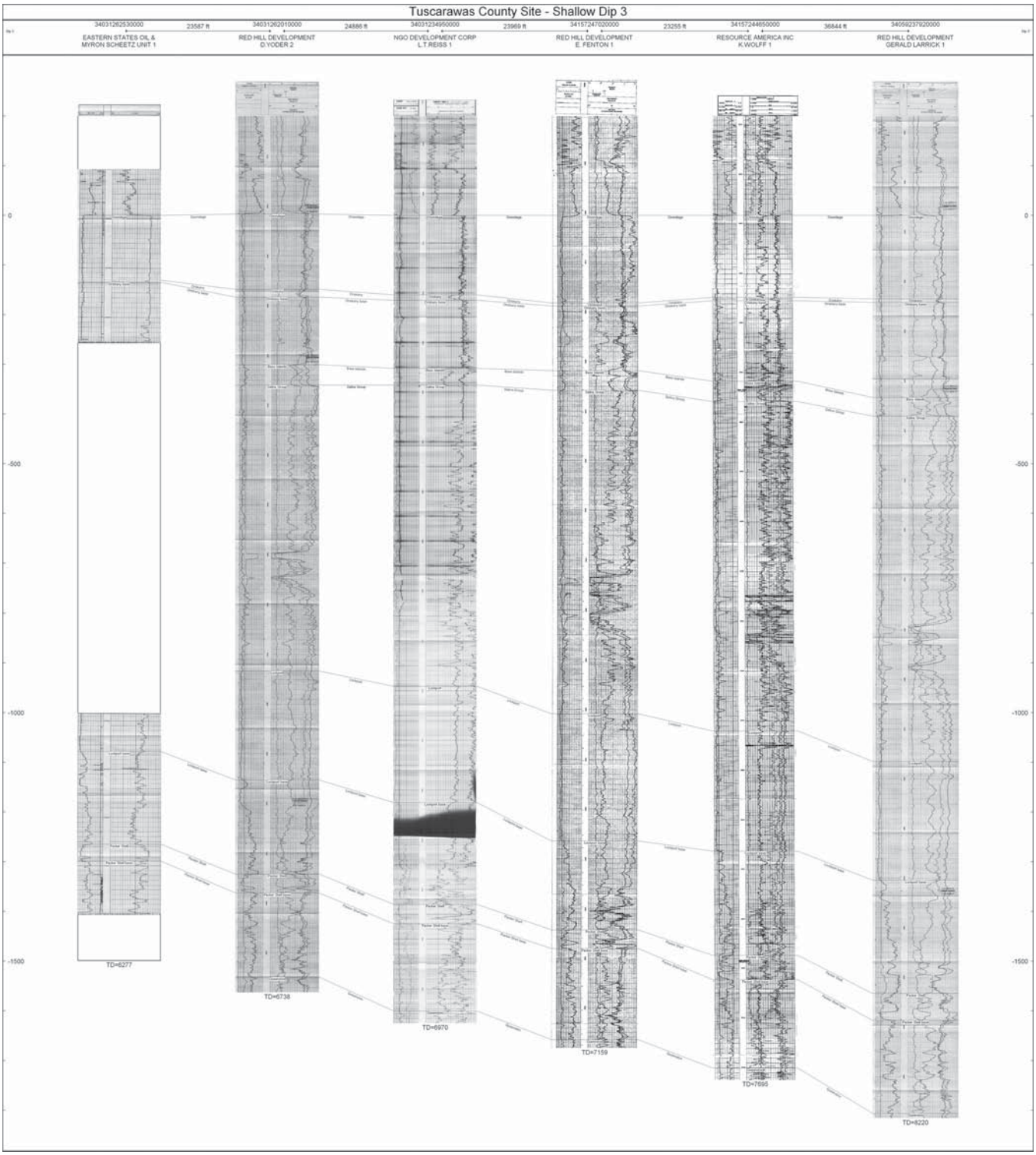


FIGURE 11.—Stratigraphic cross section Shallow Dip 3 for the Ohio Geological Survey CO_2 No. 1 test well in Tuscarawas County, Ohio, illustrating the Silurian-Devonian Queenston Shale to Onondaga Limestone interval. Datum is the top of the Onondaga Limestone.

CLICK FOR LARGER IMAGE

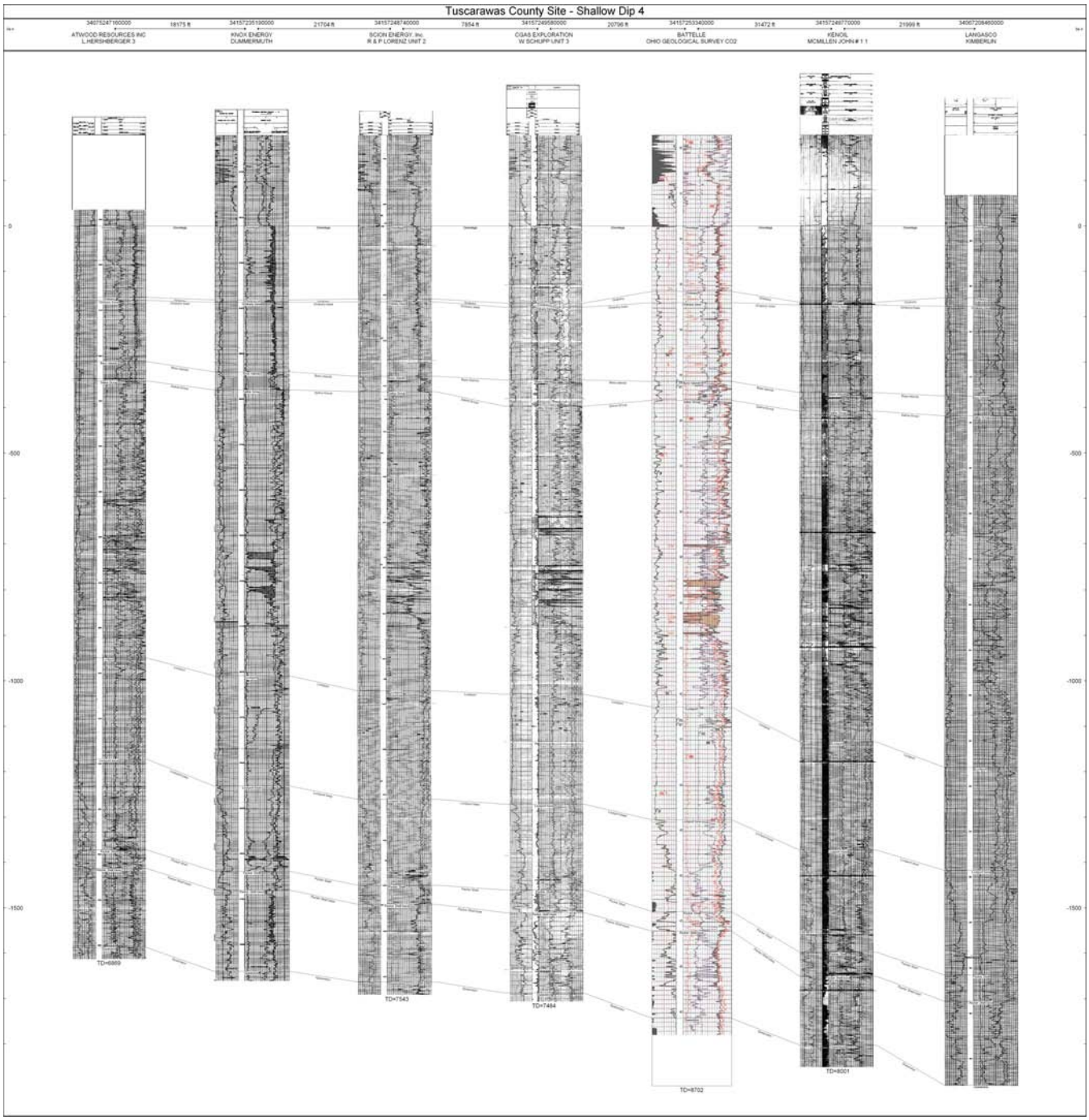


FIGURE 12.—Stratigraphic cross section Shallow Dip 4 for the Ohio Geological Survey CO_2 No. 1 test well in Tuscarawas County, Ohio, illustrating the Silurian-Devonian Queenston Shale to Onondaga Limestone interval. Datum is the top of the Onondaga Limestone.

CLICK FOR LARGER IMAGE

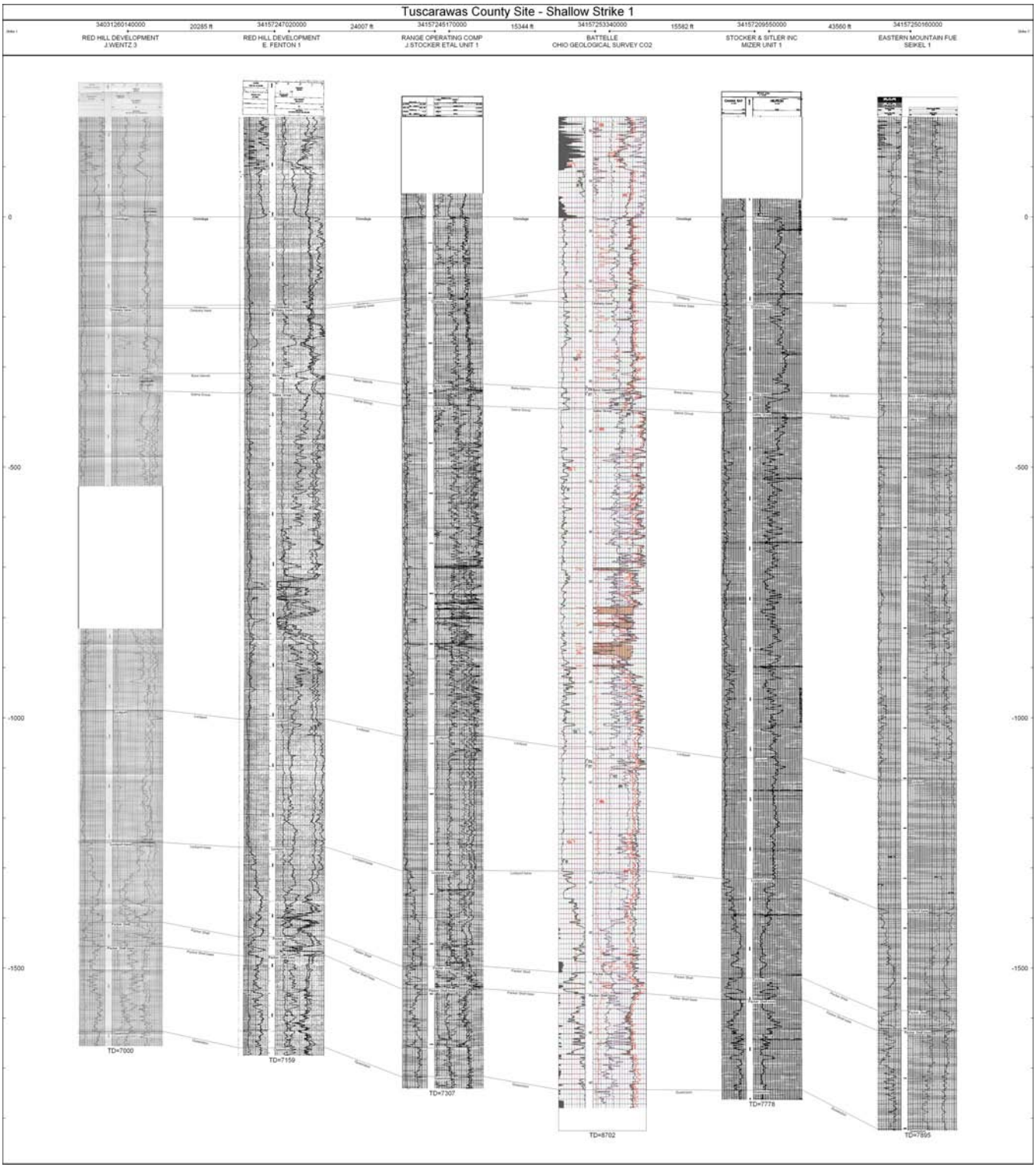


FIGURE 13.—Stratigraphic cross section Shallow Strike 1 for the Ohio Geological Survey CO_2 No. 1 test well in Tuscarawas County, Ohio, illustrating the Silurian-Devonian Queenston Shale to Onondaga Limestone interval. Datum is the top of the Onondaga Limestone.

CLICK FOR LARGER IMAGE

1 well also is shown in the statewide Precambrian structure map from Baranoski (2002; see figure 14). This structure map represents the base of the Cambrian basal sandstone, which is the deepest potential injection zone in the state. Work performed by the Ohio Geological Survey under the U.S. DOE-funded MRCSP (Wickstrom and others, 2005), and other U.S. DOE-funded CO_2-sequestration projects, has been of great value in compiling information for this project.

PREVIOUS WORK

No previous, detailed deep (Cambrian)-subsurface investigations of prospective geologic reservoirs and sealing units viable for carbon storage had been conducted for this AOR prior to Ohio's FutureGen proposal. There is limited deep subsurface data in this area. The CO_2 No.1 well is the first Precambrian test to be drilled in Tuscarawas County. The closest Precambrian well is located approximately 18 miles to the west in Coshocton County.

Member agencies of the MRCSP team have conducted several regional geologic investigations during the past three decades that include the AOR. The MRCSP Phase I Task Report (Wickstrom and others, 2005) was the source for much of the stratigraphic data and some of the maps used in this analysis. *The Atlas of Major Appalachian Gas Plays* (Roen and Walker, 1996), a comprehensive study of natural gas plays in the Appalachian Basin, facilitated the analyses of some geologic horizons within the AOR. Data in the atlas that may be of additional use for future analyses at this site include average reservoir and production characteristics of each gas field.

Other regional subsurface studies have been conducted in Ohio and adjacent states that include the AOR and provide additional data, maps and cross sections for evaluating subsurface geologic units. These include regional investigations of the Devonian Shale interval (Roen and others, 1978; Gray and others, 1982; Roen and deWitt, 1984; and Roen and Kepferle, 1993). Regional studies in Ohio of the Cambrian-Ordovician interval include Janssens (1973), Shearrow (1987), and Riley and others (1993). More recently, the state surveys of Ohio, Kentucky, Pennsylvania, West Virginia, and New York completed a regional basin-wide study of the Ordovician Trenton-Black River interval (Patchen and others, 2006).

POTENTIAL GEOLOGIC RESERVOIR TYPES

The U.S. DOE has identified several categories of geologic reservoirs for potential CO_2 sequestration (U.S. DOE, 1999, 2002, 2004, 2005). Of these categories, four are considered to have potential application in Ohio, and specifically at the Tuscarawas County site: (1) deep saline formations, (2) oil-and-gas fields, (3) unmineable coal beds and (4) carbonaceous shales.

Deep Saline Formations

Saline formations are natural salt-water-bearing intervals of porous and permeable rocks that occur beneath the level of potable groundwater. Currently, a number of saline formations are used for waste-fluid disposal in Ohio—both Class I (hazardous and industrial waste injection) and Class II (oil-and-gas brine or enhanced-recovery injection) wells. Thus, a long history of technical knowledge and regulatory experience exists that could be applied to CO_2 injection/disposal. In order to maintain the injected CO_2 in supercritical phase (i.e., liquid), the injection horizons must be at depths of or greater than approximately 2,500 feet. Maintaining the CO_2 in a liquid phase is desirable because, as a liquid, the CO_2 can mix with native formation fluids (brine) and go into solution; this is the meaning of the term *miscible*. Also, by maintaining the CO_2 in liquid or near-liquid state it is much denser, thus it takes up less volume than in the gaseous phase. One ton of CO_2 at surface temperature and pressure (in gaseous phase) occupies approximately 18,000 cubic feet. The same amount of CO_2, when injected into a formation at a depth of approximately 2,700 feet, will occupy only 50 cubic feet. Sequestration depths of at least 2,500 feet also ensure there is an adequate interval of rocks (confining layers) above the potential injection zones to act as geologic seals below the deepest underground source of drinking water (USDW).

Oil and Gas Fields

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

In active oil fields, it has been demonstrated that CO_2 can be used for enhanced oil recovery (EOR). In this process, some of the oil that remains in reservoirs (after primary production) is recovered by using CO_2 to (1) repressurize the reservoir and drive the remaining oil to a recovery well (i.e., immiscible flooding at shallow depths) or (2) repressurize (or sustain the pressure of) the reservoir, reduce the viscosity (via mixing/chemical interaction) of the remaining oil, and push it to a recovery well (miscible flooding of deep reservoirs). Approximately 129 oil fields worldwide currently inject CO_2 for EOR (Moritis, 2010) and have, collectively, produced more than 1 billion barrels of incremental oil, thereby demonstrating the effectiveness of this value-added sequestration option. Of these, 109 are CO_2 miscible flood operations in the United States and are located primarily in the Permian Basin of west Texas. These fields mainly use naturally occurring sources of CO_2 but recently have been adding anthropogenic sources to their extensive pipeline network. There are no known large, natural-CO_2 sources in the eastern United States. Having CO_2 available for EOR operations may enable the local oil industry to produce hundreds of millions of barrels of additional oil (Ohio Division of Geological Survey, 1997).

The geologic, reservoir, and engineering data provided by the CO_2 No. 1 well will significantly add to the understanding of Ohio's oil and gas reservoirs and the potential to use anthropogenic CO_2 for EOR in this region. Several proposed "clean coal" projects, which will be capable of capturing CO_2 as a byproduct, are currently examining EOR opportunities in Ohio with assistance from the Ohio Geological Survey.

Unmineable Coal Beds

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

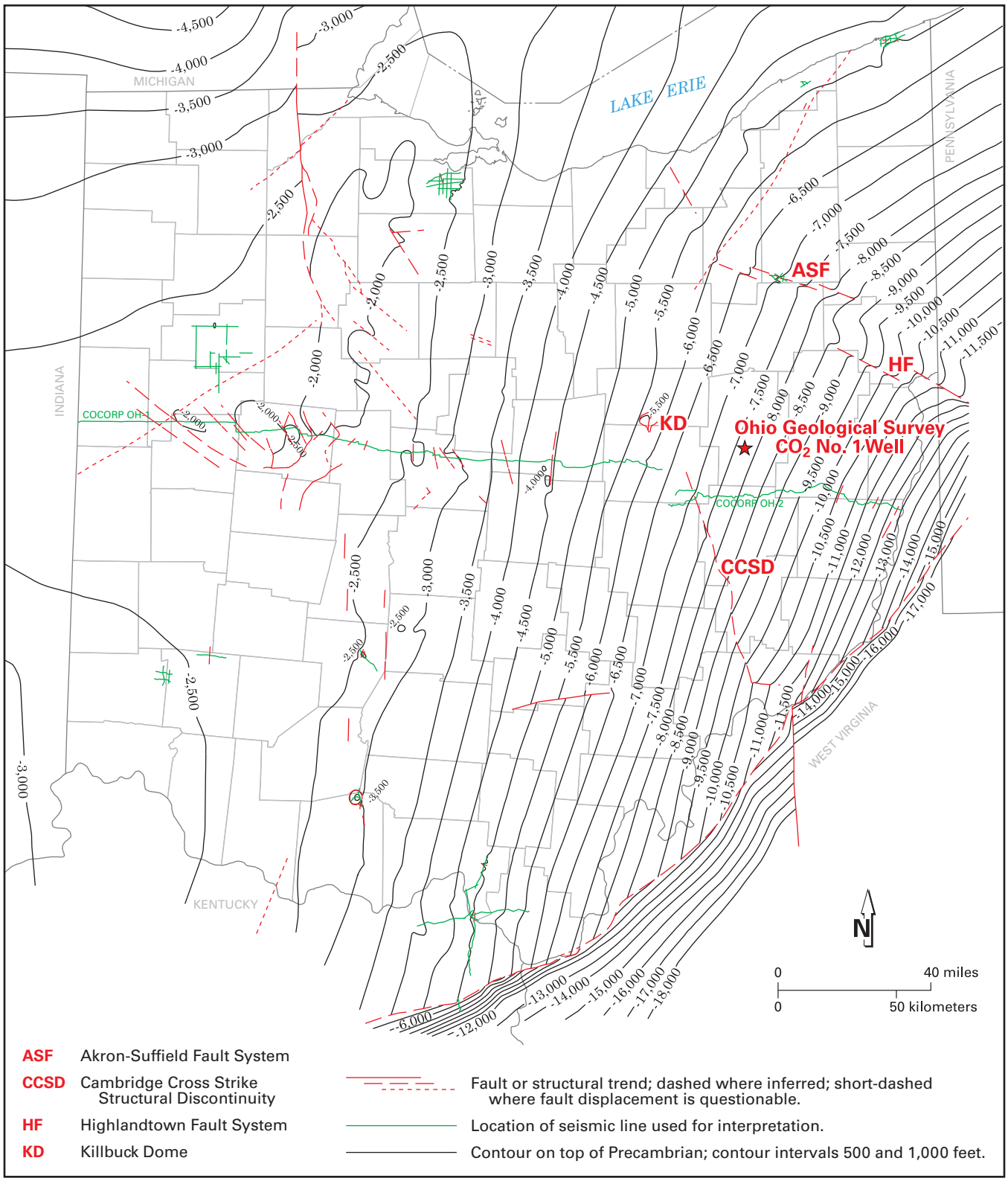


FIGURE 14.—Structure on the Precambrian unconformity surface in Ohio. Major structural trends and faults and location of COCORP seismic profile shown (from Baranoski, 2002).

occur at shallower depths than for depleted oil reservoirs and deep saline formations.

Carbonaceous Shales

Somewhat analogous to sequestration in coal beds, CO_2 injection into unconventional carbonaceous-shale reservoirs could be used to enhance existing gas production. Potential carbonaceous-shale reservoirs in Ohio and the Appalachian basin include both the Devonian and Ordovician shale intervals (fig. 3). As an added bonus, the carbonaceous shales likely would adsorb the CO_2 into the shale matrix, permitting long-term CO_2 storage, even at relatively shallow depths (Nuttall and others, 2005). Sequestration of CO_2 in carbonaceous shales has not been demonstrated and is still in the research stage.

SURFACE AND NEAR-SURFACE SITE CHARACTERIZATION

The CO_2 No. 1 well site is located in the Appalachian Highlands of the Allegheny Plateaus physiographic province. This province is classified as a dissected plateau characterized by a topographic relief of 300 to 600 feet; that portion of the plateau where the proposed site occurs is the Muskingum–Pittsburgh Plateau physiographic district (fig. 15; Ohio Division of Geological Survey, 1998). The elevation at the well site is 917 feet above sea level. Also, the site occurs in the Ohio coalfield—an historic area of extensive coal and clay mining since the early 1800s (Slucher and others, 2006).

The Tuscarawas site occurs south of the southern limit of the known glacial advance within Ohio (Pavey and others, 1999). Typically at the base of local hill slopes, broad terraced-valleys and tributaries occur and are filled with many tens of feet of unconsolidated glacial outwash and lacustrine deposits (Link, 1996a, 1996b, 1996c, and 1996d). About 200 feet of unconsolidated rock debris fill the buried Tuscarawas River valley in the vicinity of Port Washington. Generally in areas of significant topographic relief, and in those areas unaffected by mining, the bedrock occurs at the surface or is covered with a thin veneer (<10 feet) of colluvium. However, 1994-vintage topographic maps indicate that extensive areas of unreclaimed and reclaimed strip mines occur in many areas of the AOR. In areas reclaimed to the original topographic configuration, extensive deposits, many tens to perhaps a hundred feet thick, of amalgamated shale, limestone, sandstone, and other types of rock may exist between the present-day land surface and the rock surface (which denotes the lowest stratigraphic limit by surface mining methods). Approximately 32 feet of unconsolidated material was penetrated at the site before encountering bedrock during drilling of the CO_2 No. 1 well.

The bedrock geology of the vicinity is composed of an alternating sequence of sandstone, siltstone, shale, coal, limestone, and underclay that are assigned to the Pennsylvanian-age Pottsville, Allegheny, and Conemaugh Groups (fig. 16). The contact between the Pottsville and Allegheny Groups occurs at the base of the No. 4 coal bed, and the contact between the Allegheny and Conemaugh Groups is placed at the top of the No. 7 coal bed (fig. 17). The No. 4 coal occurs slightly above the general level of the Tuscarawas River valley, northeast of Port Washington (north of U.S. Route 36) and on the lower portions of hill slopes in the middle part of Frys Valley (Lamborn, 1956). The No. 7 coal is generally only a thin bed in the site area and occurs in the upper one-half to one-third portion of hilltops of the area (Lamborn, 1956; Slucher, 1997a, 1997b, 1997c, and 1997d).

The Tuscarawas area was once a center for extensive clay- and shale-mining operations for the production of brick and tile. Most mining operations exploited the clay beds associated with the No. 4 and No. 5 coal beds and shale-rich intervals that overlie the No. 4, No. 5, and No. 6 coal beds (Lamborn, 1956). Mining was by both surface and underground methods. Concurrent with clay mining was the extraction of the No. 4 and No. 6 coal beds in areas where they were several feet thick (Lamborn, 1956). In some areas, strip mining occurred in areas of abandoned deep mines[2] (fig. 18).

The Belden Brick plant site in Tuscarawas County has had a long and complex history of mining and manufacturing of brick and tile. The Belden Brick plant site was first built for manufacturing tile; it was enlarged after 1916[3], probably for the manufacturing of bricks. The plant on site consisted of two units, one of which utilized clay and the second unit which utilized shale (Lamborn and others, 1938). An underground clay mine was opened up on the east side of the property, the Belden Brick Clay Mine #1, and was open from 1916 to 1963. On the west side of the property, another underground clay mine was in operation at a slightly later date, the Belden Brick Clay Mine #2, which was in operation from 1954 to 1978. A number of small underground coal mines were located on the property. The coal from the mines was used to fire the brick-making process (Stout and others, 1923). Both sides of the property were strip mined for both clay and coal. Stout and others (1923) mentioned that clay was mined by both stripping and drifting (i.e., underground mining). When Lamborn (1956) visited the site in 1954, preparation was being made to strip mine the Brookville clay. The ODNR Division of Reclamation issued permits D-0190 and D-0398 in 1995 to the Costain Coal Company to strip the coal beds on the property.

Clay and shale were mined on the property to supply the brick and tile manufacturing business. The clay mined on the property was the Brookville clay, which underlies the Brookville coal. The Brookville clay is approximately 10 feet thick on the property and was used to make buff face brick[4] (Lamborn, 1956; Stout and others, 1923). A number of different shale beds were mined on the property to make red building brick. These shale beds included the Clarion shale[5] (Lamborn and others 1938) and shale beds above the Lower Kittanning coal bed (Lamborn, 1956). The Clarion shale is located above the Putnam Hill limestone and is approximately 26 feet thick[4] (Lamborn, 1956). The coals mined on site included both the Lower Kittanning coal bed and the Middle Kittanning coal bed. Both the Lower Kittanning and the Middle Kittanning coal beds each have an average thickness of approximately 2 feet 6 inches.

LOWEST UNDERGROUND SOURCE OF DRINKING WATER

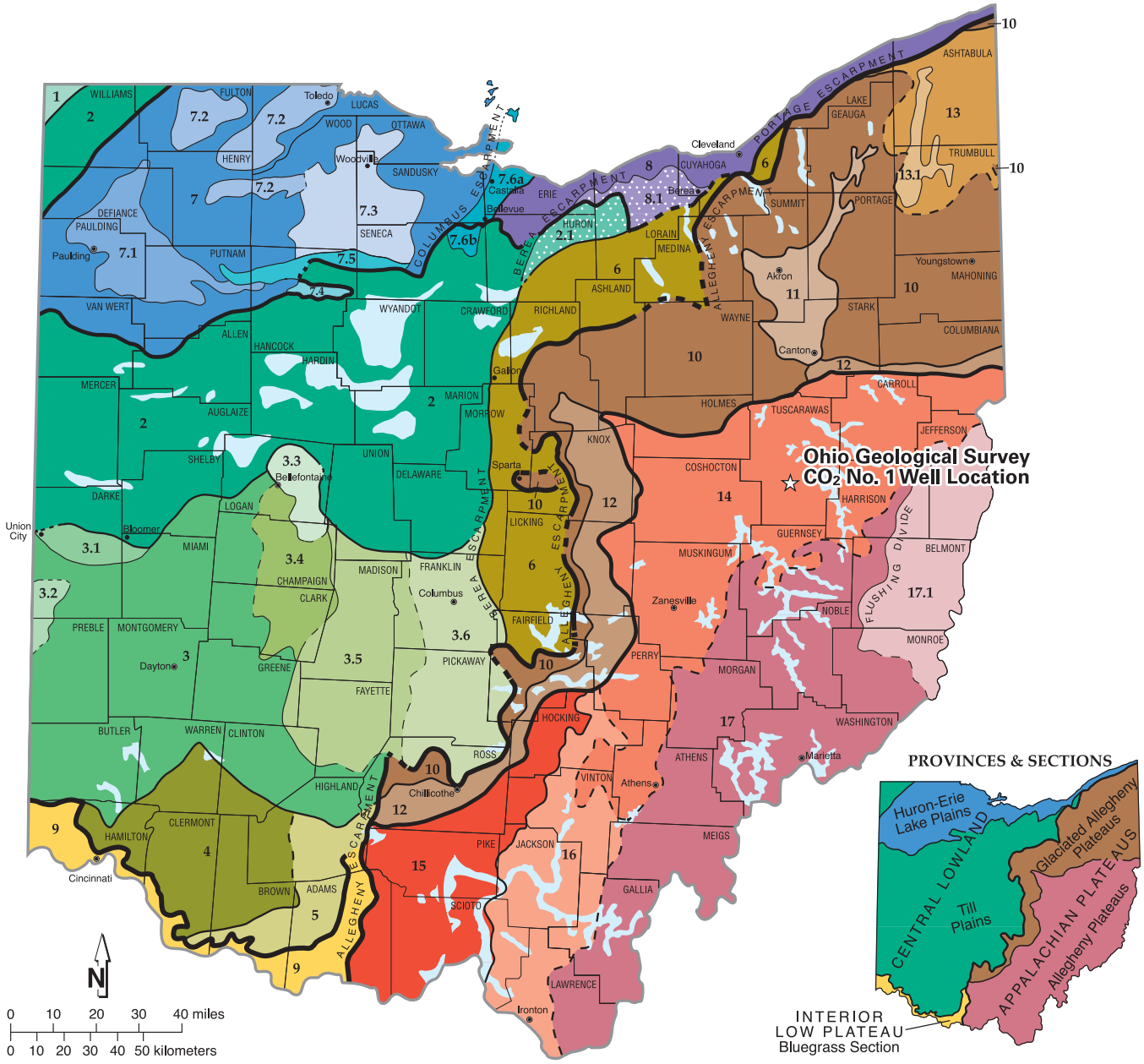
The lowest USDW (underground source of drinking water), as defined (<10,000 ppm TDS) by the U.S. EPA near the Tuscarawas site is the Mississippian Black Hand Sandstone (Black Hand Member of the Cuyahoga Formation) and the Pennsylvanian Sharon Sandstone

[2] Site-specific information of these abandoned deep mines can be found on the Ohio Abandoned Mine Locator accessible at <http://www.dnr.state.oh.us/website/geosurvey/geosurvey_mines/disclaimer.htm>.

[3] See stratigraphic section 5321, by Wilbur Stout, 1919, on file at the ODNR Division of Geological Survey of Ohio.

[4] See stratigraphic section 13371, by R. E. Lamborn, 1954, on file at the ODNR Division of Geological Survey of Ohio.

[5] See stratigraphic section 5165, by R. E. Lamborn, 1929, on file at the ODNR Division of Geological Survey of Ohio.



Till Plains

1. Steuben Till Plain
2. Central Ohio Clayey Till Plain
   - 2.1. Berea Headlands of the Till Plain
3. Southern Ohio Loamy Till Plain
   - 3.1. Union City-Bloomer Transitional Terrain
   - 3.2. Whitewater Interlobate Plain
   - 3.3. Bellefontaine Upland
   - 3.4. Mad River Interlobate Plain
   - 3.5. Darby Plain
   - 3.6. Columbus Lowland
4. Illinoian Till Plain
5. Dissected Illinoian Till Plain
6. Galion Glaciated Low Plateau

Transitional boundary

Lake basin/deposits outside Huron-Erie Lake Plains

Huron-Erie Lake Plains

7. Maumee Lake Plains
   - 7.1. Paulding Clay Basin
   - 7.2. Maumee Sand Plains
   - 7.3. Woodville Lake-Plain Reefs
   - 7.4. Findlay Embayment
   - 7.5. Fostoria Lake-Plain Shoals
   - 7.6a and 7.6b. Bellevue-Castalia Karst Plain
8. Erie Lake Plain
   - 8.1. Berea Headlands of the Erie Lake Plain

Bluegrass Section

9. Outer Bluegrass Region

Glaciated Allegheny Plateaus

10. Killbuck-Glaciated Pittsburgh Plateau
11. Akron-Canton Interlobate Plateau
12. Illinoian Glaciated Allegheny Plateau
13. Grand River Low Plateau
    - 13.1 Grand River Finger-Lake Plain

Allegheny Plateaus

14. Muskingum-Pittsburgh Plateau
15. Shawnee-Mississippian Plateau
16. Ironton Plateau
17. Marietta Plateau
    - 17.1. Little Switzerland Plateau

FIGURE 15.—Map showing the physiographic regions of Ohio (Ohio Division of Geological Survey, 1998) with the location of the Ohio Geological Survey CO_2 No. 1 Well.

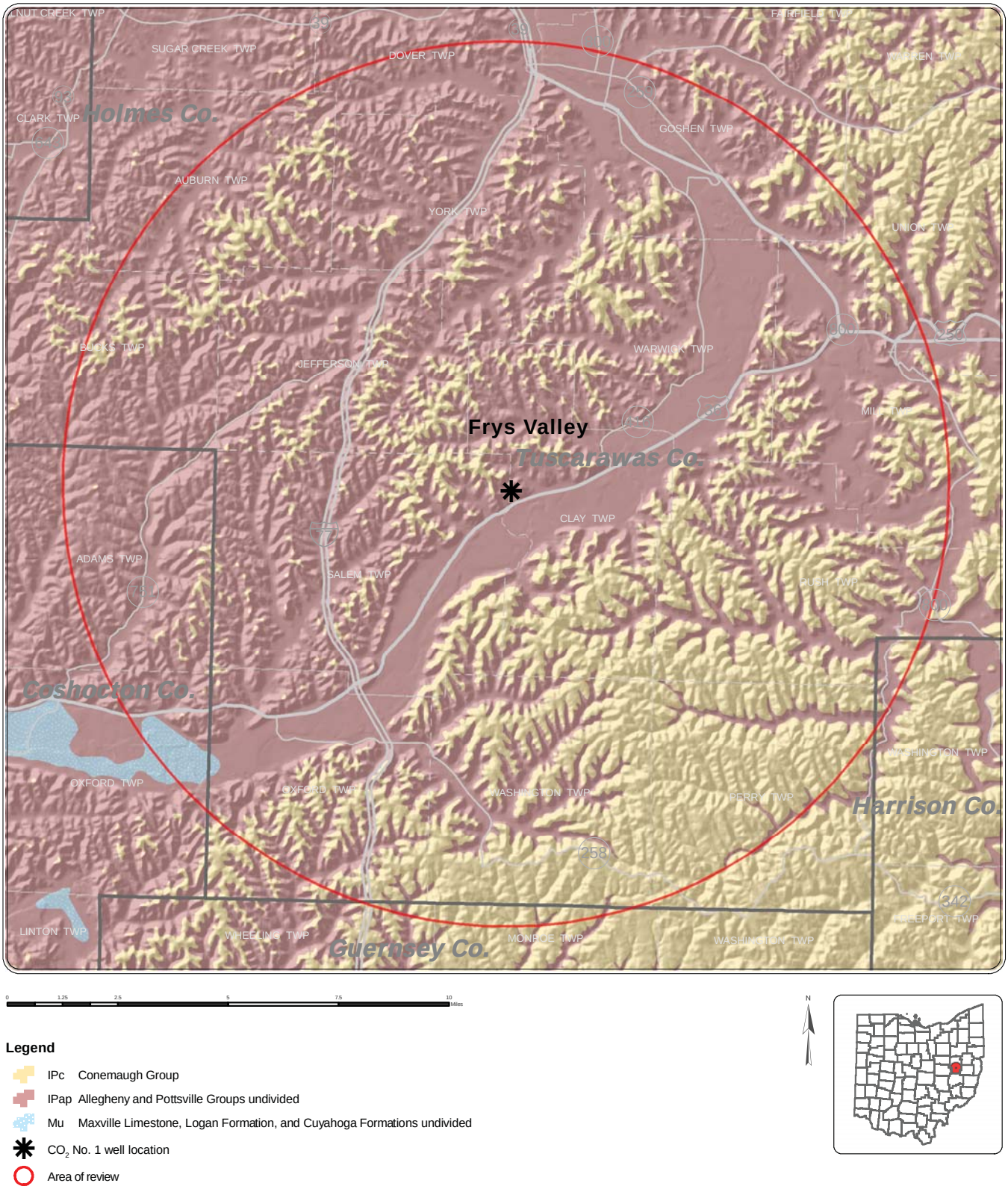


FIGURE 16.—Bedrock geologic units present within the Ohio Geological Survey CO_2 No. 1 well site area of review draped on surface topography (Bedrock polygons taken from Slucher and others, 2006; surface topography model taken from Powers and others, 2002).

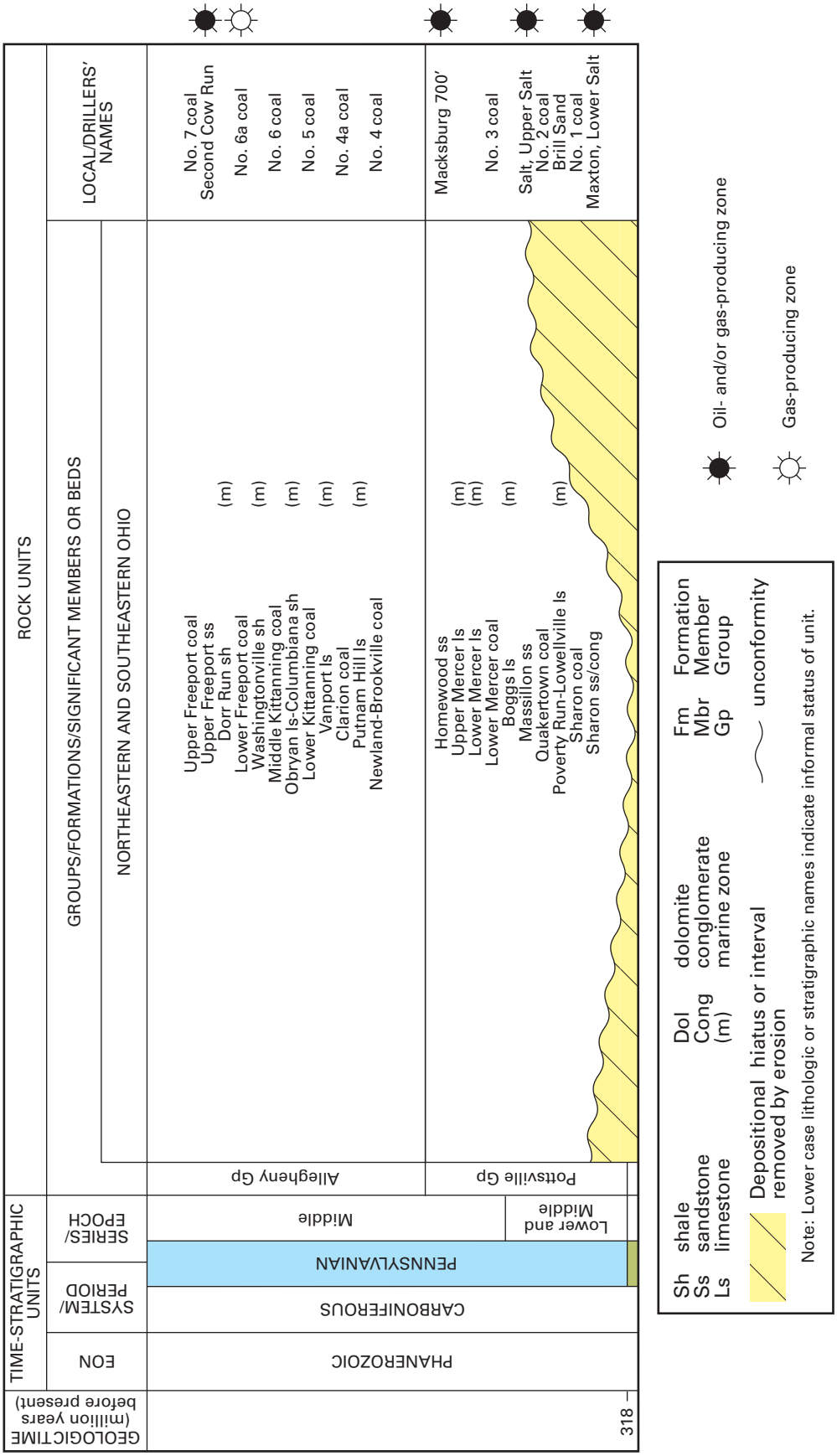


FIGURE 17.—Stratigraphic chart showing the Pennsylvanian Pottsville Group and Allegheny Group rock units at the Ohio Geological Survey CO_2 No.1 well site.

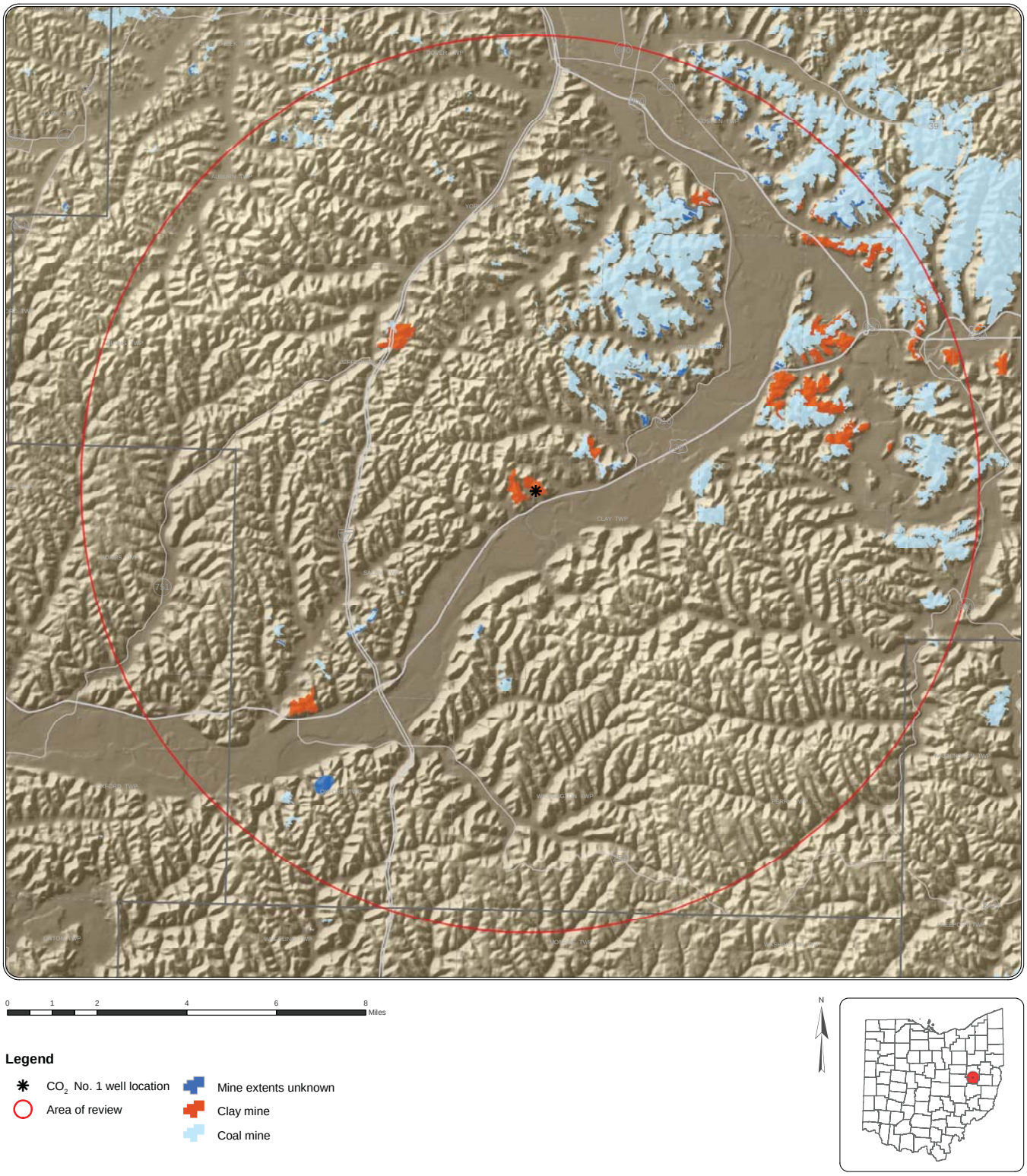


FIGURE 18.—Location of abandoned-underground mines within the Ohio Geological Survey CO_2 No. 1 well site area of review, shown on surface topography. Abandoned-underground mines from Crowell and others (2008); surface topography model taken from Powers and others (2002).

(basal unit of the Pottsville Group; fig. 3). Due to a complex relationship involving the post-Mississippian unconformity and deep channeling of the Sharon, the two units are juxtaposed near the site[6], making it difficult to determine by individual well logs alone which rock unit is present at a specific site. The elevation of the lowest USDW across the Tuscarawas AOR varies from 250 feet above sea level on the far eastern side to 550 feet above sea level on the northwestern edge. In the CO_2 No. 1 well, the drill depth to the base of the deepest USDW (Sharon Sandstone) is 434 feet above sea level. In the AOR, the deepest USDW elevations range from a depth of about 750 feet on the tallest hills to 430 feet at the Tuscarawas River valley edge. While this is the lowest defined USDW in the AOR, most residential water wells along the Tuscarawas River valley extract ground water from alluvial and glacial-outwash deposits at depths ranging from a few tens of feet to greater than 250 feet.

REGIONAL GEOLOGIC SETTING

The Precambrian Era basement complex is the foundation for overlying Paleozoic Era (and younger) rocks of eastern North America. In general terms, the Precambrian complex of the region includes all rocks older than 600 million years, and Paleozoic rocks include rocks less than 600 million years old. A thorough understanding of the geologic structure, character, and history of the underlying Precambrian complex is necessary to understand the geologic framework of the Paleozoic strata. Therefore, a very general description is provided based on our interpretation of the limited data.

The Precambrian basement complex of Ohio consists of portions of the Grenville Province, East Continent Rift Basin System, and the Eastern Granite-Rhyolite Province (fig. 19). The basement at the CO_2 No. 1 well is part of the Grenville Province. Age dates using U/Pb have not been determined for the Grenville Province in Ohio. However, regional geochronological investigations outside Ohio indicate the Grenville Province is approximately 1.0 to 1.2 billion years old (Culshaw and Dostal, 2002).

The Grenville Province is an extension of the Grenville metamorphic and igneous terrane exposed in southern Canada and consists of regionally metamorphosed igneous and sedimentary rocks formed during the Grenville Orogeny, a late Precambrian mountain-building event. The Grenville Province underlies eastern Ohio and adjacent Pennsylvania and West Virginia and forms the underpinning structure beneath Paleozoic sedimentary cover. The Grenville Province is known to contain numerous fault blocks where it has overridden the East Continent Rift System in central and western Ohio. However, few deep-seated faults are known within the Precambrian in eastern Ohio and no regionally extensive, deep-seated faults are identified in published work within 25 miles of the well site (fig. 19).

During the Paleozoic Era, periodic structural adjustment occurred along pre-existing Precambrian faults and associated zones of weakness. This adjustment affected faulting, sedimentation, and depositional patterns during the Paleozoic (Beardsley and Cable, 1983; Riley and others, 1993).

Two regional structural features developed on the eastern Laurentian craton, which was the deeply eroded Grenville Province—the Rome Trough (McGuire and Howell, 1963) and the Appalachian Basin (fig. 19). The Rome Trough, which was first described by Woodward (1961) as a "Cambrian coastal declivity," is considered an Early to Middle Cambrian-age, failed interior rift (Harris, 1978). The Rome Trough is a regional northeast-trending structure extending from southwestern Pennsylvania, where it is termed the Olin Basin (Wagner, 1976), to northern Tennessee and is very prominent on magnetic intensity maps (King and Zietz, 1978). Sparse deep-well data and seismic-reflection data correlate to this magnetic trend and indicate the Rome Trough is an asymmetric failed-rift zone with the deepest portion on the northwest side (Ryder and others, 1998; Gao and others, 2000).

The Appalachian Basin did not begin to take on its present configuration until after Middle Cambrian time following the major movement of the Rome Trough. The Rome Trough is thought to have controlled, in part, the formation and orientation of the northern Appalachian Basin (Ammerman and Keller, 1979). The subsidence of the Appalachian Basin culminated with the Alleghenian Orogeny and development of the Allegheny structural front.

PALEOZOIC STRATIGRAPHY AND GEOLOGIC HISTORY

Regional and localized areas of recurrent crustal movement of the Precambrian basement and later regional uplifts, subsidence, and compressional forces affected the distribution, character and thickness of Paleozoic rock units. Thickness of Paleozoic Appalachian Basin rock units in Ohio ranges from approximately 3,000 feet in central Ohio to more than 13,000 feet in southeastern Ohio. The Paleozoic stratigraphic column of Ohio ranges in age from Middle Cambrian to Early Permian (Slucher and others, 2006; fig. 3). A range of sedimentary rock types (carbonates, evaporites, shale, sandstone, siltstone, k-bentonites, chert, etc.) are present throughout the state.

The stratigraphy of the Middle Cambrian in eastern Ohio is particularly problematic because of sparse deep-well data and a lack of nearby continuous cores. Another difficulty has been a lack of Cambrian paleontological studies to adequately constrain lithostratigraphic correlations (Babcock, 1994). A recent investigation of all available continuous core and geophysical logs from deep wells across the state has resulted in an updated Cambrian nomenclature and stratigraphy, which is used in this report (fig. 20). This recent investigation shows that the Mount Simon Sandstone pinches out in central Ohio, the Rome Formation is not present in Ohio, and the Conasauga Formation (Janssens, 1973) has been redefined to the Conasauga group (Baranoski, unpub. data, 2011).

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

From latest Precambrian through most of Middle Cambrian time, eastern Ohio remained an emergent area as a stable cratonic platform. During this time, the erosion of the exposed Grenville base-

[6] See "Mapping the Deepest Underground Sources of Drinking Water in Ohio," by R. A. Riley, 2001, final report to the Ohio Environmental Protection Agency per CWA Section 319(h) Nonpoint Source Program Agreement C9995009-97-0, Project Number 97(h)EPA-2d.

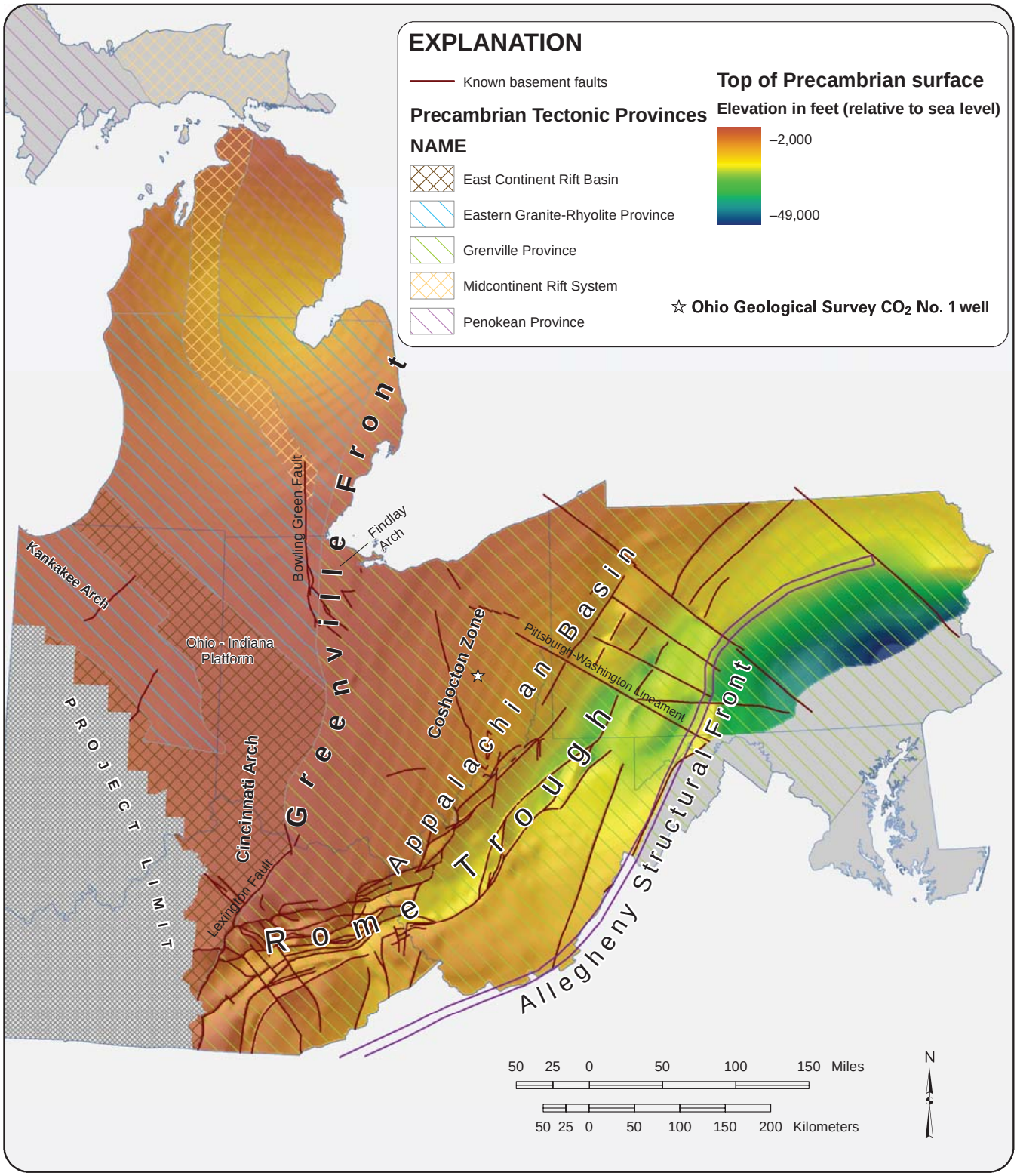


FIGURE 19.—Map of major basement faults (known), Precambrian tectonic provinces, elevation on top of the Precambrian unconformity, and other structural features. From Wickstrom and others (2005).

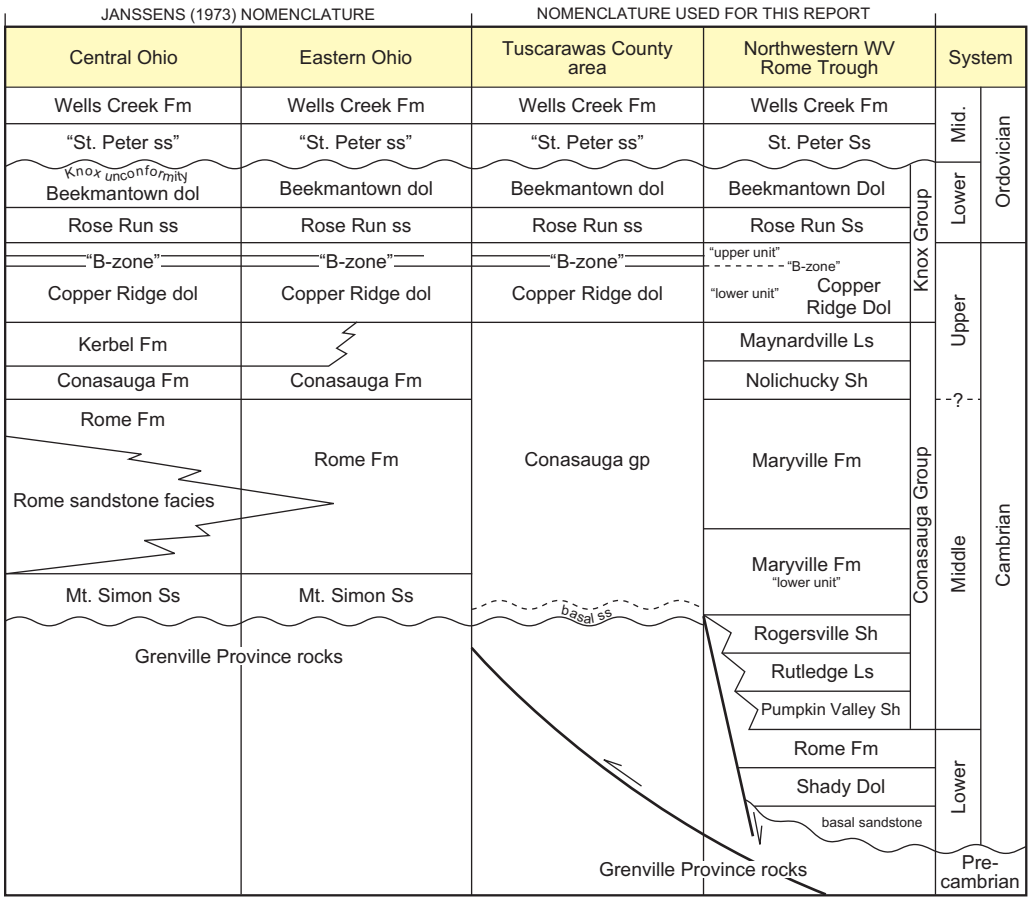


FIGURE 20.—Stratigraphic correlation chart showing old and proposed Cambrian nomenclature as used in Open-File Report 2011-3. From Baranoski (unpub. data, 2011).

ment complex in Ohio and northwestern West Virginia supplied clastic sediment to the Rome Trough while carbonates dominated east of the trough. Scattered seismic reflection data (Class I public data and oil-and-gas industry proprietary data) in Ohio indicates local areas where Cambrian sediments older than the Conasauga group may be present in structurally low areas. Near the end of the Middle Cambrian, seas had completely transgressed the exposed Precambrian basement complex in Ohio, resulting in near-shore to marginal marine deposition of Mount Simon Sandstone in western Ohio while marginal marine and marine deposition of the Conasauga group occurred in eastern Ohio. The Mount Simon Sandstone, which is a 200- to 300-feet-thick, highly permeable, porous quartz sandstone in western Ohio, pinches out or is in facies transition with the Conasauga group in the eastern portion of Ohio or occurs as both. In northwestern West Virginia and the Rome Trough region, deposition of the Conasauga Group continued into the Upper Cambrian with a minor marine regression represented by Nolichucky Shale, followed by a transgression with deposition of the Maynardville Limestone.

Open-marine conditions continued with deposition of the Knox Dolomite. As used in this report, the Knox Dolomite is subdivided in ascending order into the Copper Ridge dolomite, the Rose Run sandstone, and the Beekmantown dolomite (figs. 3 and 20). Minor regressions took place with input of clastics in the "B-zone" and to a greater degree, the Rose Run sandstone.

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

Marine sedimentation in the region temporarily ceased during

Late Ordovician-Early Silurian time as another major regression began and a regional unconformity developed on top of the Cincinnati group. By the end of the Ordovician, the western margin of the Appalachian Basin was delineated by the Indiana-Ohio Platform and the Cincinnati and Findlay Arches. As Silurian time progressed, repeated fluctuations of sea level flooded and retreated from the coastal lowlands on the western flank of the Appalachian Basin. Silurian-age Tuscarora Sandstone and other clastic equivalents ("Clinton" and Medina sandstones) were deposited in near-shore to marginal marine deposition on this unconformity surface at the onset of another marine transgression. A mixture of clastics and carbonates followed with deposition of the Rose Hill Formation, and its equivalents, and the overlying Lockport Dolomite, Salina Group, Bass Islands Dolomite and Helderberg Formation. Another period of regression is marked by an unconformity within Lower Devonian strata and is followed by a period of transgression and subsequent deposition of the Oriskany Sandstone, overlying Onondaga Limestone, and shales of the Hamilton Group, including the Marcellus Shale (marking the onset of the Acadian Orogeny).

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

DISCUSSION OF POTENTIAL SALINE INJECTION ZONES

Stratigraphic analysis of geologic units deeper than 2,500 feet in the AOR indicate nine deep-saline formations to have potential as injection zones (fig. 3). In ascending order these include: the Cambrian basal sandstone; the Copper Ridge dolomite, which contains both vuggy carbonate zones and the "B- zone" clastic interval within this unit; the Rose Run sandstone; the Beekmantown dolomite; the Cataract Group ("Clinton" sandstone); the Lockport Dolomite; the Bass Islands Dolomite; and the Oriskany Sandstone. Unfortunately, although many oil-and-gas wells have been drilled in this area, aside from standard geophysical logs, relatively little quantitative data is available for most of these units. Data such as drill-stem tests, step-rate tests, core and core analyses (e.g., porosity, permeability, capillary pressure, injectivity testing), and advanced logging suites are generally not collected on Appalachian Basin wells. The CO_2 No. 1 well, however, provided an opportunity to conduct advanced geophysical log suites and collect detailed core, pressure, and injection data that otherwise would not be available for this portion of the state. A preliminary interpretation of this data is presented herein; however, the data will continue to be analyzed and correlated with existing and new data as part of continuing efforts to characterize eastern Ohio's deep subsurface and potential for carbon sequestration, which will enable us to create a more detailed injection model with quantitative data from all potential injection horizons and seal units.

Cambrian Conasauga Group

Prior to the CO_2 No. 1 well, there were no Conasauga Group or deeper penetrations in Tuscarawas County. The nearest pre-Knox penetration is approximately 18 miles to the west in Coshocton County. As mentioned above, the Mt. Simon Sandstone, which is a thick, continuous unit over the entire Illinois and Michigan Basins, pinches out in central Ohio. Analysis of geophysical logs and well samples indicate much of this equivalent interval in eastern Ohio is predominantly dolomite with thin, laterally discontinuous, sandstone lenses. However, the same data indicate a number of the deep wells surrounding the Tuscarawas County area may contain appreciable amounts of porous sandstone in the basal Cambrian position (fig. 21).

Regionally, the lower Conasauga Group consists dominantly of dolomite to feldspathic quartz dolomite. The upper portion is light- to medium-gray, cryptocrystalline to fine- and medium-crystalline, laminated to irregular, massive-bedded, slightly arenaceous dolomite. Glauconite, anhydrite-filled vugs, rip-up clasts, stylolites, shaley discontinuity surfaces, scour surfaces, and bioturbation are locally common. Depositional environments range from shallow subtidal to shallow marine and continental slope. The lower portion of the Conasauga group (Baranoski, unpub. data, 2011) is feldspathic quartz dolomite to feldspathic quartz sandstone. It consists of light-pink to white and light-brown, fine- and medium-grained, poorly to well-sorted, rounded to subrounded, laminated to irregular, massive bedded, feldspathic dolomitic quartz arenite. Trough cross-bedding, fining upwards sequences, anhydrite replacement clasts, shaley discontinuity surfaces, scour surfaces, bioturbation, vertical burrows, trace fossils, and intraformational breccia are locally common. Depositional environments range from near-shore and shallow-subtidal to shallow marine environments (Harris and others, 2004; Baranoski, unpub. data, 2011). The quartz sandstone content and porosity (net porosity thickness) of the lower Conasauga group cannot be reliably mapped in the AOR because of a paucity of wells drilled through this interval. However, based on geophysical logs alone, the closest Precambrian penetrations to the CO_2 No. 1 well indicate appreciable amounts of porous sandstone in the lower Conasauga group, commonly referred to as the Cambrian basal sandstone (fig. 21).

From selected sidewall cores in the Cambrian basal sandstone from the CO_2 No. 1 well, this unit consists of an arkose with interbedded dolomite. The arkose is comprised dominantly of monocrystalline and polycrystalline quartz (51 percent) and feldspar (21 percent). Lithic fragments occupy 1 percent or less of the framework. The contact of the Cambrian basal sandstone is marked by a sharp change in dip at the unconformable contact with the underlying Precambrian crystalline rocks (fig. 22).

From geophysical log interpretation, the CO_2 No. 1 well contains approximately 110 feet (gross thickness) of the Cambrian basal sandstone ranging in depth from 8,524 to 8,634 feet (fig. 23). Within this interval, there are approximately 56 feet of net sandstone with greater than 6 percent porosity. Maximum log-derived porosity is 15 percent and averages 10 percent. From 12 sidewall cores selected in this interval, the porosities range from 2.8 to 10.7 percent (see Appendix 2G). Permeabilities from core analyses reach a maximum value of 1.06 millidarcies (mD) in one sample with the remainder being less than 0.18 mD. Thin section petrography indicates the dominant cements include quartz and feldspar overgrowths, and pore-lining clay (fig. 24A and 24B). Pore types include intergranular and secondary dissolution between detrital sand grains. Reservoir quality has been reduced by low permeabilities from the presence

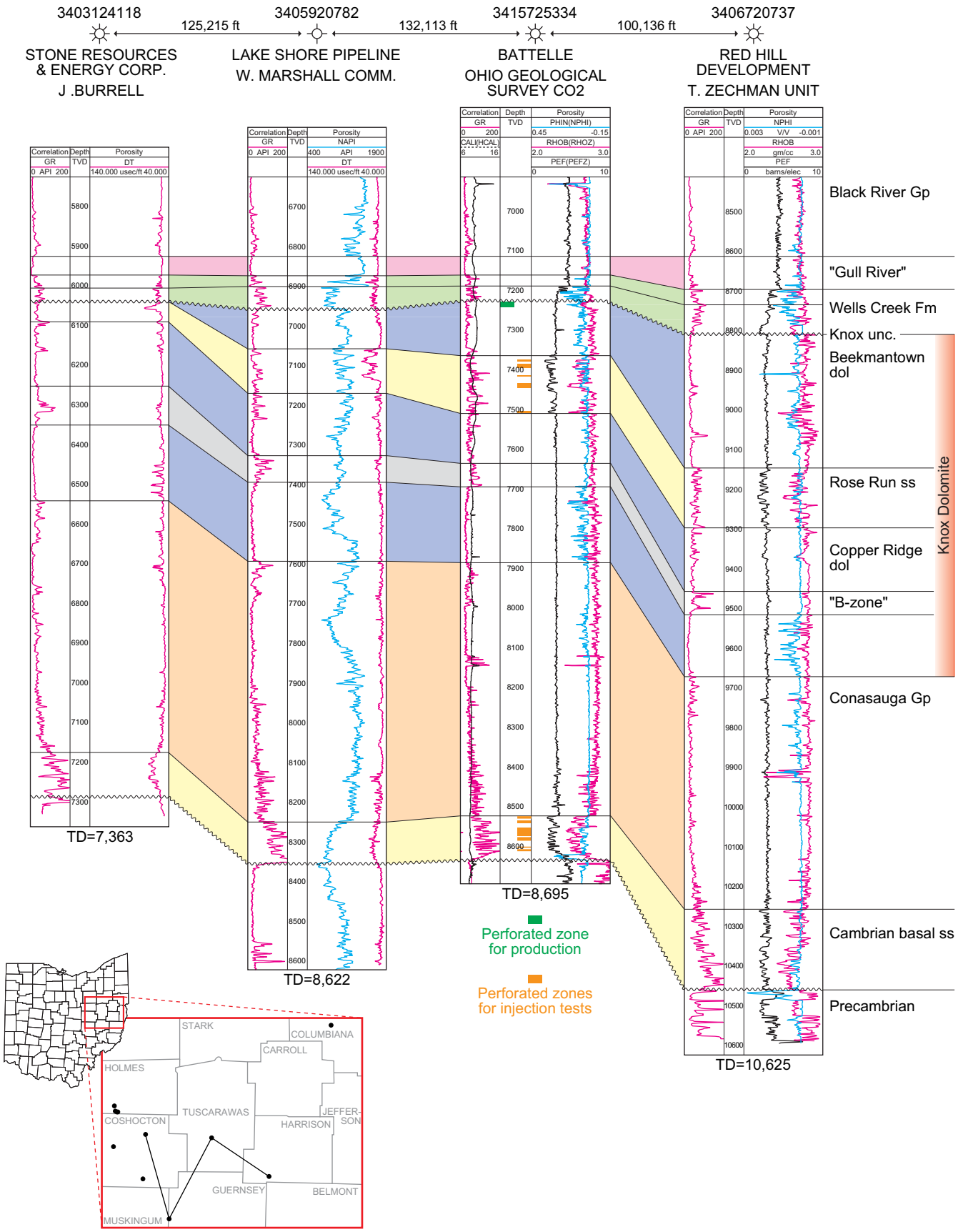


FIGURE 21.—Stratigraphic cross section through the Ohio Geological Survey CO_2 No. 1 well, illustrating the Precambrian through Ordovician Black River Group interval. Datum is the top of the "Gull River" limestone. Also shown are the perforation zones for injection tests and production. TD = Total Depth.

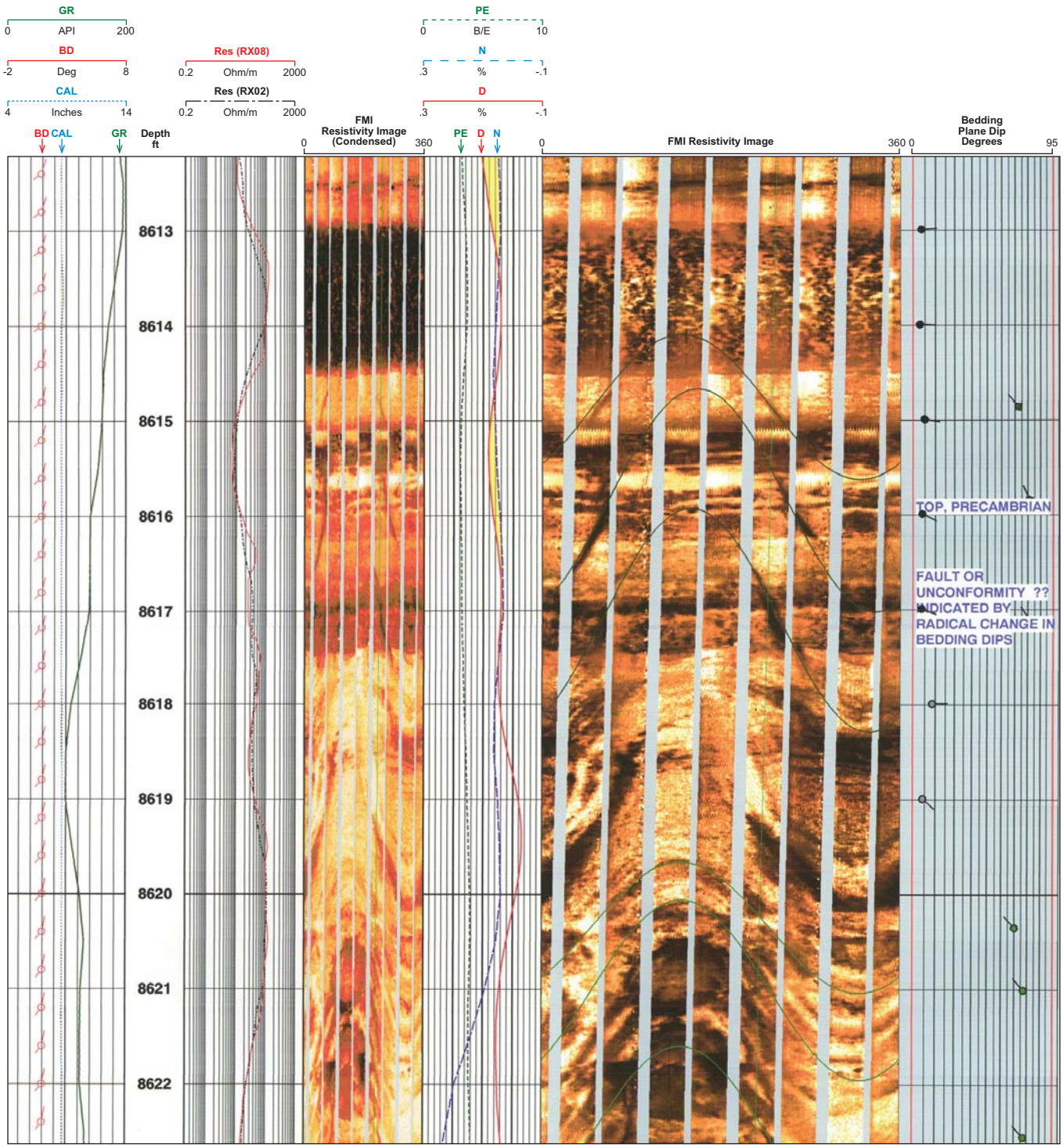


FIGURE 22.—Formation Microscanner Image of the Precambrian and overlying Cambrian basal sandstone in the Ohio Geological Survey CO_2 No. 1 well area of review. Note the high-angle dips at the Precambrian unconformity. **GR** = Gamma Ray, **BD** = Borehole Drift, **CAL** = Caliper, **PE** = Photo Electric factor, **N** = Neutron, **D** = Density, **Res** = Resistivity.

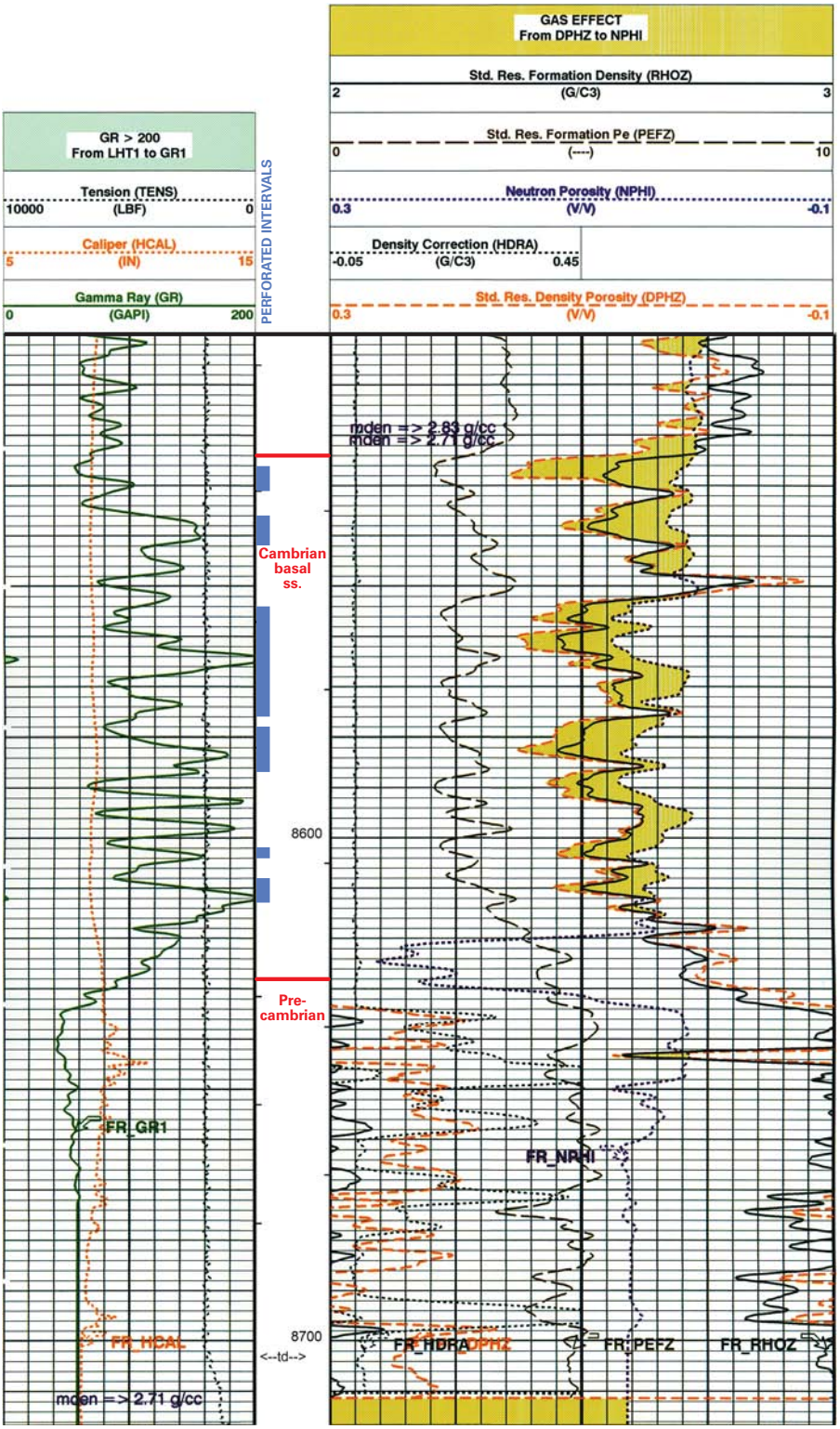
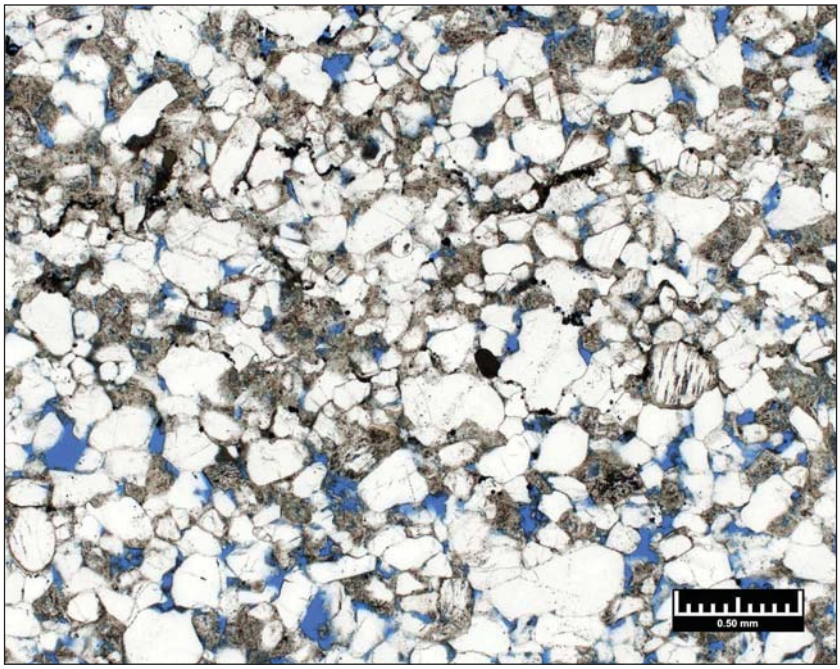
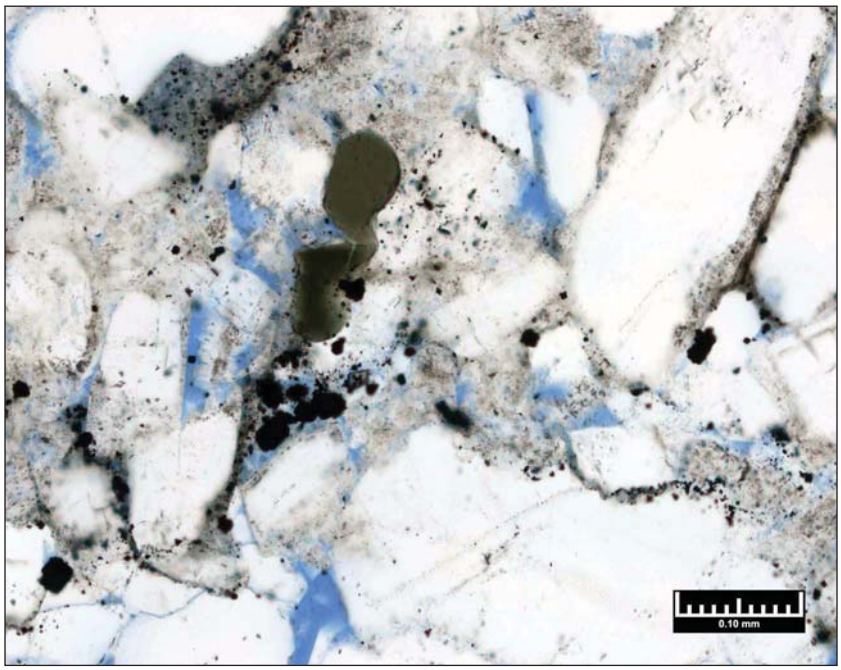


FIGURE 23.—Geophysical log of the Precambrian and Cambrian basal sandstone interval in the Ohio Geological Survey CO_2 No. 1 well site. Also shown are the perforated intervals used for the brine injection zones.



A



B

FIGURE 24.—Thin-section photomicrographs of the Cambrian basal sandstone at the Ohio Geological Survey CO_2 No. 1 well site at a depth of 8,561 feet. An arkosic sandstone composed dominantly of altered feldspar and quartz. Authigenic pyrite (black grains) reduces pore space and replaces grains. Porosity is indicated by blue epoxy. **A**, magnification of 40X; **B**, magnification of 200X.

of numerous thin-shale laminations, pore-lining clays, and cementation from quartz and feldspar overgrowths.

Cambrian-Ordovician Knox Dolomite (Group)

The Cambrian-Ordovician Knox Dolomite in Ohio consists of a mixed carbonate-siliciclastic sequence deposited in a tidal flat to shallow marine environment along a broad continental shelf (Riley and others, 2002). In eastern Ohio, the Knox Dolomite is subdivided into the Copper Ridge dolomite, Rose Run sandstone, and Beekmantown dolomite in ascending order. The widespread Knox unconformity developed during the initial collision of the passive margin and lowering of eustatic sea level in Middle Ordovician time (Mussman and others, 1988; Read, 1989). Throughout the Appalachian region, this surface is distinguished by numerous large-scale paleokarst features. Via well analyses, subsurface mapping, and seismic reflection data, paleotopographic hills have been recognized, together with sinkholes, caves, intrastratal breccias, solution-enlarged joints, and vugs (Mussman and Read, 1986; Mussman and others, 1988). The progressive westward truncation of Knox units along this regional unconformity created the Knox subcrop trends (fig. 25). Thus, which Knox units are present and subcrop at the unconformity varies regionally (fig. 25). From log correlations and regional mapping prior to drilling, it was anticipated that the CO_2 No. 1 well would encounter a complete section of Rose Run sandstone overlain by Beekmantown dolomite in the test well. Drilling of the well confirmed the Beekmantown dolomite at the subcrop of the Knox unconformity overlying a complete Rose Run and Copper Ridge section. The Rose Run sandstone was one of the primary intervals to evaluate for sequestration potential at this site.

Cambrian Copper Ridge Dolomite

The Copper Ridge dolomite is the basal unit of the Knox Dolomite (Group). Dolostones of the Copper Ridge range from dense to vuggy. Erosional remnants containing vuggy porosity in the Copper Ridge are the primary reservoir of the large Morrow Consolidated oil-and-gas field of central Ohio. In addition to porosity development at the unconformity, vuggy dolostones may occur at zones deeper within the unit. Vuggy porosity zones have been observed throughout an interval of at least 400 feet in this unit (Shrake and others, 1990). Secondary porosity in Knox carbonates occurs at two scales: (1) mesoscopic—breccia porosity, solution-enlarged fractures, large vugs and caverns—and (2) microscopic—intercrystalline, intracrystalline, molds, small vugs, and microfractures. Mesoscopic pores provide the major reservoir storage capacity and are produced by intrastratal solution and collapse of carbonate layers, whereas microscopic pores typically form by leaching of individual carbonate grains. Most pore types in Knox carbonates develop during subaerial exposure that is tied to falls of relative sea level (Smosna and others, 2005). The distribution of reservoir-quality porosity is heterogeneous and is typically confined to zones related to subaerial exposure or zones that have been fractured.

These thick zones of vuggy porosity have been encountered in a number of deep wells within the Copper Ridge dolomite. However, the presence and lateral continuity of these vuggy zones within the

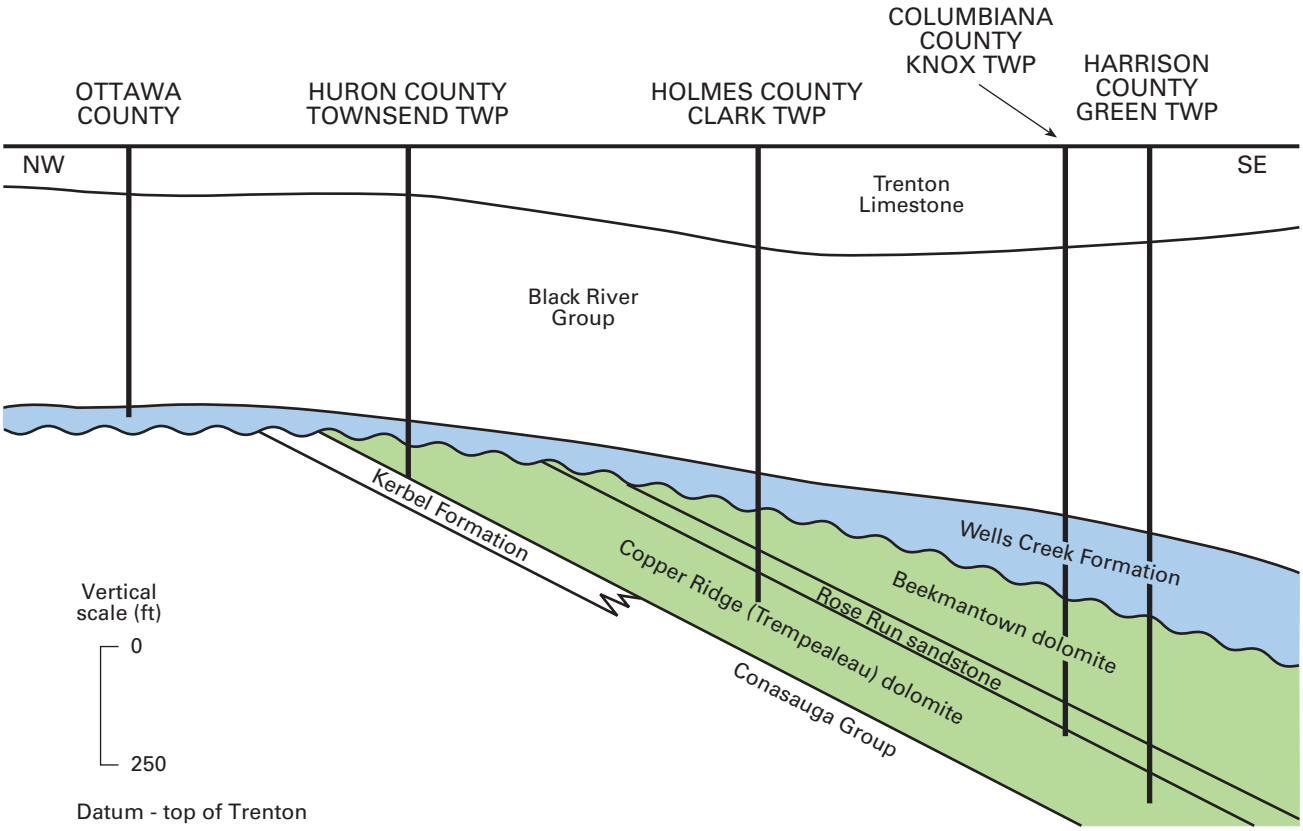


FIGURE 25.—Diagrammatic cross section illustrating the units subcropping at the Knox unconformity in Ohio.

Copper Ridge are, thus far, unpredictable; they may be present in one well and absent in the next nearest well. Vuggy dolostones of the Copper Ridge have been used as the injection zone in the DuPont WAD Fee well in Louisville, Kentucky, for the disposal of industrial waste fluids and for injection of CO_2 at the AEP Mountaineer test site in Mason County, West Virginia. The interval of vuggy dolostone is sealed above by dense dolostones of the Copper Ridge. Well-developed vuggy porosity is also present throughout various zones in the Copper Ridge in the Ohio Geological Survey core DGS 2627 in Warren County, Ohio. An example of this Copper Ridge porosity is evident on both the geophysical log and the core for DGS 2627 at a depth of 1,990 to 2,000 feet below surface (fig. 26).

The Copper Ridge interval is 390 feet thick in the CO_2 No.1 well, ranging from a driller's depth of 7,508 to 7,898 feet. Interpretation of geophysical logs and sidewall cores from the CO_2 No. 1 well indicate no appreciable amount of rock with good reservoir quality in the Copper Ridge interval. The only noticeable porosity is a thin zone (<2 feet) of enhanced porosity that is present at a depth of 7,729 to 7,731 feet. This zone is 40 feet below the base of the "B-zone" and correlates to the approximate stratigraphic position of the injection zone in the AEP no.1 well. Thin section petrography in this zone of the CO_2 No. 1 well indicates enhanced porosity at the microscopic scale. However, sidewall core analyses had a measured permeability of 0.0001 mD and porosity of 1.3 percent. Core analyses from 7 selected intervals throughout the Copper Ridge indicate porosities ranging from 1.0 to 3.8 percent, and permeabilities less than 0.03 mD.

The Copper Ridge dolomite also contains a siltstone-sandstone unit within this dominantly carbonate sequence and is referred to informally as the "B-zone." In the CO_2 No. 1 well, the "B-zone" is identified on logs from depths of 7,638 to 7,693 feet. Geophysical logs and core data in the "B-zone" indicate no significant reservoir development. In Tuscarawas County and the surrounding region, this interval is approximately 200 feet above the base of the Knox and can be as much as 50 feet thick. It is composed of glauconitic siltstone, microcrystalline dolomite, and very fine-grained sand with good intergranular porosity (Janssens, 1973).

Cambrian Rose Run Sandstone

The Rose Run sandstone occurs within an otherwise thick sequence of predominantly shallow-water carbonates that comprise the Knox Dolomite, between the Copper Ridge dolomite and the Beekmantown dolomite. This sequence has been interpreted to consist of the vertical stacking of various peritidal facies resulting from cyclical sea-level changes on a broad carbonate shelf (Read, 1989; Osleger and Read, 1991; Riley and others, 1993). The individual Rose Run sandstone units represent low-stand deposits, related to both third-order sea-level falls and short-term sea-level cycles (Read, 1989). Thin-section petrography indicates that the Rose Run sandstone has a continental block provenance with a source in the craton interior to the north and northwest of the project area (Riley and others, 1993). Thus siliciclastic (sand) deposition in the Rose Run decreases to the south and southeast away from the subcrop. Generally, the gross interval of the Rose Run thickens to the east and southeast downdip towards the basin center. It is important to note that while the gross interval thickens to the southeast, the amount of siliciclastics or potential injection zone in this interval may decrease in this direction, which supports previous ideas on Rose Run provenance work that the sandstone-to-carbonate ratio decreases to the east and southeast away from the depositional source (Riley and others, 1993; Baranoski and others, 1996).

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

The Rose Run sandstone is present throughout the entire AOR. In the subsurface it can be regionally correlated from the CO_2 No. 1 well to the east and to where it subcrops in the west (figs. 4 through 8). The CO_2 No. 1 well is located approximately 10 miles downdip and east of the Rose Run subcrop (fig. 27). Thus, it is situated in an area that was anticipated to encounter a complete Rose Run interval with overlying Beekmantown dolomite. Subsea elevations at the top of the Rose Run sandstone in Ohio dip to the east and southeast and range from –1,750 feet within the subcrop to –11,750 feet in extreme southeastern Ohio (fig. 27). The small paleotopographic irregularities apparent at a 50-feet contour interval and closures (not evident at this contour interval) that dominate the area to the west of the site are erosional remnants caused by erosion on the Knox unconformity (fig. 27). These are common in the Rose Run and other units of the Knox Dolomite within and near the subcrop trend.

Within the AOR, the subsea elevations for the top of the Rose Run sandstone dip eastward and range from –5,750 to –7,200 feet (fig. 28). Locally, irregularities are present, which are the result of paleotopography on the Knox unconformity. Based on subsurface mapping from public-domain geophysical logs, there are no major faults or structures evident in the AOR. Proprietary 3-D seismic data indicates a northwest–southeast trending monoclinal feature informally named the York-Clay feature. This feature is located approximately 3.5 miles to the east of the CO_2 No. 1 well. In the AOR, the net sandstone thickness (greater than 6 percent porosity) ranges from 12 to 74 feet but is typically 20 to 30 feet (fig. 29).

From geophysical logs of the CO_2 No. 1 well, the Rose Run had a gross interval thickness of 134 feet between the depths of 7,374 and 7,508 feet (fig. 30). There is approximately 24 feet of net sandstone (greater than 6 percent porosity). Eleven sidewall cores were taken in the Rose Run interval, and many could be identified on the Formation Microscanner Image (FMI) log (fig. 31). The FMI allows for a more detailed interpretation and correlation of geophysical logs to cores. The porosity ranges from 6 to 13.5 percent with an average of 8 percent. Permeability measurements from selected core range from 0.001 to 31.6 mD (see Appendix 2G). There were 3 Rose Run cores that contained permeabilities of greater than 1.0 mD. These

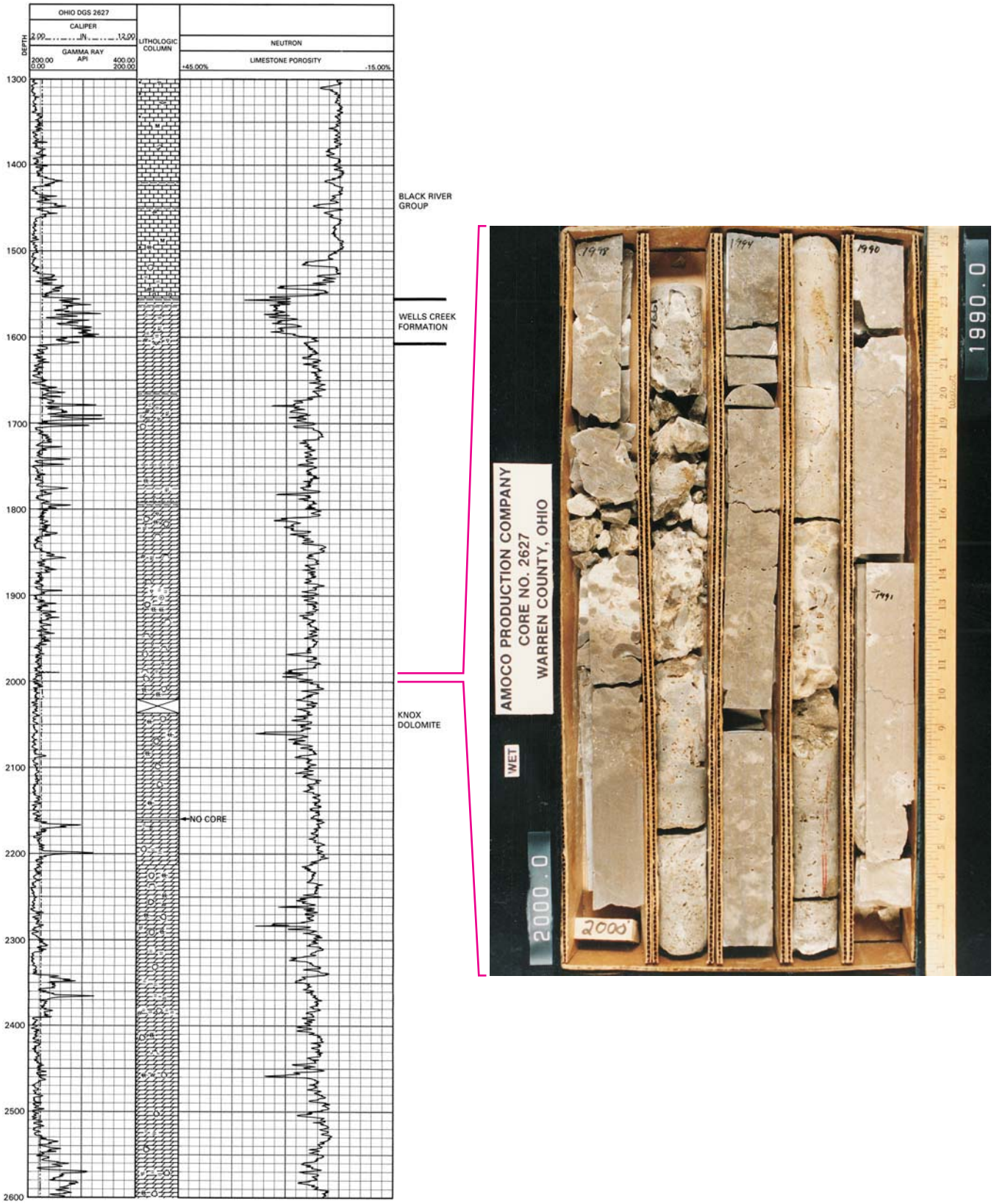


FIGURE 26.—Gamma ray-neutron log of the Ohio Geological Survey core DGS 2627 in Warren County, Ohio. Also shown is the cored interval of the Copper Ridge dolomite from 1,990–2,000 feet below surface (core photography and analyses performed by Amoco Production Company). Note the vuggy porosity and breccia zones.

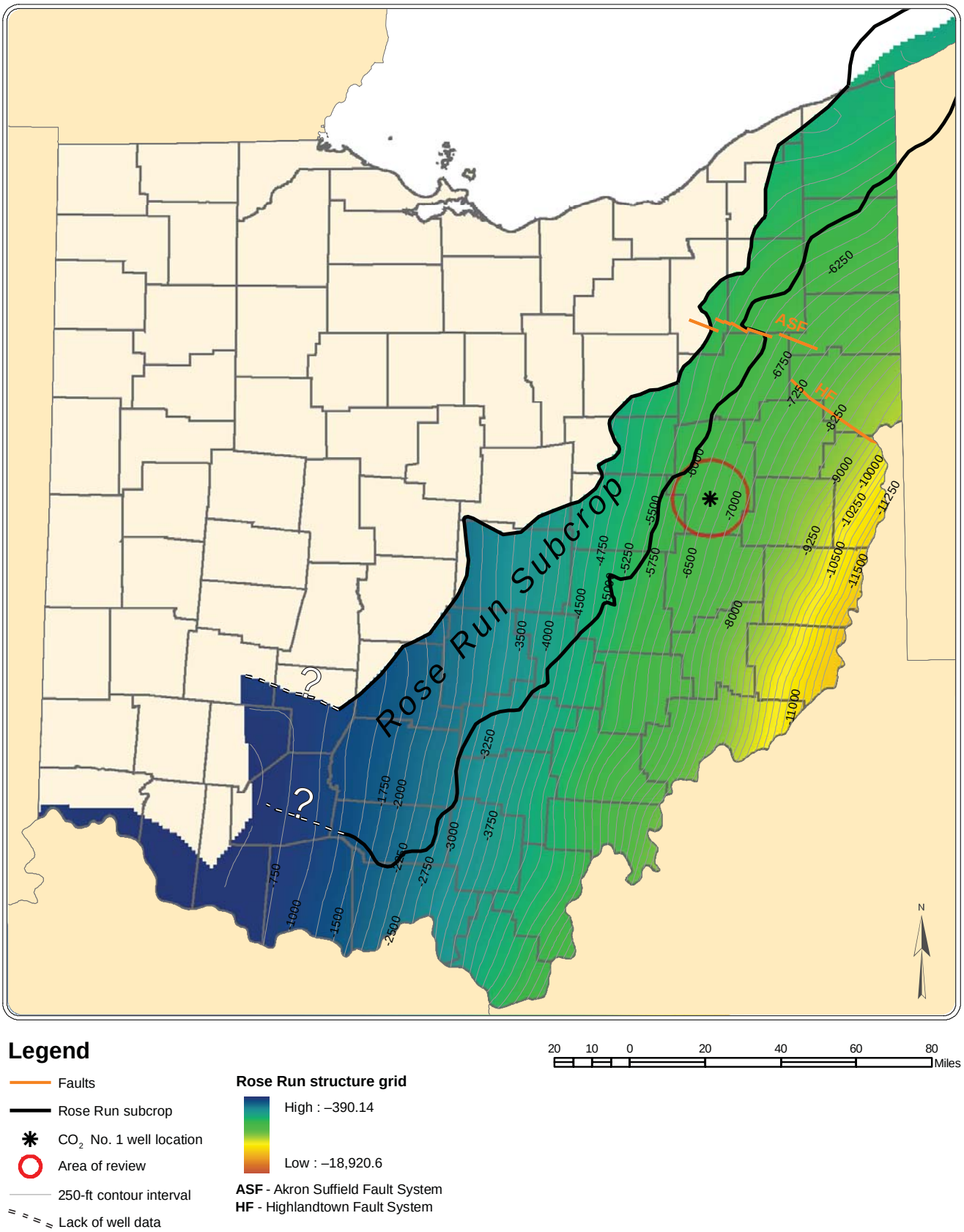


FIGURE 27.— Structure map on the top of the Rose Run sandstone in Ohio with subcrop.

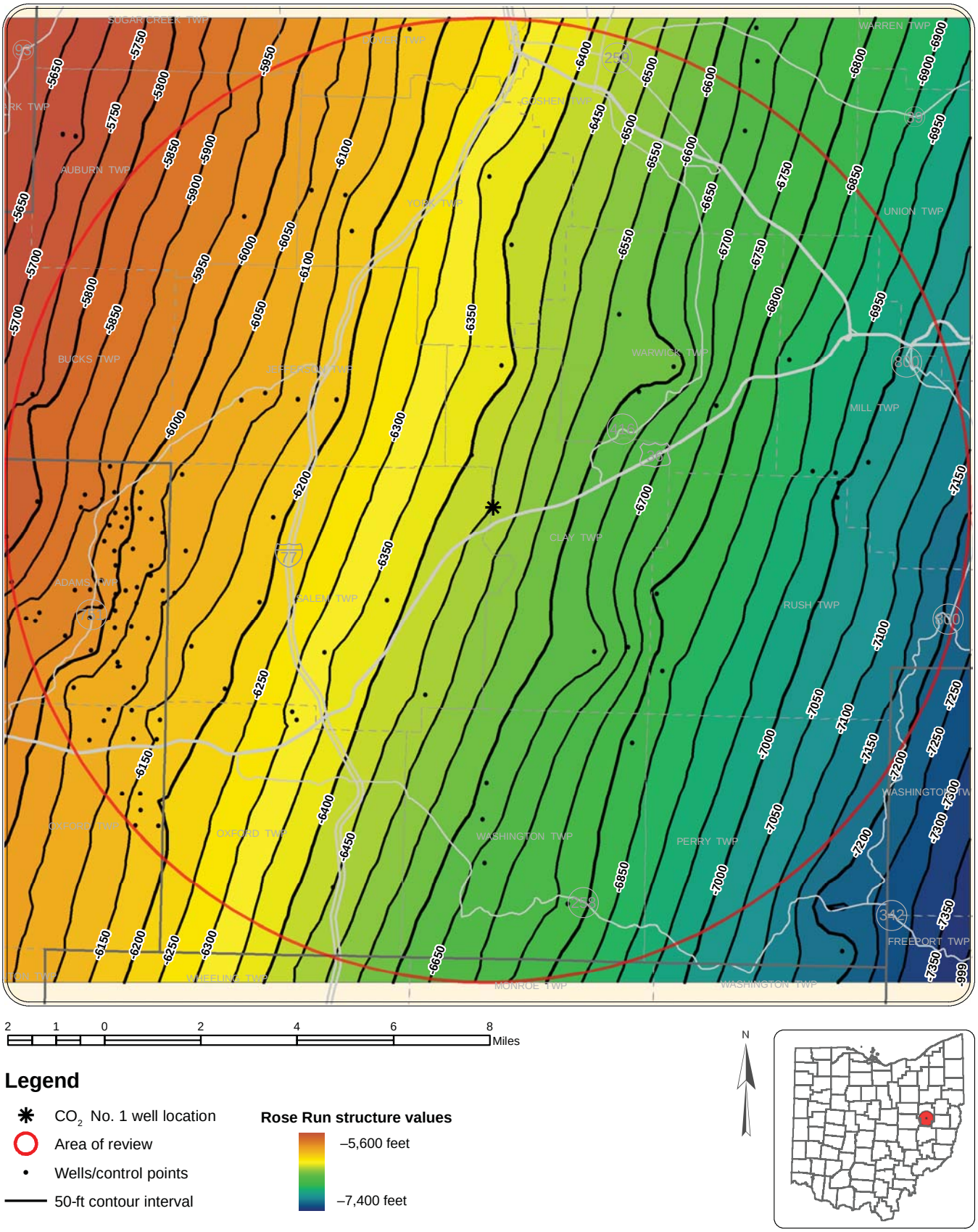


FIGURE 28.—Structure map on the top of the Rose Run sandstone within the Ohio Geological Survey CO_2 No. 1 well area of review.

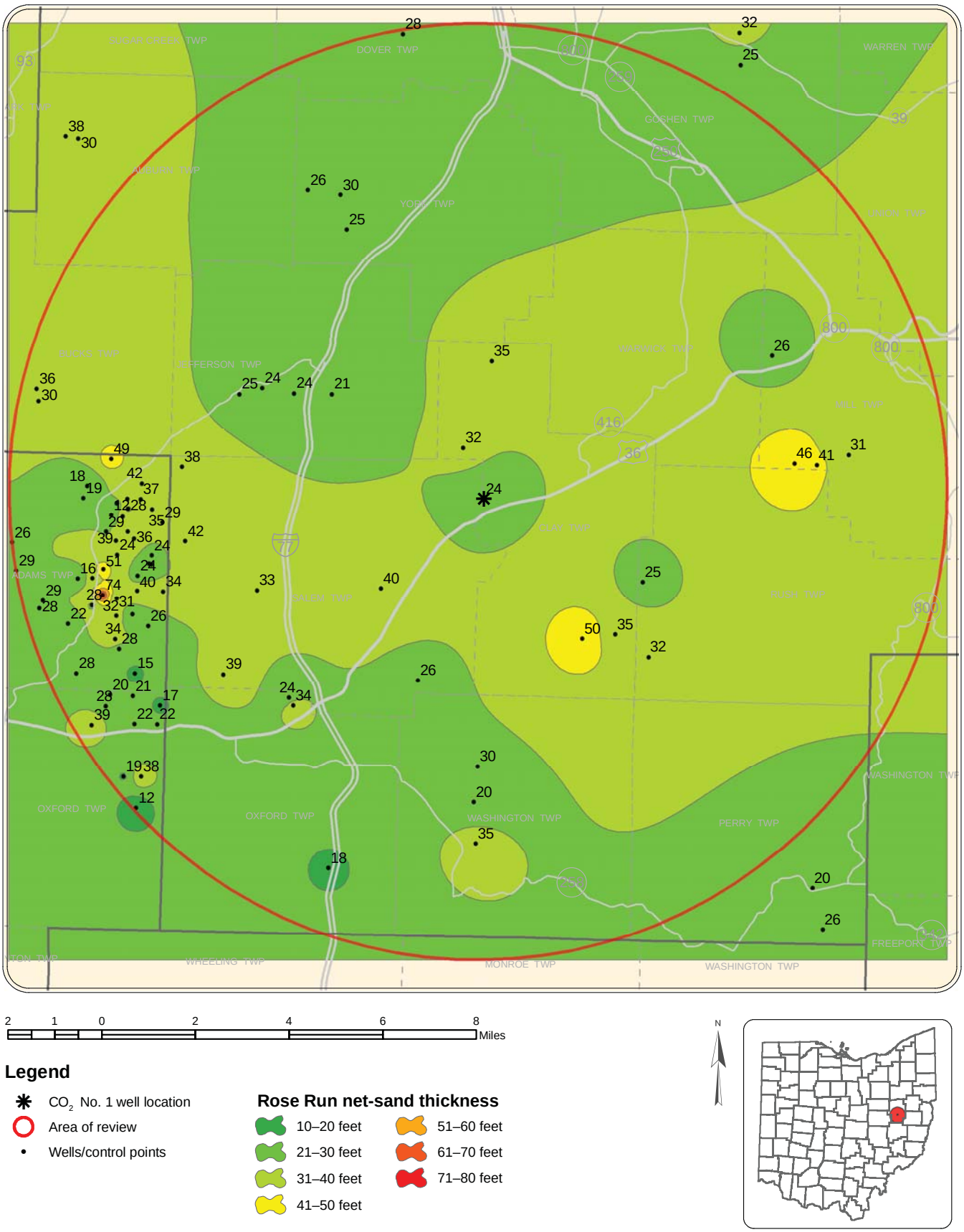


FIGURE 29.—Net-sandstone thickness map of the Rose Run sandstone interval (>6 percent porosity) within the Ohio Geological Survey CO_2 No. 1 well area of review.

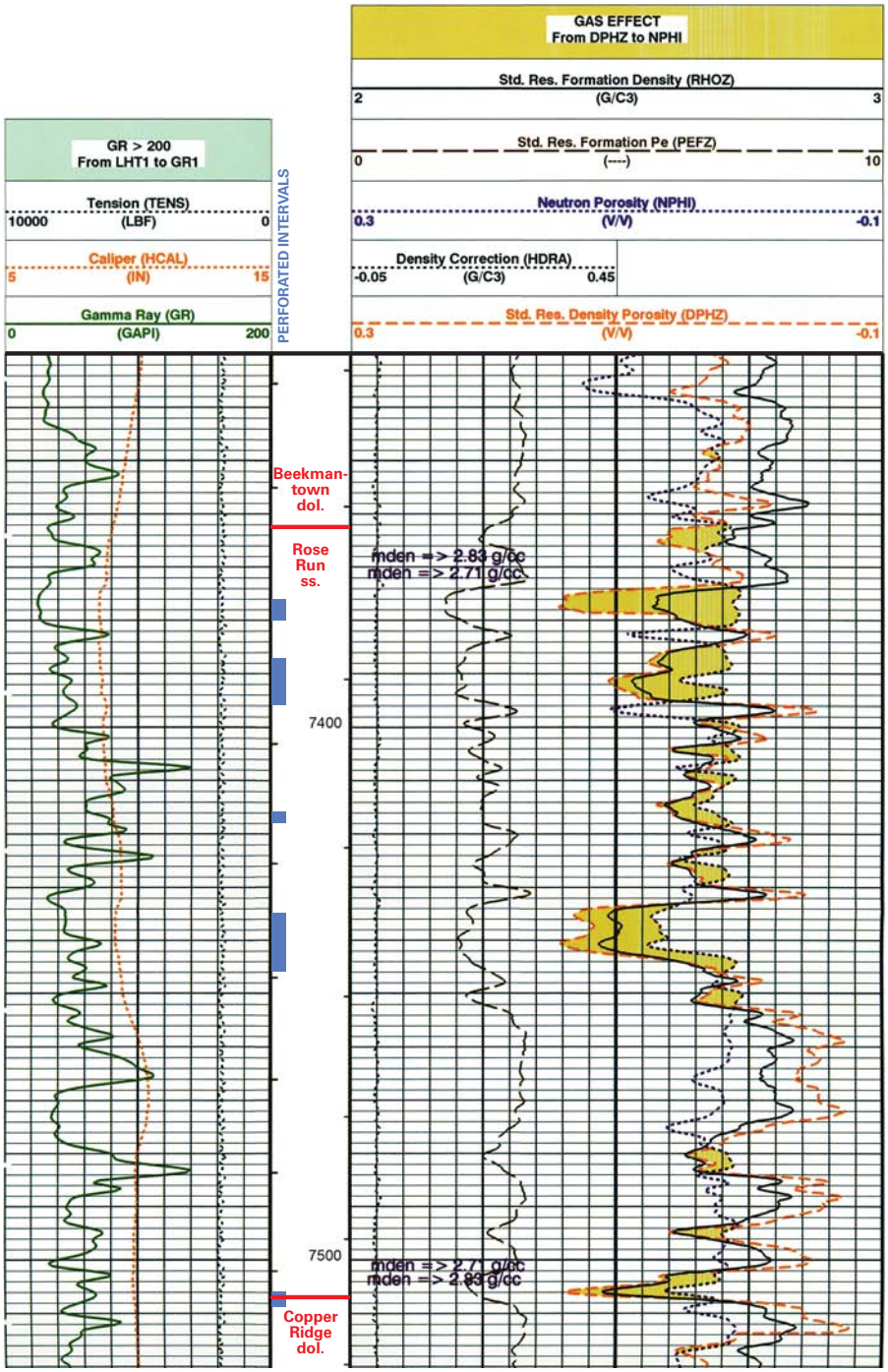


FIGURE 30.—Geophysical log of the Rose Run sandstone interval at the Ohio Geological Survey CO_2 No. 1 well site. Also shown are the perforated intervals used for brine injection zones.

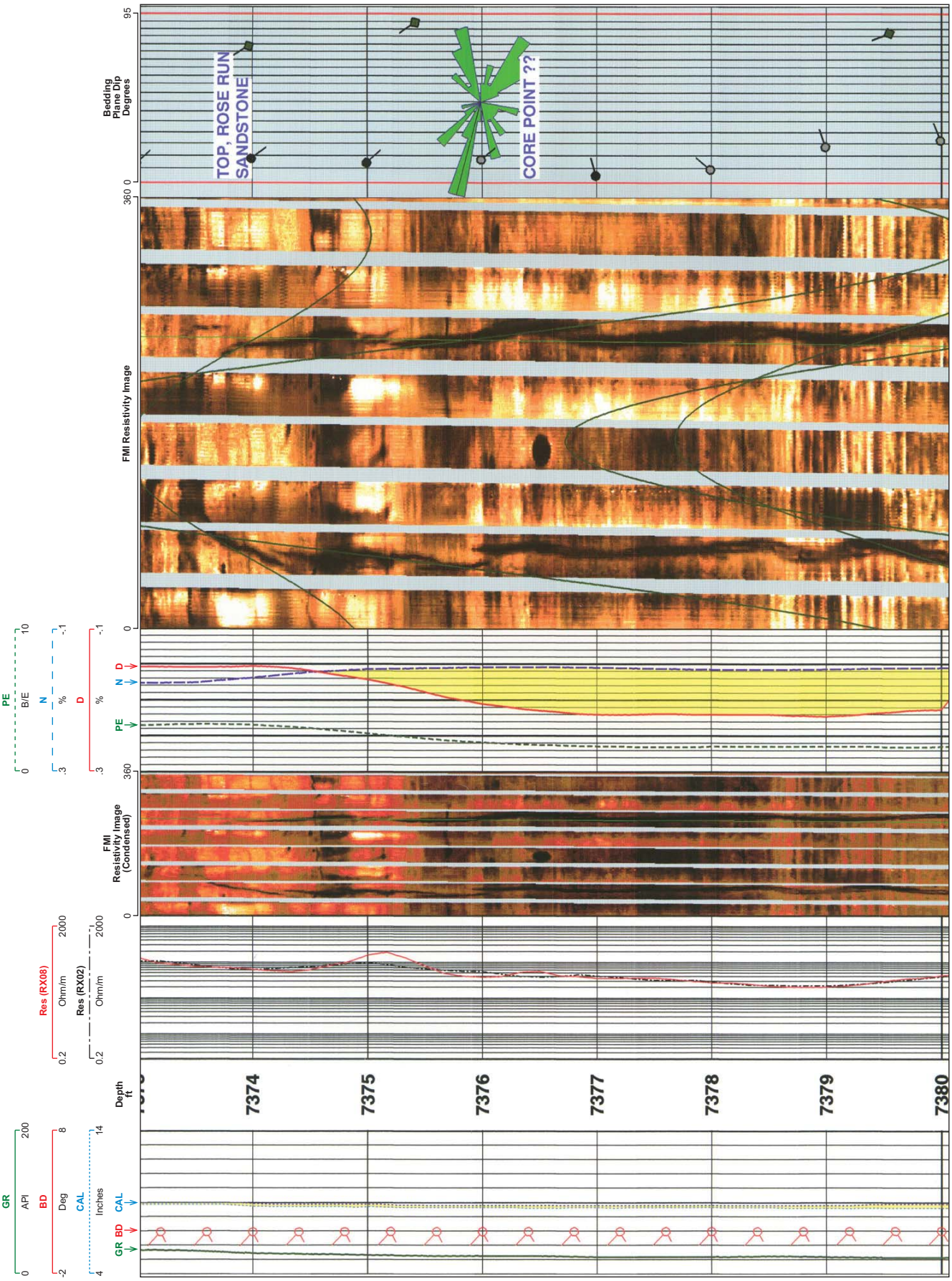


FIGURE 31.—Formation Microscanner Image of the upper portion of the Rose Run sandstone at the Ohio Geological Survey CO_2 No. 1 well site between depths of 7,372 feet and 7,380 feet. Note the location of a sidewall core point. **GR** = Gamma Ray, **BD** = Borehole Drift, **CAL** = Caliper, **PE** = Photo Electric factor, **N** = Neutron, **D** = Density, **Res** = Resistivity.

occurred at depths of 7,506, 7,434, and 7,392 feet and correlate with the zones of highest porosity indicated on the GR-N/D wireline log curves (fig. 30). Based on X-ray diffraction and thin section petrography, the Rose Run is a subarkose composed dominantly of monocrystalline quartz and k-feldspar (figs. 32A, 32B). Polycrystalline quartz, plagioclase feldspar, lithic fragments, and muscovite also are present. Pore types include intergranular, grain-moldic, and intragranular (leached feldspar). Cementation from quartz and feldspar overgrowths reduces the effective porosity (figs. 32A, 32B).

Ordovician Beekmantown Dolomite

The Beekmantown dolomite consists of light- to medium-brown, fine- to medium-crystalline, locally stylolitic dolomite. Accessory minerals include locally occurring glauconite, chert, pyrite, and quartz. Thin green- to black-shale beds interbedded with dolomite also occur locally. Pervasive dolomitization has been fabric destructive and obliterated much of the original texture and sedimentary structures. The dominant sedimentary structure is burrow mottling; soft sediment deformation and nodular bedding are also observed locally. Vertical stacking of meter-scale, shallowing-upward facies that are capped with subaerially exposed surfaces is present in several eastern Ohio cores. These subaerially exposed surfaces are associated with scoured erosional surfaces, dessication features, paleokarst collapse features, algal stromatolites, open and mineral-filled vugs, and trace amounts of anhydrite (Smosna and others, 2005).

Typically, the Beekmantown has low porosity (less than 2 percent) and permeability (less than 0.1 mD) and can thus serve as an effective extra barrier (confining unit) to vertical migration. Locally, however, good reservoir-quality rock with higher porosity (10–20 percent) and permeability (up to 240 mD) is present that contain pinpoint and vuggy porosity. These zones of higher porosity are thought to be associated with subaerial exposure surfaces. Good correlation exists between cores and wireline logs in identifying these porosity zones. Porosity types observed in core include intergranular, vuggy, and fracture (Smosna and others, 2005).

Within the project AOR, the Beekmantown dips to the east-southeast and is found at subsea depths ranging from approximately –5,750 to –7,000 feet (fig. 33). Net porosity thickness (4 percent or greater) in the AOR ranges from 0 to 24 feet (fig. 34). Zones of localized porosity typically are associated with erosional remnants. The Beekmantown has not been considered as an injection horizon for the purposes of the modeling at this site, but based on results from the CO_2 No. 1 well, it may have future potential in localized areas where there is no hydrocarbon production or after hydrocarbon production ceases.

In the CO_2 No. 1 well, the total thickness of the Beekmantown dolomite ranges from drill depths of 7,226 to 7.374 feet. From GR-N/D log interpretation, the CO_2 No.1 well has approximately 6 feet of net-porosity thickness (4 percent or greater) in the Beekmantown dolomite (fig. 35). Porosity development is largely related to subaerial exposure and paleokarst development on the Knox unconformity. In this well, the Beekmantown porosity development is located within twelve feet of the top of the Knox unconformity (fig. 35). The FMI log and the sidewall cores correlate with the GR-N/D logs and indicate well-developed pinpoint and vuggy porosity in the upper Beekmantown (figs. 36, 37A and 37B). Breccia and angular rip-up clasts up to 1 foot across are observed at the top of the Knox unconformity on the FMI. From seven sidewall cores in the Beekmantown, porosity measurements range from 1.5 to 9.4 percent and permeabilities range from 0.0009 to 0.941 mD (see Appendix 2G). It should be noted that these are taken from selective intervals and thus measured porosities and permeabilities may be substantially lower than what is actually present throughout the entire interval. Thin section petrography indicates the Beekmantown to be a fine- to medium-crystalline dolomite that contains secondary intergranular and vuggy porosity (figs. 37A, 37B). Saddle dolomites (large, infilling crystals from secondary dolomitization) and minor amounts (1 percent or less) of pore-lining clays are present that reduce the porosity.

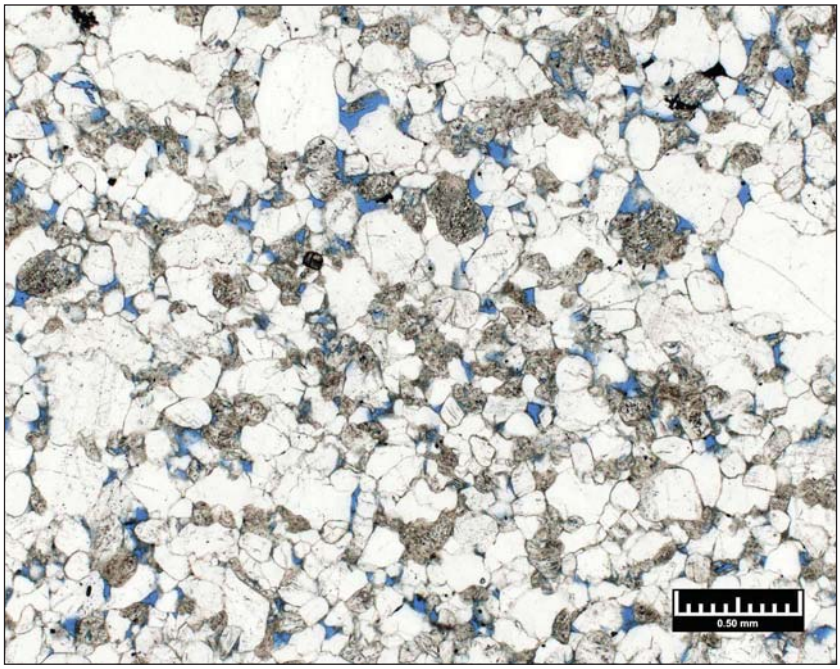
Porosity on GR-N/D logs for the entire Beekmantown interval ranges from less than one percent to a maximum of 4 percent. Natural fractures are interpreted on the FMI in four Beekmantown intervals at depths of 7,284; 7,294; 7,322; and 7,360 feet. A discussion of Beekmantown dolomite oil and gas production in the CO_2 No. 1 well and AOR is discussed later in the "Significant Oil and Gas Horizons" section.

Ordovician Utica Shale, Trenton Limestone, and Black River Group Interval

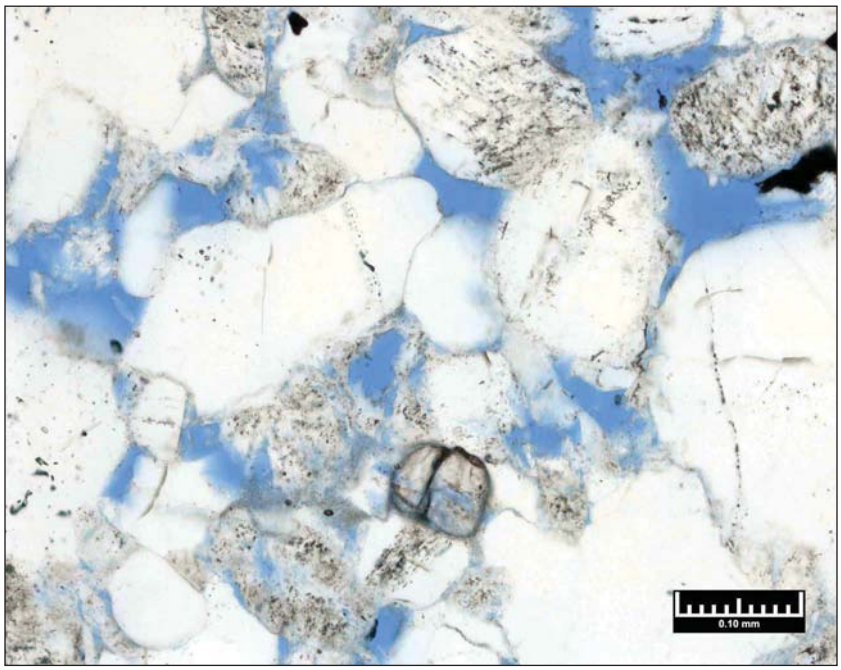
A regional study, conducted by the Ohio Geological Survey in conjunction with the Appalachian Basin state surveys, established the regional stratigraphic correlations of the Trenton Limestone and the Black River Group (Patchen and others, 2006). At this site, the Trenton-Black River interval is largely considered to be a confining interval and was not considered as an injection horizon for CO_2 modeling purposes. Most porosity development within this interval in the Appalachian Basin is in fault and fracture-controlled systems, where fluid migration along the faults allows porosity development. Thus, in these settings, the interval may have sequestration potential in localized areas where there is no hydrocarbon production or after hydrocarbons have been produced. This is a current topic of investigation within the MRCSP.

The Black River Group directly overlies the Wells Creek Formation, or the Knox on paleotopographic highs where the Wells Creek is absent. Regionally, as examined in core and outcrop, this unit has a relatively consistent and uniform lithology across the state. Black River Group facies consist of shallow subtidal to peritidal carbonates that were deposited across a very low-relief carbonate ramp (Keith, 1989; Pope and Read, 1997). It consists dominantly of a light-medium brown to gray, burrow-mottled, stylolitic mudstone. Fossils are not abundant but occur locally. Chert is present locally, especially in the upper part of the unit. Rip-up clasts also are present locally, indicating higher energy deposition. The lower interval of the Black River Group contains a clean, and typically tight, carbonate mudstone that is referred to by Ohio drillers as the "Gull River." This unit can be regionally correlated on geophysical logs across most of Ohio. The gamma-ray log response typically is very low in this clean carbonate unit with low shale content.

Numerous volcanic ash beds, commonly referred to as potassium bentonites, or K-bentonites, are found within the Black River Group through Trenton strata. Volcanic ash beds are valued as geologic time markers as they represent a widespread, instantaneous geologic event—a volcanic eruption. Within the Trenton-Black River project study area, the Millbrig (mud cave of drillers; alpha of Stith, 1979), Deicke (pencil cave of drillers; beta of Stith, 1979) and Ocoonita (gamma of Stith, 1979) are the most continuous and correlatable of the K-bentonites found in the outcrop and subsurface. In cores in western and southern Ohio, the Millbrig occurs near the top of the Black River Group and marks a change from a bioturbated mudstone Black River Group lithology to the overlying highly fossiliferous, grainstone/packstone lithology typical of the Trenton.

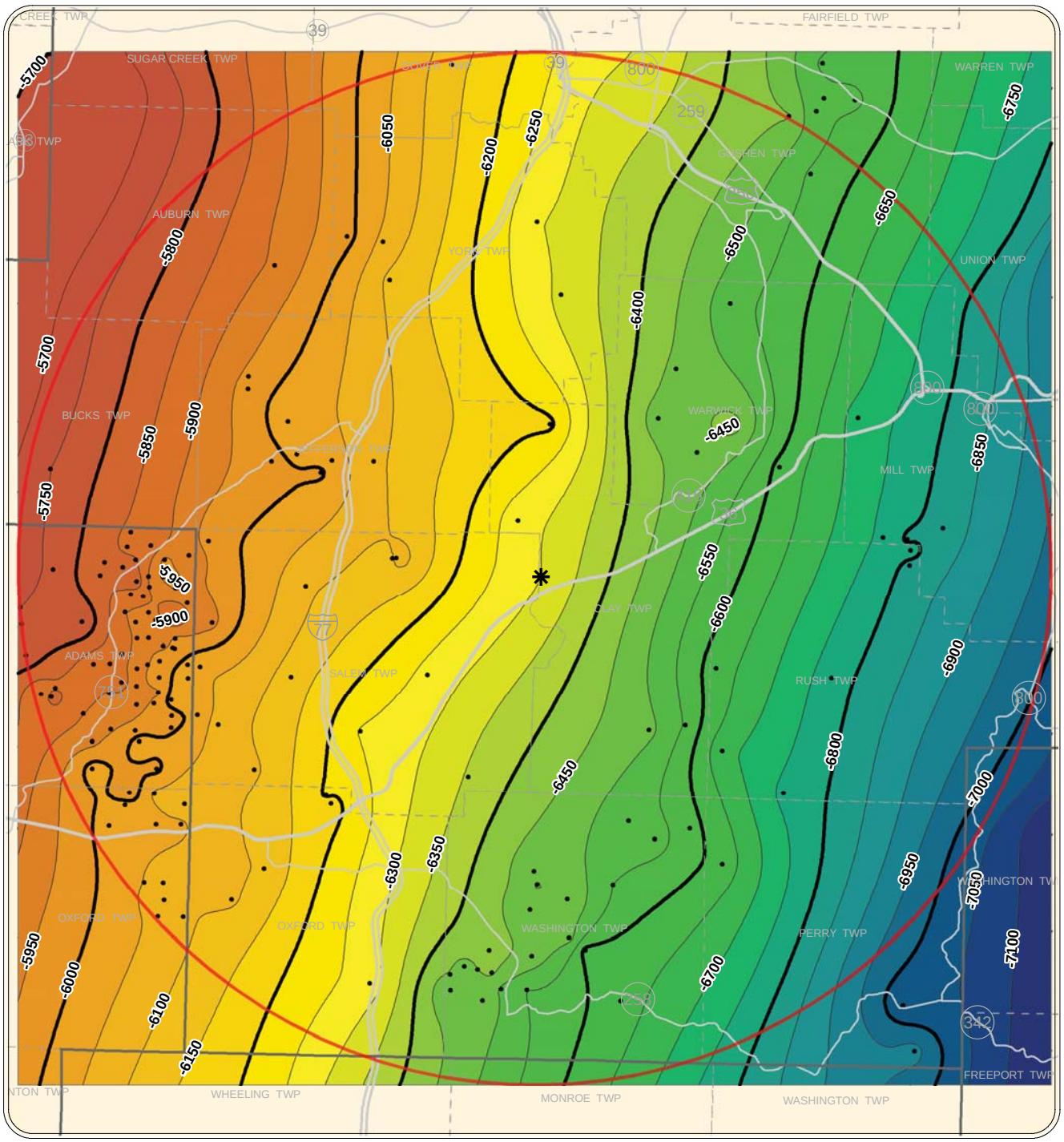


A



B

FIGURE 32.—Thin section photomicrographs of the Rose Run sandstone at the Ohio Geological Survey CO_2 No. 1 well site at a depth of 7,441 feet. Porosity is indicated by blue epoxy. **A**, magnification 40X, subarkose composed dominantly of quartz and feldspar; **B**, magnification 200X, pore types include intergranular and intragranular (leached feldspar).



2 1 0 2 4 6 8 Miles

Legend

- ✱ CO_2 No. 1 well location
- Area of review
- Wells/control points
- 50-ft contour interval

Beekmantown structure values

–5,750 feet

–7,150 feet

FIGURE 33.—Map on the top of the Knox unconformity (Beekmantown dolomite) within the Ohio Geological Survey CO_2 No. 1 well area of review.

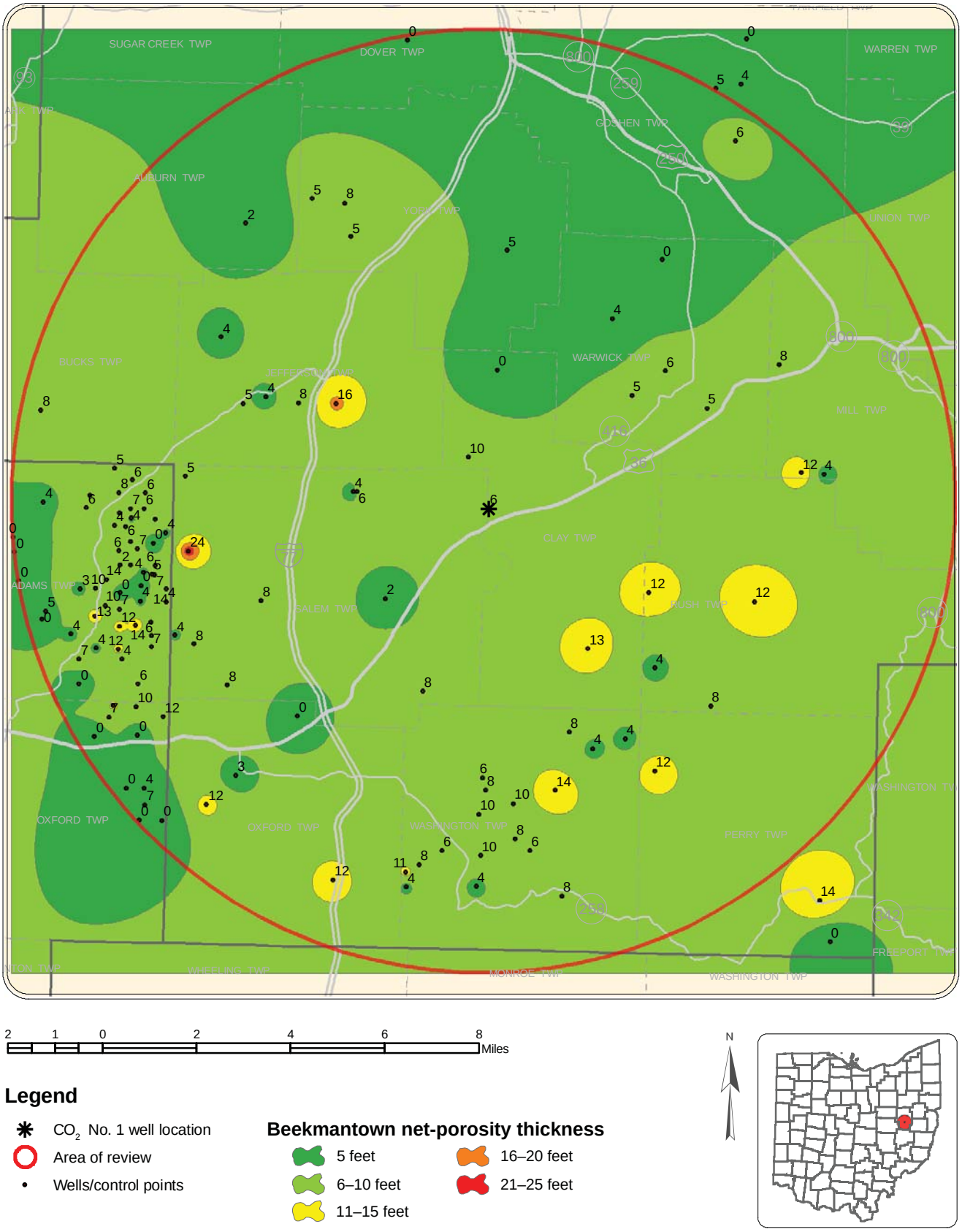


FIGURE 34.—Net-porosity (>4 percent) thickness map of the Beekmantown dolomite within the Ohio Geological Survey CO_2 No. 1 well area of review.

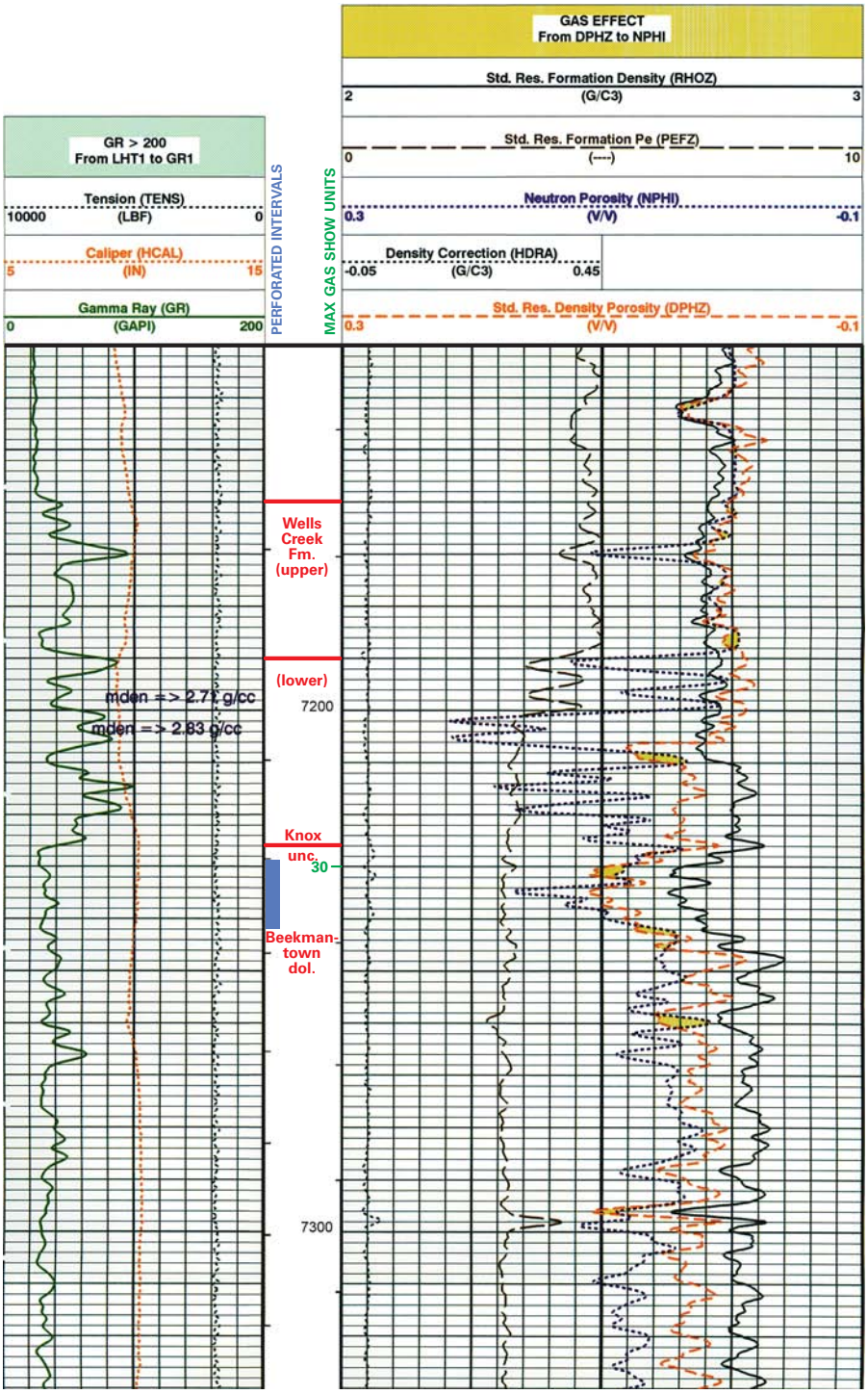


FIGURE 35.—Geophysical log of the upper Beekmantown dolomite and overlying Wells Creek Formation interval at the Ohio Geological Survey CO_2 No. 1 well site. Also shown are the perforated intervals for the producing zone. Gas show is also noted.

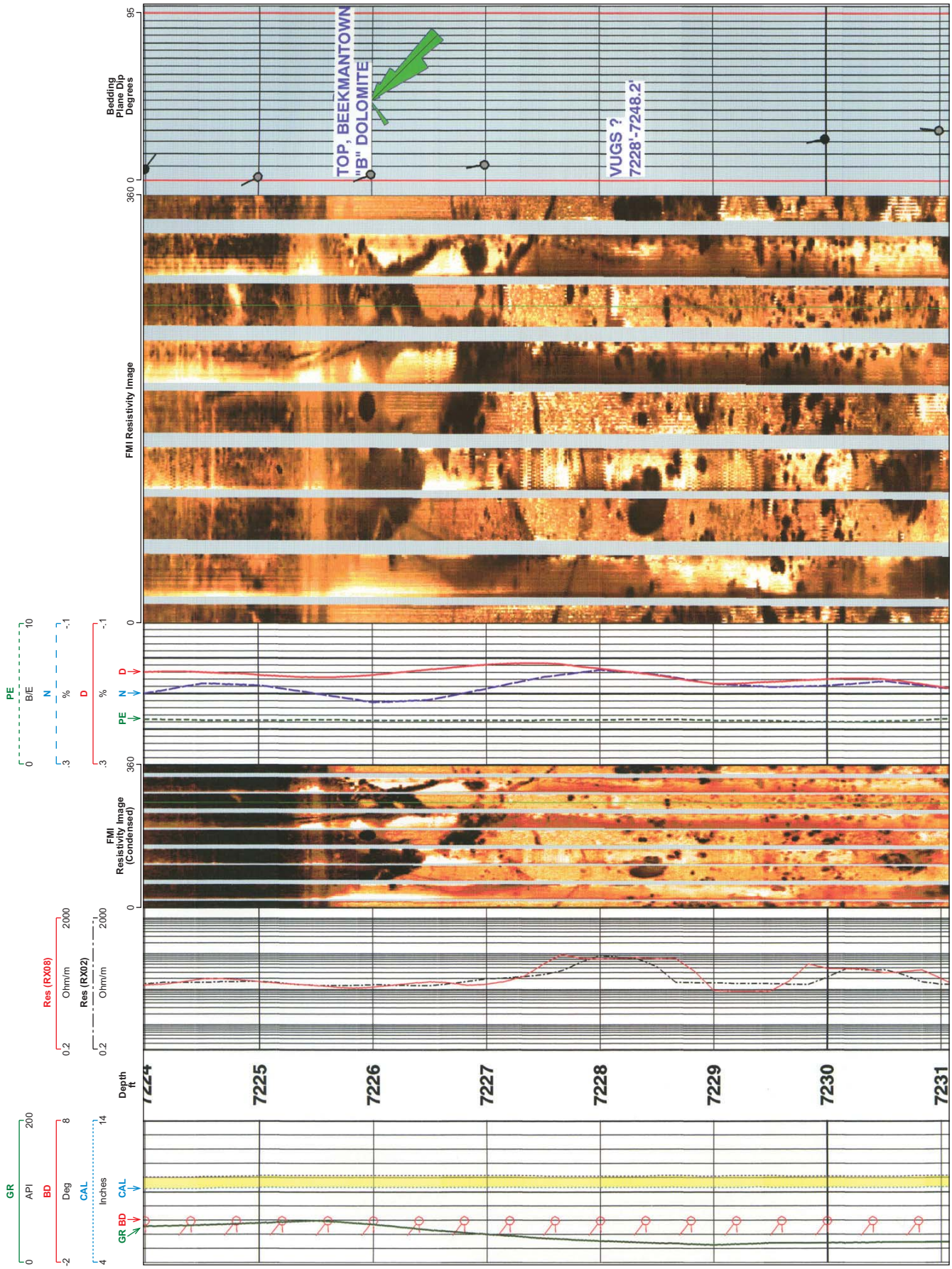
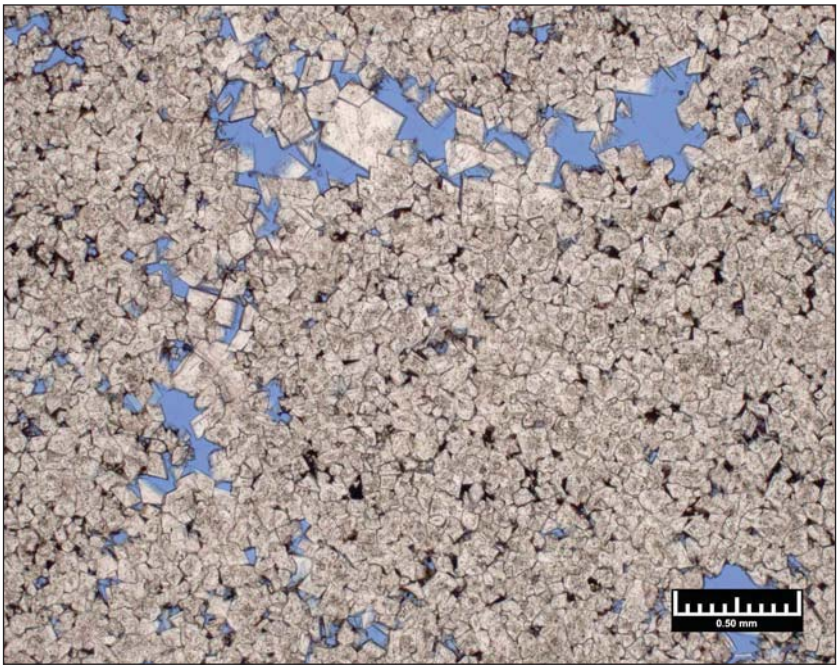
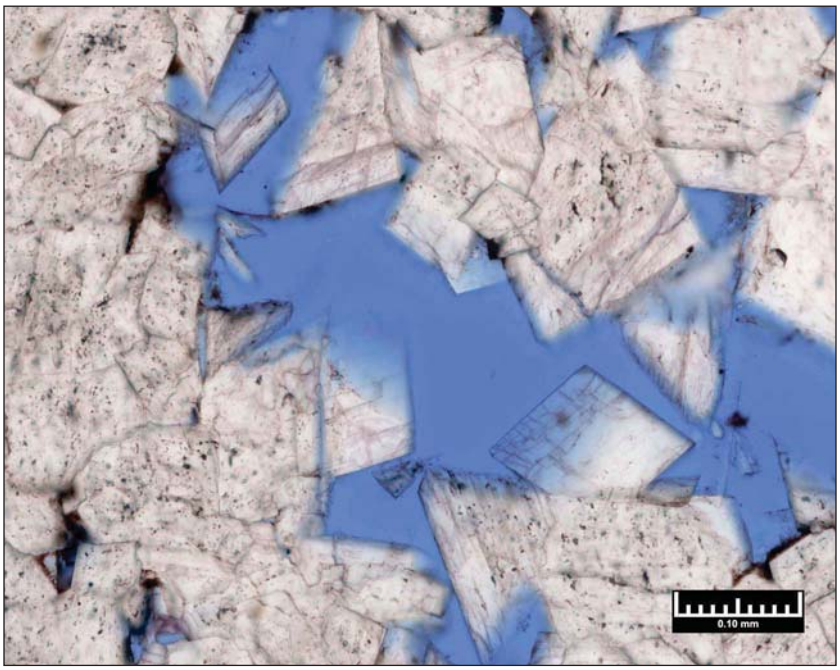


FIGURE 36.—Formation Microscanner Image of the Knox unconformity displaying the Beekmantown dolomite and overlying Wells Creek Formation at the Ohio Geological Survey CO_2 No. 1 well site. Note brecciated zone with clasts up to 1 foot across. Well-developed pinpoint and vuggy porosity is present. **GR** = Gamma Ray, **BD** = Borehole Drift, **CAL** = Caliper, **PE** = Photo Electric factor, **N** = Neutron, **D** = Density, **Res** = Resistivity.



A



B

FIGURE 37.—Thin section photomicrographs of the Beekmantown dolomite at the Ohio Geological Survey CO_2 No. 1 well site at a depth of 7,231 feet. Porosity is indicated by blue epoxy. **A**, magnification 40X, large fracture voids are filled with secondary dolomite; **B**, magnification 200X, note euhedral crystals of the pore-filling dolomite.

The Trenton-Black River Group contact is generally a gradational zone in which Black River and Trenton lithologies are interlayered through a zone up to 10 feet thick.

In the CO_2 No. 1 well, the Black River Group interval is 642 feet thick, ranging from a depth of 6,518 to 7,160 feet below surface. Numerous porosity zones and associated gas shows are present in the Black River interval (fig. 38). Most of these porous zones have log porosities in the 4 to 6 percent range. However, one porous zone at a depth of 6,930 feet that may be fractured had log porosities that exceeded 20 percent. This porous zone had a maximum gas show of 700 units above background while drilling on air. Reservoir rock is interpreted to be a fractured limestone based on both log and core data; GR, N/D and PEF curves indicate the interval to be a fractured limestone. Core data also indicates a dominantly limestone lithology with less than 4 percent dolomite. The apparent fractured zone at 6,930 feet is evident on the FMI log and has a N 69° W orientation (fig. 39). This is consistent with the dominant orientation of the major regional faults in eastern Ohio, including the Akron-Suffield and Highlandtown fault systems (fig. 14). Prolific oil-and-gas production is present in the "Clinton" sandstone and Rose Run sandstone on the northern side of the Akron-Suffield fault system. Beekmantown gas production also has occurred in wells located near the Highlandtown fault system. Enhanced permeability pathways and porosity are thus evident along these faulted and fractured trends. These localized, fractured zones of enhanced porosity and permeability could serve as potential sequestration targets assuming they have adequate confining intervals.

Based on detailed, regional stratigraphic correlations, the sharp contact at the top of the Trenton Limestone in the Trenton Platform area of northwestern Ohio and eastern Indiana is correlated to the gradational top of the Lexington Limestone (fig. 3) in the Utica/Point Pleasant Sub-basin (Patchen and others, 2006). In Tuscarawas County and eastern Ohio, the Trenton/Lexington Limestone is subdivided, in ascending stratigraphic order, into the Curdsville Member, the Logana Member, and the Lexington Undifferentiated Member. Both core and geophysical well logs indicate that the Logana and Lexington Undifferentiated are relatively higher in shale content than the Trenton of the platform or the Curdsville. Pope and Read (1997) subdivide the late Middle to Late Ordovician supersequence into four large, third-order sequences. The Curdsville Member represents the transgressive systems tract (TST) of sequence 1 and consists of medium-gray to brownish-gray, medium- to fine-crystalline wackestone to grainstone. The Curdsville is a relatively clean carbonate similar to the Trenton in the platform region and has a gradational contact with the overlying Logana. The Logana Member is thought to represent a maximum flood surface (MFS) of sequence 1 (Pope and Read, 1997). It consists of deeper-water, olive-gray to black, calcareous, medium- to thin-bedded, fossiliferous (primarily thin-shelled brachiopods) shale and thin beds of coarse- to fine-crystalline, argillaceous, fossiliferous, olive-gray limestone. The Lexington Undifferentiated Member is dominantly limestone with a grainstone-packstone texture and contains thin interbeds of shale and calcareous shale. It has a gradational contact with the overlying Point Pleasant Formation.

In the CO_2 No. 1 well, the Trenton/Lexington interval is 182 feet thick, ranging from a depth of 6,336 to 6,518 feet. There was no significant porosity development or gas shows encountered within the Trenton interval in this well. Both core and geophysical logs indicate this interval to contain low porosity and permeability. It would serve primarily as a confining interval for the underlying sequestration targets, which include the Cambrian Rose Run sandstone and basal sandstone.

The Utica Shale is defined as a dark-brown to black, organic-rich shale that overlies the Point Pleasant Formation. The boundary of the Utica Shale with the underlying Point Pleasant is gradational, and the top of the Point Pleasant is placed at the occurrence of thin, interbedded limestone in the shale interval overlying the Trenton. The Utica Shale represents a major transgression across the eastern United States, and the shales indicate a large influx of organic material, restricted circulation, and low-energy conditions (Bergstrom and Mitchell, 1992; Ryder, 1992, Wickstrom, 1996). Average thickness for the Utica to Trenton interval (includes the Point Pleasant Formation) in eastern Ohio is approximately 200 feet. The Utica Shale is generally considered a confining interval because of the low porosities and permeabilities. Locally where it is extensively fractured, however, it may be an oil-and-gas producing interval. In eastern Ohio Utica production has occurred in Muskingum, Fairfield, and Hocking counties.

In the CO_2 No. 1 well the Utica to Trenton interval is 198 feet thick, ranging from a depth of 6,138 to 6,336 feet. Geophysical logs indicate this interval to have low porosities, typically less than 4 percent. A permeability of 0.0002 mD was measured from a sidewall core taken at a depth of 6,141 feet (see Appendix 2G). There were 2 thin zones (less than 2 feet) at depths of 6,182 and 6,240 feet that had porosities of approximately 10 percent. No gas shows were noted on the mud log for these zones.

Silurian Cataract Group ("Clinton" Sandstone)

The "Clinton" sandstone interval (informal partial equivalent of the Cataract Group in Ohio) occurs as a sequence of interbedded sandstones, siltstones, and shales (figs. 3 and 40). Depositional environments include fluvial, delta-front, barrier island, and shelf sands (McCormac and others, 1996). The source is to the east and northeast as the deltaic sedimentation prograded westward and channel sands were deposited off the delta front. Lithologically, the individual reservoir beds consist of a white to gray to red, medium- to very fine-grained, monocrystalline, quartzose sandstone (McCormac and others, 1996). The "Clinton" interval (within the Cataract Group) overlies the Queenston Shale and underlies the "Packer Shell" (informal equivalent of the Dayton Formation), a mappable carbonate unit that is easily correlated in the subsurface (figs. 3 and 40).

For mapping purposes, the "Packer Shell" is often used to evaluate structure because it is a more consistent mapping horizon due to the heterogeneity and lateral variability of the "Clinton" interval. The structure on the top of the "Packer Shell" displays regional dip to the east and southeast with subsea depths ranging from –3,250 in the northwest to –4,350 feet in the southeast of the AOR (fig. 41). Across the mapped area, the "Clinton" net-sandstone thickness (greater than 50 percent shale free) ranges from 10 to 67 feet (fig. 42). The interval thins to the west and southwest with narrow east–west trending channel-type deposits resembling a fluvial-deltaic environment as documented by previous workers (McCormac and others, 1996). Regionally, log porosities in the "Clinton" sandstone interval range from 6 to 14 percent. "Clinton" permeabilities are widely variable, with average values typically ranging from less than 0.1 mD to 40 mD (McCormac and others, 1996). However, isolated permeabilities of individual layers in this sequence can have permeabilities in excess of 200 mD (McCormac and others, 1996). Detailed characterization of this unit for injection potential needs to be performed at any prospective site because of these lithologic variations within the "Clinton" interval.

The CO_2 No.1 well contains approximately 24 feet of net sandstone (greater than 50 percent shale free) based on log interpreta-

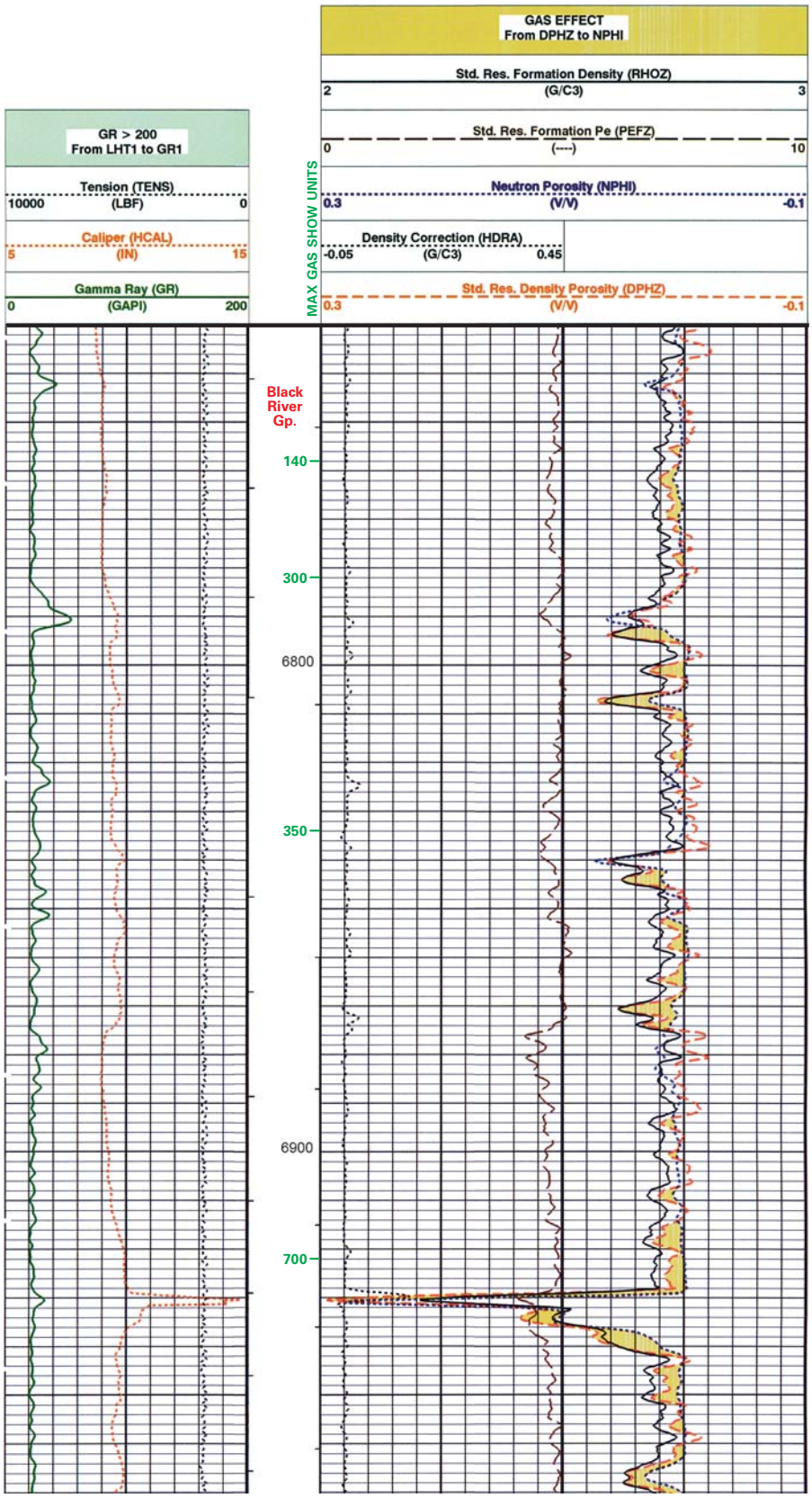


FIGURE 38.—Geophysical log of a portion of the Black River Group interval at the Ohio Geological Survey CO_2 No. 1 well site. Gas shows are also noted.

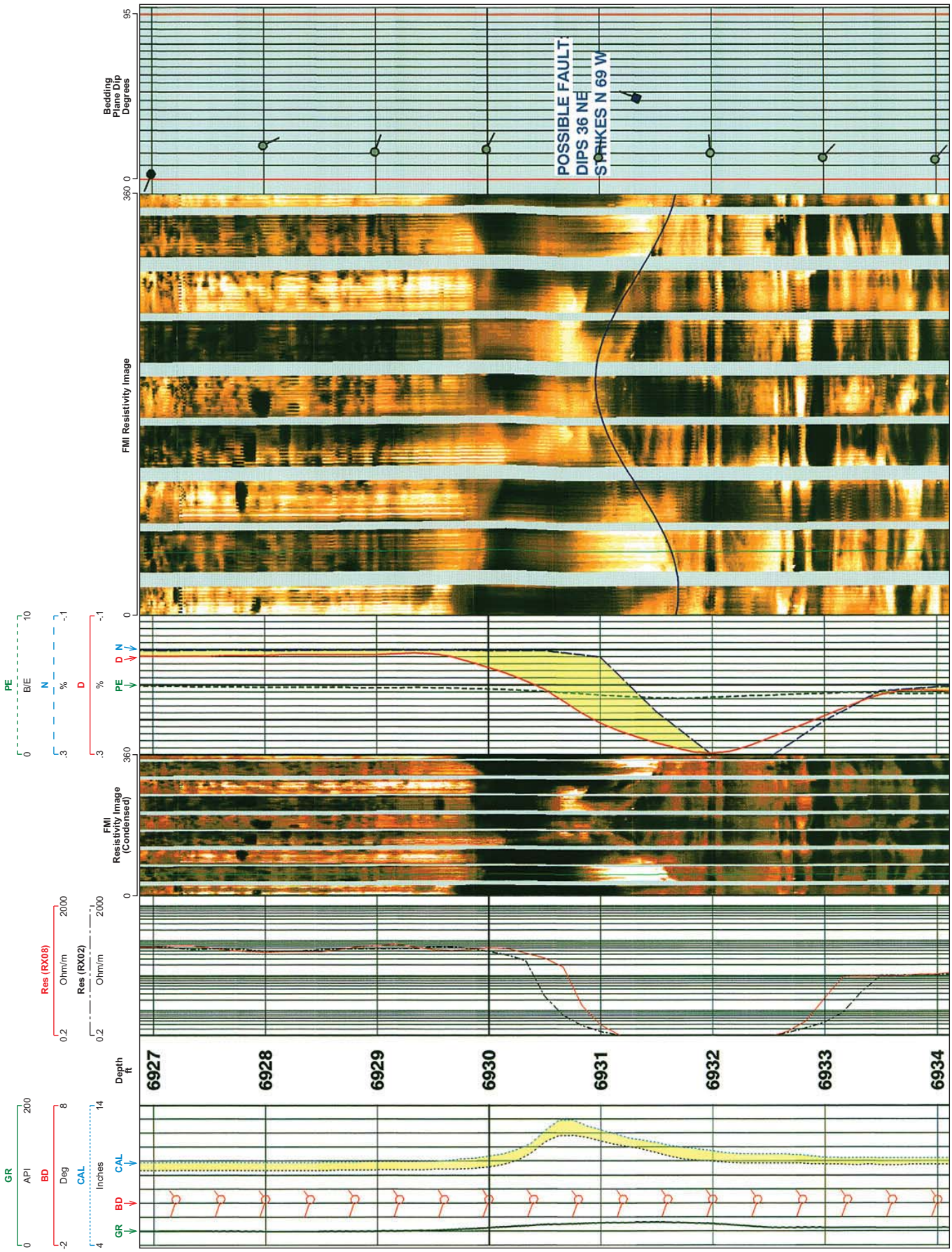


FIGURE 39.—Formation Microscanner Image of an interpreted fault/fracture in the Black River Group at the Ohio Geological Survey CO_2 No. 1 well site. **GR** = Gamma Ray, **BD** = Borehole Drift, **CAL** = Caliper, **PE** = Photo Electric factor, **N** = Neutron, **D** = Density, **Res** = Resistivity.

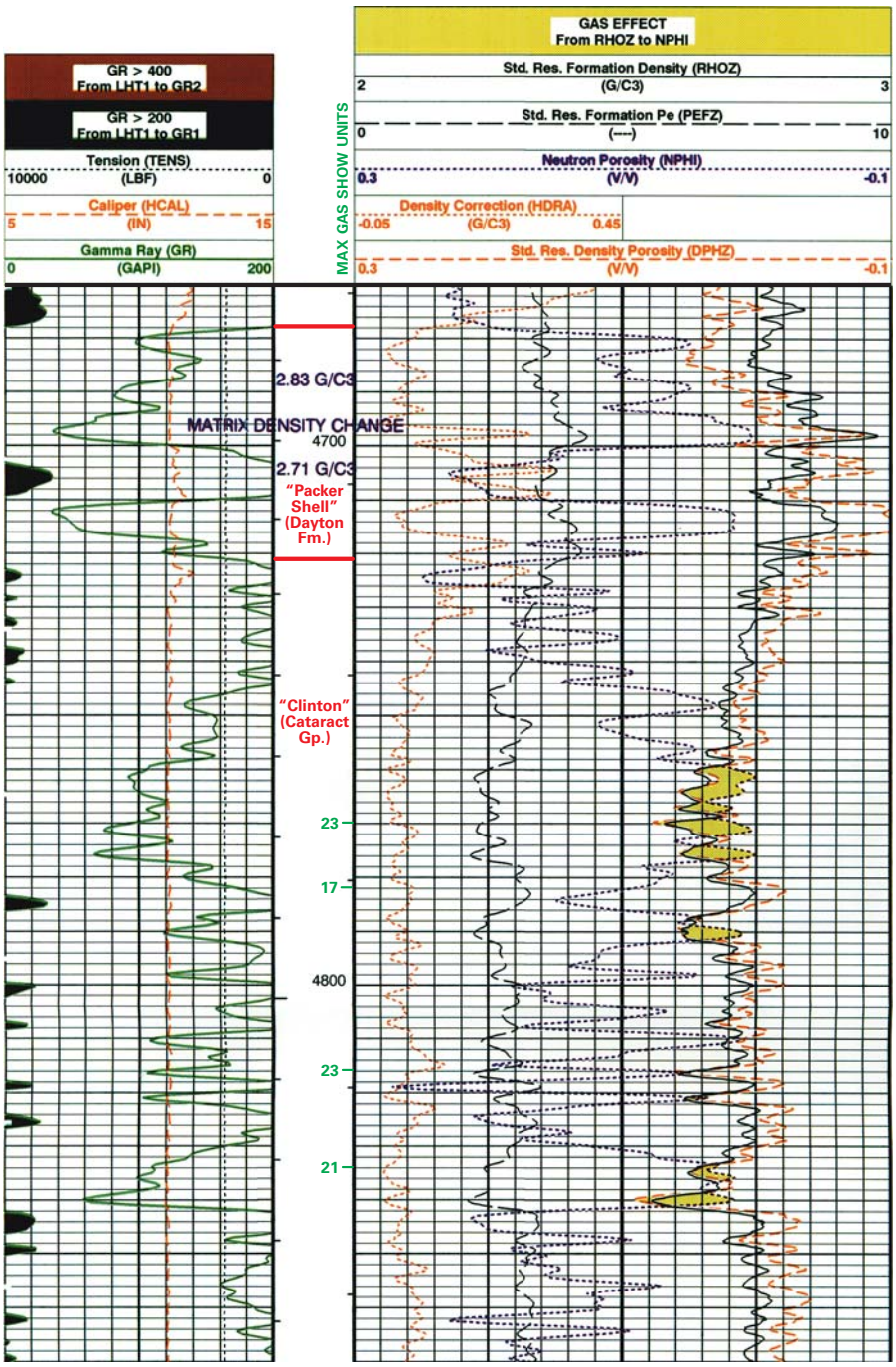


FIGURE 40.—Geophysical log of the "Clinton" sandstone (Cataract Group) interval and overlying Packer Shell" (Dayton Formation) at the Ohio Geological Survey CO_2 No. 1 well site. Gas shows are also noted.

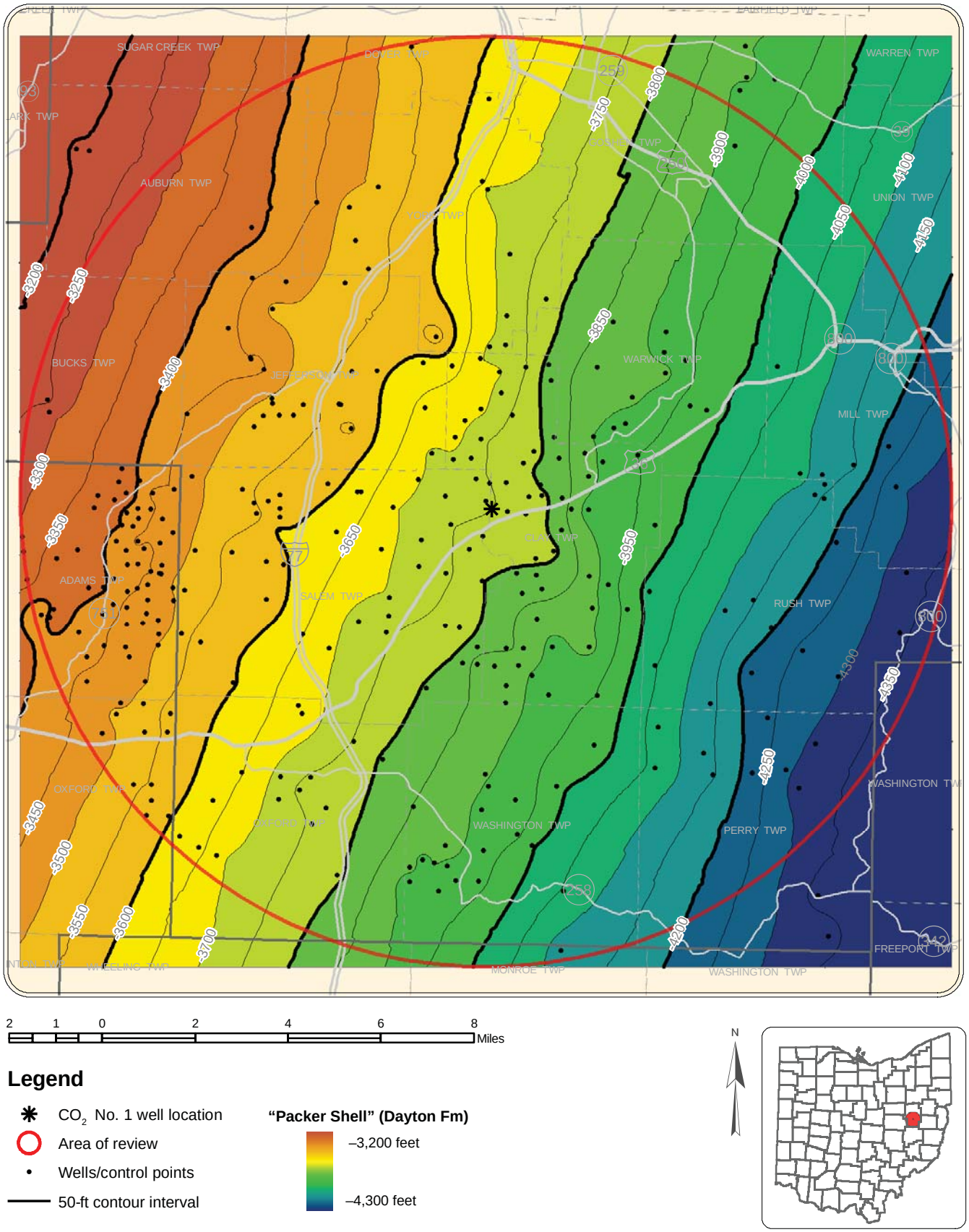


FIGURE 41.—Structure map on top of the "Packer Shell" (Dayton Formation) within the Ohio Geological Survey CO_2 No. 1 well area of review.

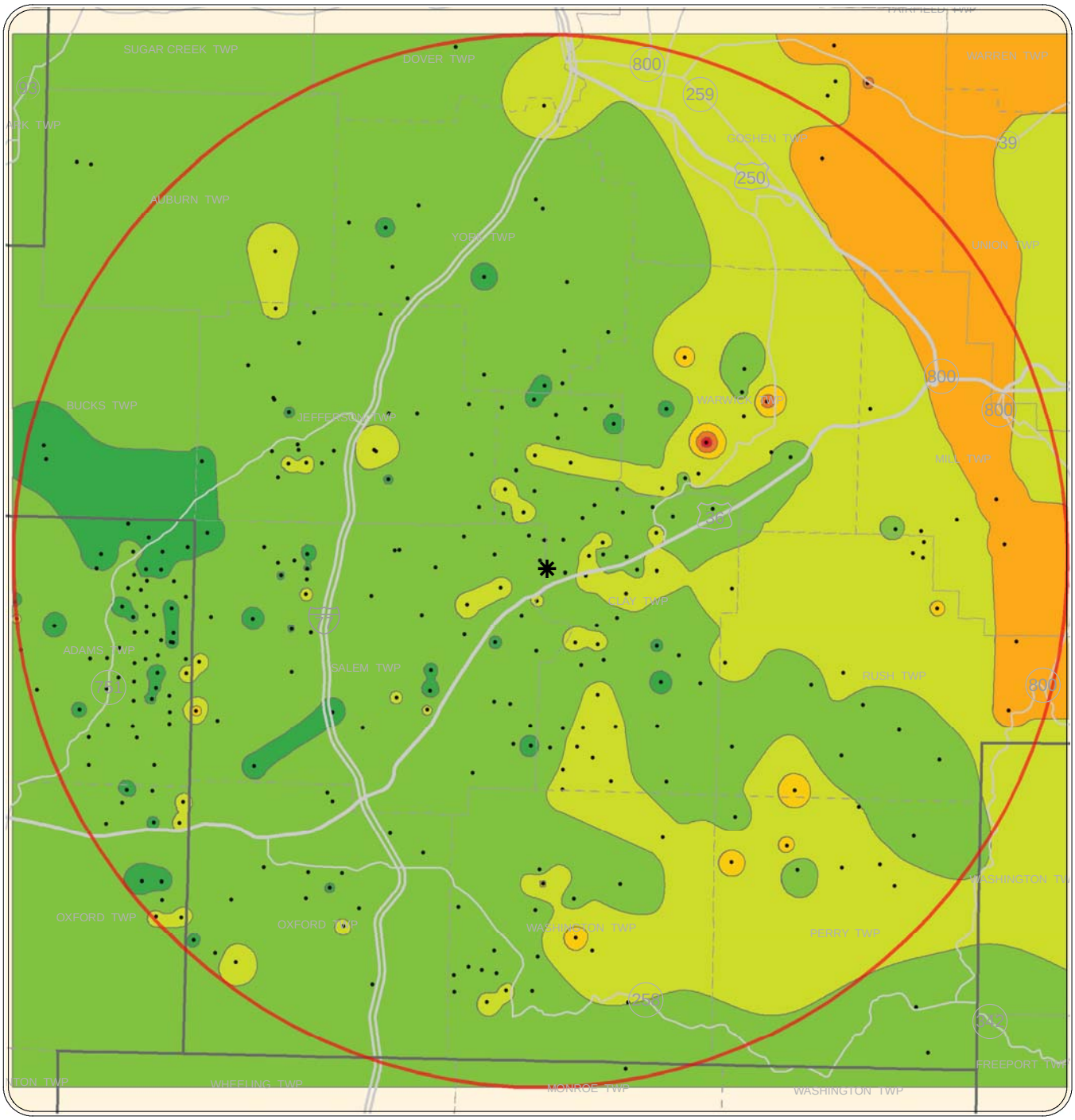


FIGURE 42.—Net-sand (>6 percent) thickness map of the "Clinton" sandstone interval within the Ohio Geological Survey CO_2 No. 1 well area of review.

tion. The gross thickness of the "Clinton" interval is 96 feet, ranging from driller's depths of 4,746 to 4,842 feet (fig. 40). The "Clinton" and overlying Rochester Shale were the uppermost stratigraphic units of the first sidewall core run attempted within the well. Unfortunately, the tool failed after only eight sidewall cores were obtained within the "Clinton" and one in the Rochester Shale. No further cores were obtained in the overlying Silurian-Devonian units. From these "Clinton" cores, porosities ranged from 3.6 to 8.6 percent and permeabilities were very low with all measured values of 0.01 mD or less (see Appendix 2G). Thin section petrography indicates the "Clinton" sandstone interval is a quartz arenite to subarkose. The primary framework grains consist dominantly of monocrystalline quartz (48–63 percent), feldspar (1–3 percent), lithic fragments (1–4 percent), and carbonaceous shale (2–3 percent). Cements comprise 15 to 18 percent of the rock and consist primarily of quartz overgrowths and pore-lining clay.

As discussed later, the "Clinton" has been the most drilled oil-and-gas target in Ohio for decades. While known for its low porosity and permeability, it is yet able to deliver large volumes of hydrocarbons to the wellbore. However, the budget and staging of casing programs for the CO_2 No. 1 well would not allow pressure and injection testing of this horizon at this location.

Silurian Lockport Dolomite

The Lockport consists dominantly of fine- to medium-crystalline, slightly argillaceous and fossiliferous dolomite that was deposited in a carbonate shelf environment. In central and eastern Ohio, portions of the Lockport are often referred to informally as the "Newburg" and represent any significant porosity zone. Porosity development in the Lockport Dolomite is primarily controlled by depositional environment and diagenesis. These porous zones are often associated with patch reef development within the Lockport interval (Floto, 1955; Janssens, 1977).

The Lockport Dolomite is considered a secondary injection horizon because of its regional variability in terms of reservoir quality. At this site, the Lockport is the shallowest horizon designated as a potential injection target for modeling purposes. It occurs at subsea depths ranging from approximately –2,770 to –3,927 feet (3,875- to 5,032-feet-below ground level) within the AOR. The net-porosity thickness (greater than 4 percent) within the Lockport Dolomite in the AOR ranges from 0 to 60 feet (fig. 43). Regionally, average log-derived porosities for gas-productive intervals in the Lockport Dolomite are typically 8 to 10 percent with values as high as 14 percent (Noger and others, 1996).

While the Lockport may indicate a high potential for CO_2 storage in some wells, this zone and other shallower zones must be viewed cautiously if considered within areas of close-in "Clinton" oil and/or gas production. Often the cement used to anchor the production string of casing within "Clinton" wells will not extend to cover the entire Lockport interval or those above, thus potentially exposing bare casing to CO_2 and brine mixtures, which could be corrosive to the casing, leading to possible leakage avenues.

In the CO_2 No. 1 well, the Lockport interval is 248 feet thick, ranging from a depth of 4,228 to 4,476 feet below ground level (fig. 44). There were no significant zones of porosity development noted on logs within the Lockport. Due to failure of the sidewall coring mechanism, no cores were obtained above the Rochester Shale interval in the well. Five gas shows were encountered in this horizon while drilling on air, with a maximum of 72 units above background.

Silurian Bass Islands Dolomite

The Bass Islands Dolomite in Ohio and northwestern Pennsylvania is a laminated, brown to buff to gray, argillaceous, micritic, dolomitic limestone and calcareous dolostone that is locally brecciated and ranges from 70 to 150 feet in thickness. Within many wells of eastern Ohio, this interval is a brecciated carbonate zone, perhaps associated with the Wallbridge unconformity found at the base of the Oriskany Sandstone. These brecciated zones often have very high porosities and permeabilities. Some of the state's highest volume Class II brine-injection wells utilize this zone. This interval has had very little detailed study in the subsurface of eastern Ohio but preliminary work indicates that locally it appears to have high potential as a CO_2 injection zone. However, to date there does not appear to be a method to predict quality injection zones within this horizon prior to drilling.

The Bass Islands Dolomite is 124 feet thick in the CO_2 No. 1 well, ranging from a depth of 3,430 to 3,554 feet below ground level. There were no zones with significant reservoir quality (greater than 4 percent porosity) noted in samples or logs within this well. It should be noted that at the time of this report, the Bass Islands currently is being used as a CO_2 injection zone in the test well in Otsego County, Michigan, as part of the U.S. DOE-funded MRCSP project.

Devonian Oriskany Sandstone

The Oriskany Sandstone is an unconformity sandstone overlying the Helderberg Formation and underlying the Onondaga Limestone (fig. 3). Lithologically, this unit consists of well-sorted, white to light-gray, and gray-brown, quartzose sandstone (Opritza, 1996). The updip pinchout of the Oriskany sandstone trends north-south through Coshocton County and is approximately 25 miles west of the CO_2 No. 1 well site (Opritza, 1996). The unit steadily increases in thickness to the east and southeast. Within the Tuscarawas County AOR, this unit is generally thin and poorly developed (2–14 feet) because of its proximity to the updip pinchout. However, Oriskany producing fields to the west and south of the AOR indicate localized potential exists for areas of better reservoir development with CO_2 sequestration potential.

The Oriskany Sandstone is considered to be a potential secondary injection horizon in this region. In the CO_2 No. 1 well, the Oriskany Sandstone is 23 feet in thickness, ranging from a depth of 3,313 to 3,336 feet below ground level. However, based on well cuttings and geophysical logs, the Oriskany reservoir quality at this site is poor with no significant porosity development greater than 4 percent.

SIGNIFICANT OIL AND GAS HORIZONS

Discussion

Ohio has a long history of oil-and-gas production extending back to 1860. Over 1,000 oil-and-gas fields have been discovered and over 250,000 wells drilled (fig. 45). CO_2-assisted enhanced oil recovery (EOR) is a common tertiary recovery procedure for obtaining additional oil from reservoirs in the Permian Basin of West Texas and a growing number of other western-United States areas. These projects utilize large, naturally occurring CO_2 reservoirs as the main feedstock to the extensive pipeline network for distribution of the CO_2. Because of its unique properties, CO_2 has proven to be one of the most efficient mediums known for sweeping remaining oil from a reservoir. There are no known comparable natural-CO_2 sources

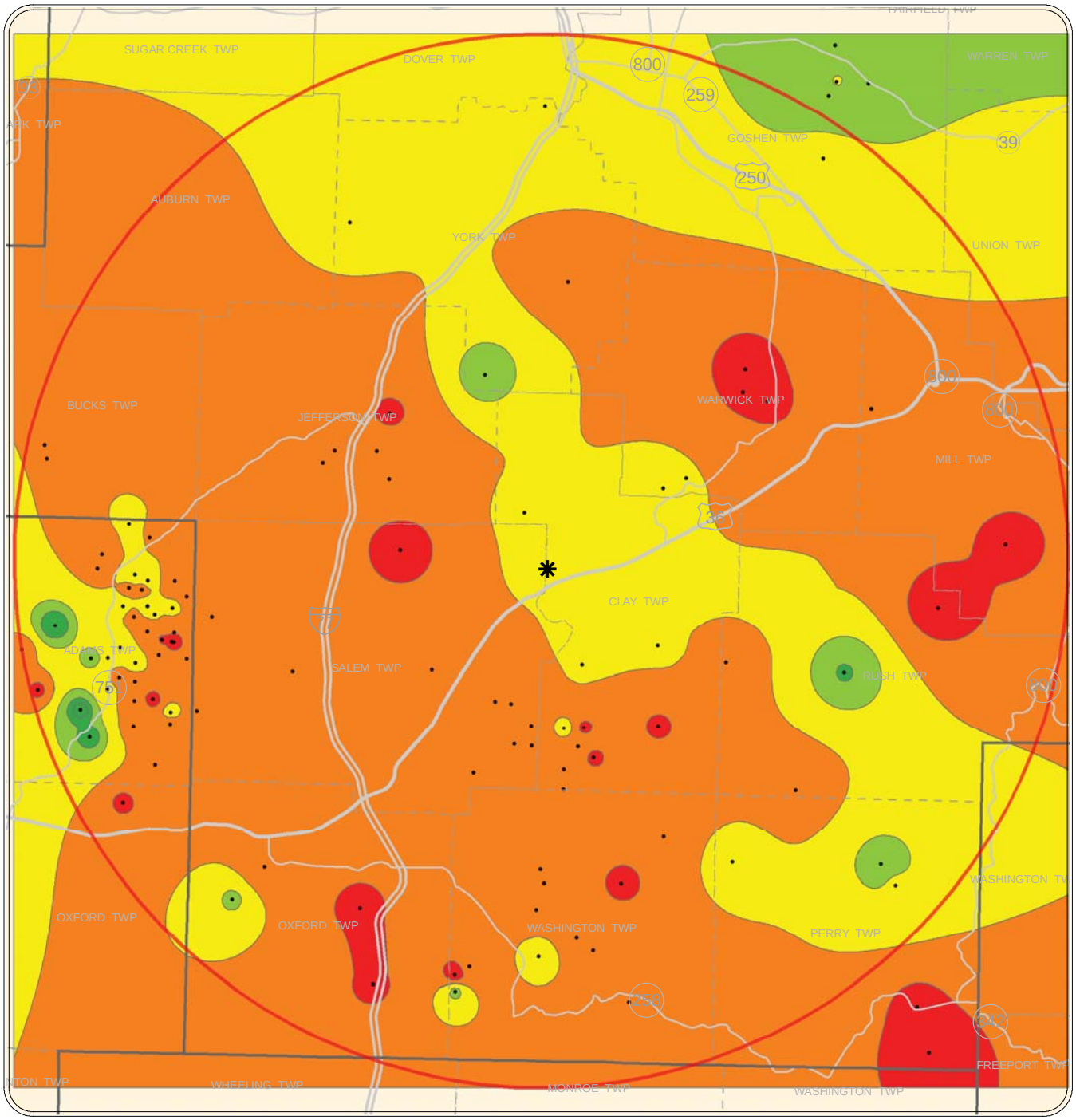


FIGURE 43.—Net-porosity (>4 percent) thickness map of the Lockport Dolomite within the Ohio Geological Survey CO_2 No. 1 well area of review.

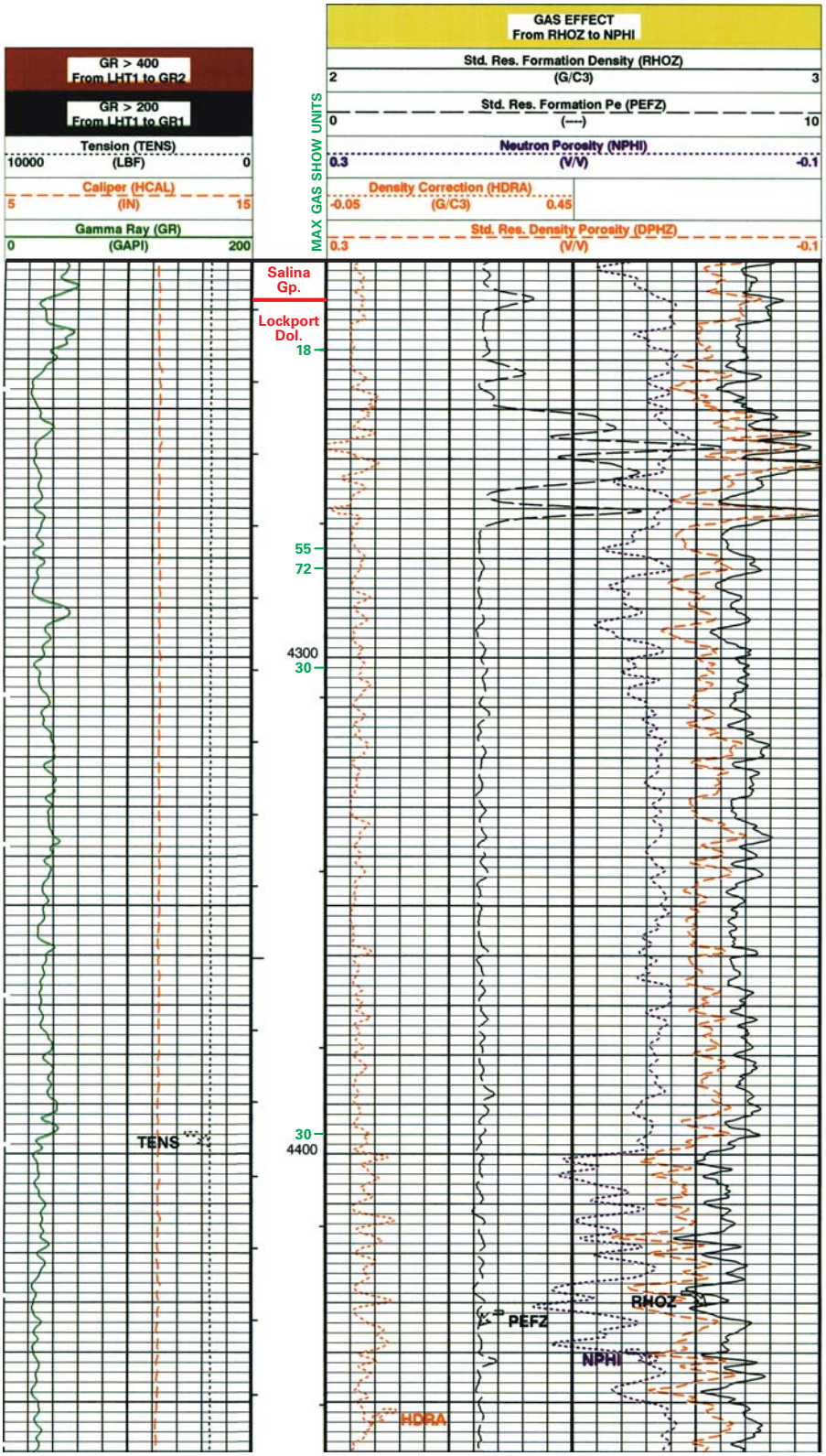


FIGURE 44.—Geophysical log of a portion of the upper Lockport Dolomite and the contact with the overlying Salina Group at the Ohio Geological Survey CO_2 No. 1 well site. Gas shows are also noted.

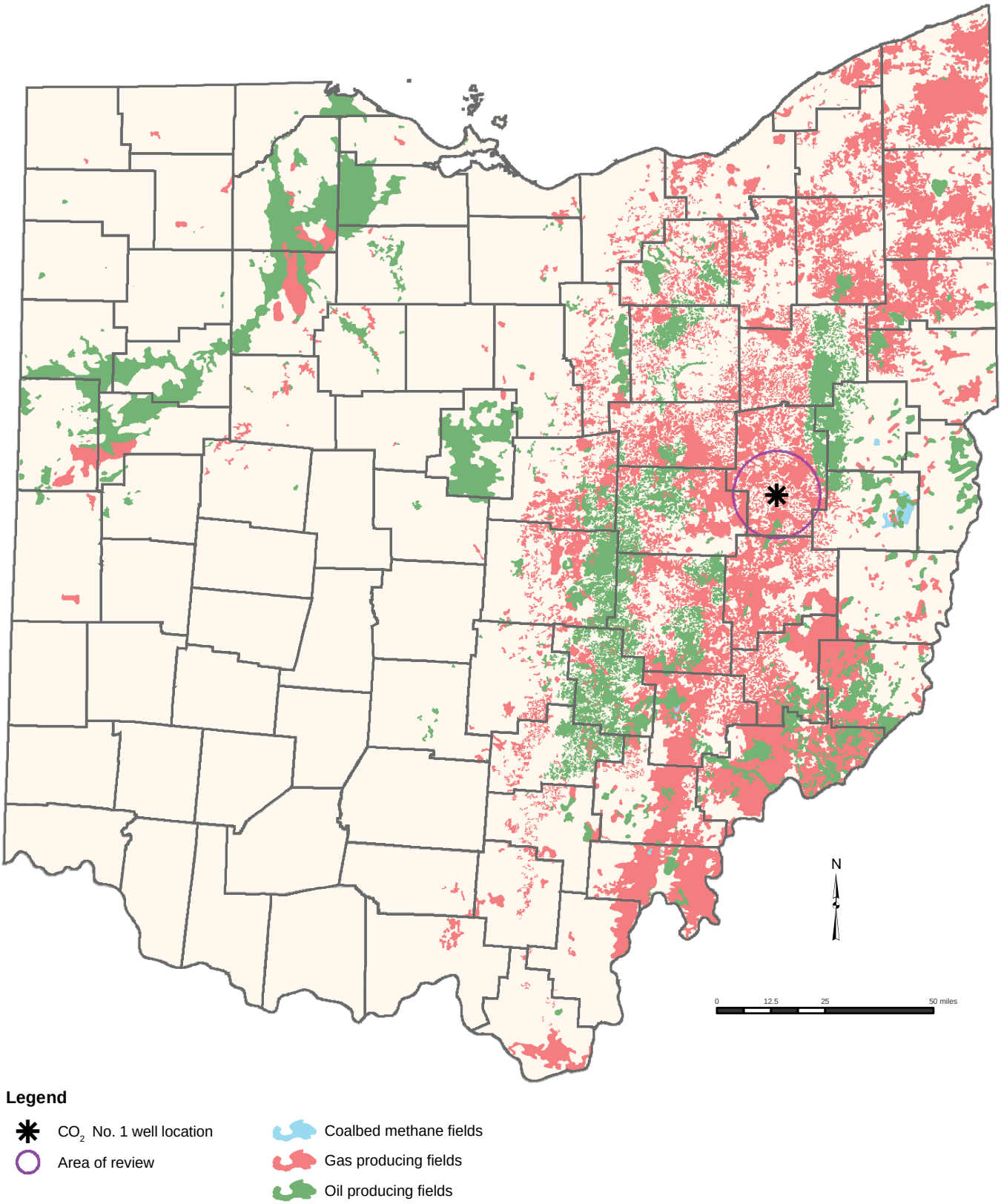


FIGURE 45.—Map of oil, gas, and coalbed methane fields in Ohio, showing the location of the Ohio Geological Survey CO_2 No. 1 well area of review.

in the Appalachian Basin. Thus, even though the Appalachian Basin was the birthplace of the oil-and-gas industry, and this area pioneered the early forms of secondary recovery, up to this point it has not been able to utilize this very efficient medium to maximize the recovery of hydrocarbons from its reservoirs. Quite possibly, CO_2-assisted EOR could eventually produce many millions of additional barrels of oil and also provide a very significant percentage of total CO_2 sequestration capacity within Ohio, which may eventually be necessary for coal-fired power plants and proposed synfuel and biofuel facilities in the state. CO_2-EOR could add significantly to the economics of these operations and reduce the total number of saline formation injection wells necessary for the state's objectives. A 1996 study of 31 Ohio oil reservoirs revealed that a conservative 500 million barrels of additional oil could be recovered by successful secondary- and tertiary-oil recovery techniques (Ohio Division of Geological Survey, 1997).

Enhanced oil recovery is thought by most workers to provide the best economics for CO_2 sequestration. Thus, CO_2-EOR could be the first "movers" in the development of a CO_2 gathering-and-distribution pipeline system connecting current and future anthropogenic CO_2 sources with viable geologic reservoirs. Providing such momentum to a new area of the country could add important oil production capacity to our nation and further assist in reducing our dependence on imported energy.

The southern portion of the East Canton oil field, which produces from the Silurian "Clinton" sandstone, is located about 10 miles northeast of the CO_2 No. 1 well site. This is the largest actively producing oil field in Ohio, with over 95 million barrels of oil produced through primary recovery since 1953.

The following paragraphs describe the oil fields, by stratigraphic unit, with significant miscible EOR potential in close proximity to the proposed site.

Cambrian-Ordovician Knox Dolomite

Ohio's deepest commercial hydrocarbon production occurs in the Beekmantown dolomite, Rose Run sandstone, and Copper Ridge dolomite of the Knox. Within the vicinity of the Tuscarawas site, pools/fields producing from both the Beekmantown dolomite and Rose Run sandstone are present (fig. 46). Most of these pools have been discovered and put in production since 1980 (Riley and others, 2004). Thus, well locations, completion techniques, and plugging technology are well recorded by the DMRM (Division of Mineral Resources Management) and more modern logging suites were used. While most wells are gas dominant, oil production from the fields has been significant, and residual oil saturation is thought to be high. Many of the gas wells within these fields are reaching the end of their productive lives; hence, the timing is optimal to repressurize the reservoirs using CO_2 in order to produce the remaining hydrocarbons.

The Baltic Field, which produces from the Rose Run sandstone at an average depth of about 6,200 feet, is located approximately 10 miles west of the CO_2 No. 1 well site (fig. 46). The original oil-in-place in this field has been calculated to be about 99 million barrels, of which only about 1.5 million has been produced. The field has high gas content and most production from the field has been natural gas. As the natural gas has been produced from the field, depleting reservoir pressure, it makes it more difficult to produce the remaining oil. This field could present a good opportunity to sequester large volumes of CO_2 while repressurizing this field and producing the remaining oil.

The CO_2 No.1 well is located within an area of active Beekmantown exploration (fig 46). The first Beekmantown producing field was the Bakersville field discovered in 1980. The discovery well was the No. 1 Mizer well (APINO 3403123893), which has produced approximately 3 billion cubic feet of gas (BCFG) and 9 million barrels of oil (MMBO). Development of the Bakersville field in the 1980s and 1990s spread to the east and south in Coshocton, Tuscarawas, and Guernsey counties. The Beekmantown reservoirs have great potential with high ultimate reserves, and large areas of the basin remain to be tested. Thus, if reservoir optimization can be proven using CO_2, future discoveries can employ such technology as part of standard practice.

More recently, Artex Oil Company has been very active in Beekmantown exploration in the AOR and vicinity. A 30-unit gas show was encountered while drilling on fluid through the top of the Beekmantown interval in the CO_2 No. 1 well (fig. 35). After completion of the injection testing, the well was turned over to Artex Oil Company, who perforated the Beekmantown interval between the depths of 7,229–7,242 feet. Following acidization, the CO_2 No. 1 well had an initial flow rate of 12 BO & 1.2 million cubic feet of gas (MMCFG). The total cumulative production through 2009 for the CO_2 No. 1 well was 553 MMCFG and 3,770 BO.

Ordovician Trenton-Black River Interval

The Trenton-Black River interval has produced oil and gas in Ohio since its initial discovery in 1884. This discovery set off a major drilling boom in northwestern Ohio that spread to eastern Indiana and led to the successful Lima-Indiana trend, which has produced an estimated 485 MMBO and 1 trillion cubic feet of gas (TCFG). Recent discoveries in West Virginia, New York, Pennsylvania and northeast Ohio have prompted current exploration activity for this reservoir throughout the region.

The Black River interval in the CO_2 No. 1 well has not been perforated for production yet, but porous, fractured zones and gas shows in multiple horizons indicate potential hydrocarbon reservoir rock (fig. 38). Several wells within the AOR that produce from both the Beekmantown and Black River interval indicate exploration potential for a fractured Black River gas reservoir in this area.

There is no reported Trenton production within the AOR. The nearest significant Trenton production is 50 miles to the west in the Utica field in northern Licking County (Riley and others, 2004). However, fractured Trenton reservoirs and production such as that in the Utica field and western West Virginia also could exist in this area.

Silurian Cataract Group ("Clinton-Medina" Sandstone Interval)

The "Clinton-Medina" sandstone interval has been the most actively drilled oil-and-gas horizon in Ohio since the 1970s. Ohio has 186 "Clinton-Medina" sandstone fields with approximately 60,000 wells that have produced over 5 TCFG (McCormac and others, 1996). The "Clinton" has consistently been the most drilled oil-and-gas target in Ohio for many years; in most years it accounts for approximately 70 percent of all wells drilled. Scattered "Clinton" gas wells, both producing and plugged, are located throughout the Tuscarawas site vicinity. The East Canton oil field is located approximately 10 miles to the northeast (fig. 47). The Ohio Geological Survey has calculated that this field contains in excess of 1.1 billion barrels of original oil in place, yet has only produced an estimated 95 million barrels (less than 10 percent recovery factor). This field presents a very important challenge and opportunity for CO_2-assisted enhanced oil recovery close to the AOR. If successful CO_2 flooding can be proven in this field, hundreds of millions of

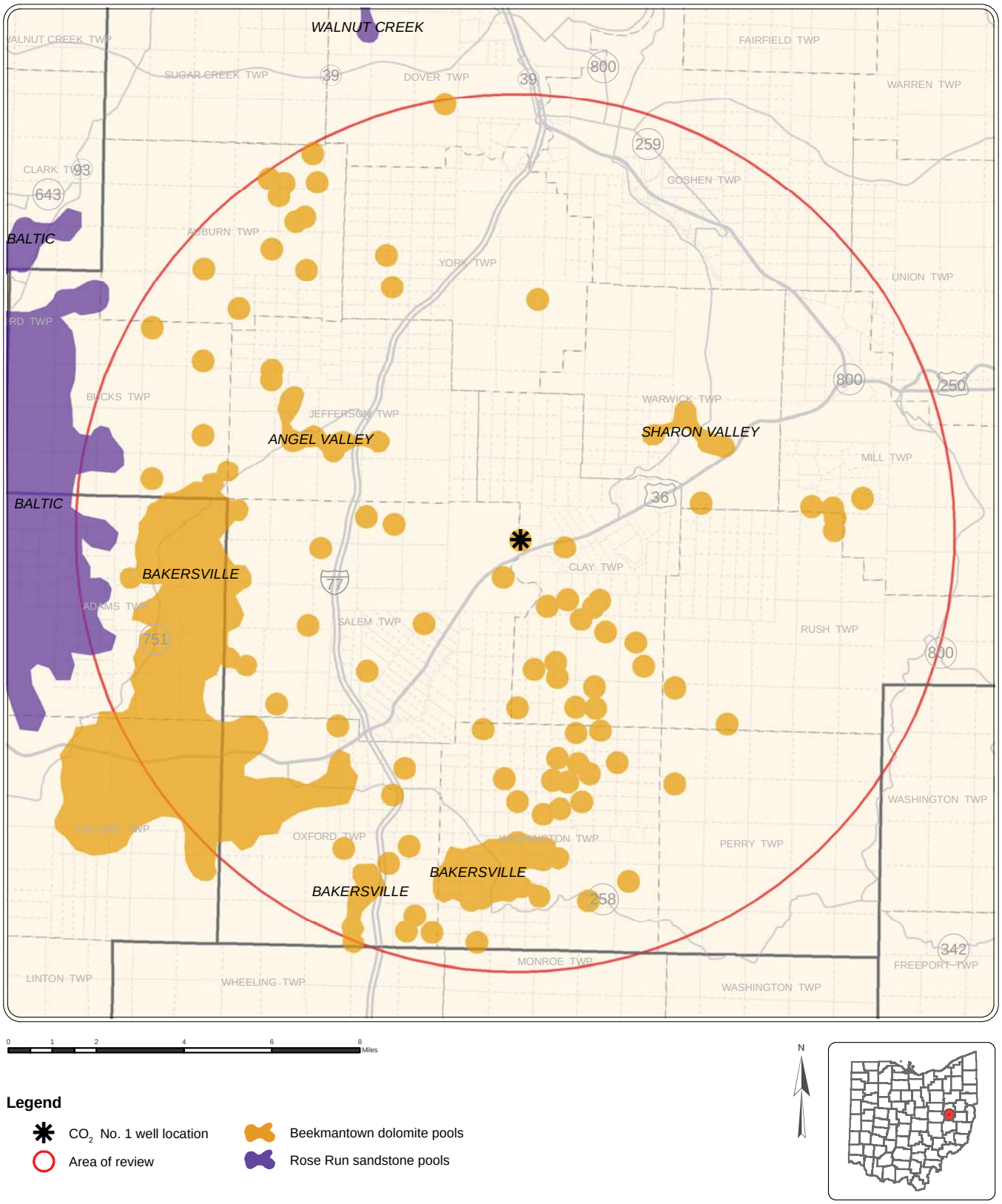


FIGURE 46.—Knox Dolomite (Beekmantown dolomite and Rose Run sandstone) oil and gas fields map for the Ohio Geological Survey CO_2 No. 1 well area of review.

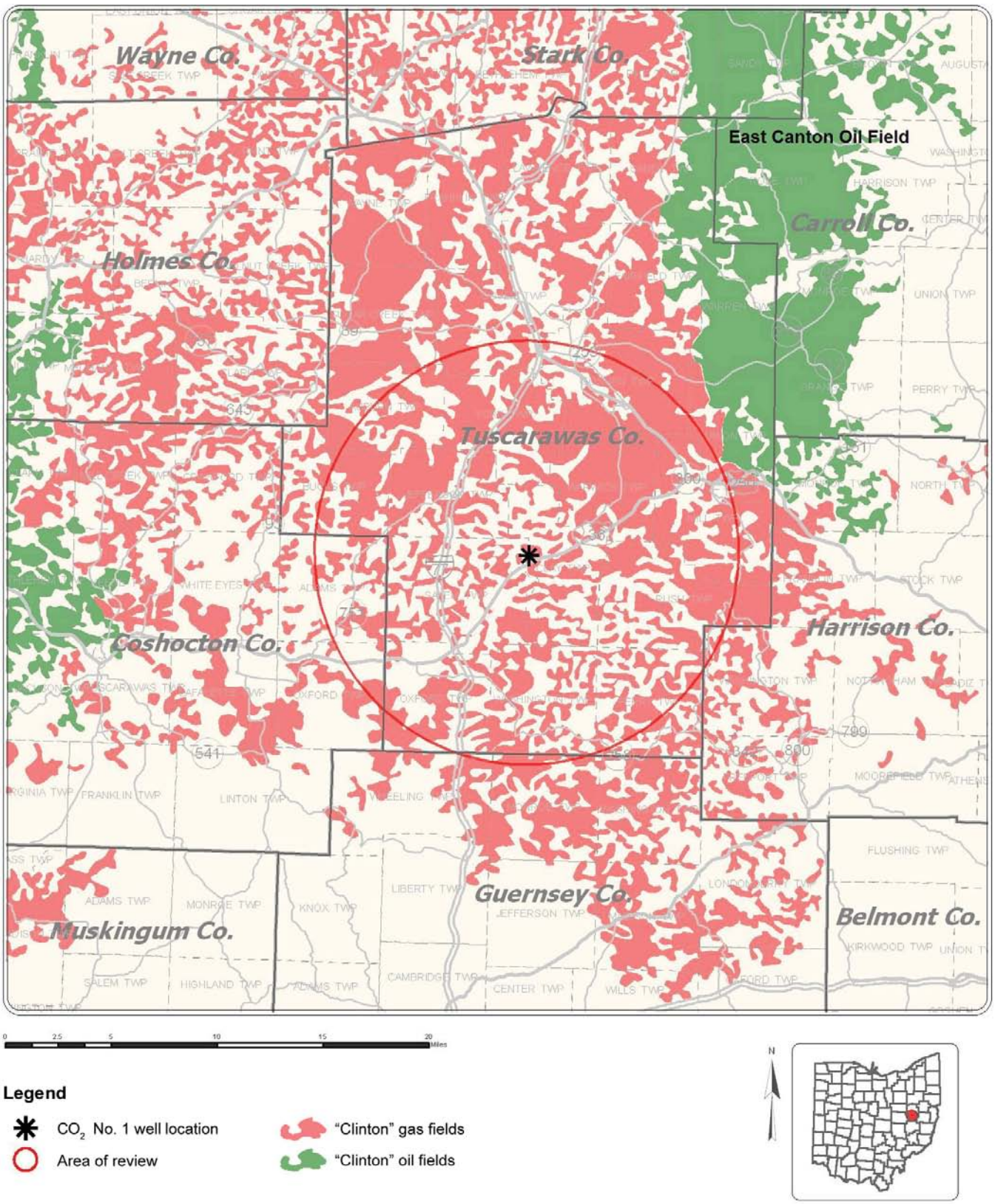


FIGURE 47.—"Clinton" sandstone oil and gas fields map for the Ohio Geological Survey CO_2 No. 1 well area of review and vicinity.

barrels of oil can be produced from it and other "Clinton" fields in the region. The northern part of the field was originally developed in the 1950s (prior to oil and gas regulations in Ohio), while the southern extent of the field (closest to the proposed site) was originally drilled in the 1970s and 1980s. Thus, well locations, construction, and plugging practices in the southern portion of the field are better documented and have been performed under supervision of Ohio's regulatory authority, the ODNR Division of Mineral Resources Management (DMRM).

A recent cyclical CO_2 injection pilot study in the northwest portion of the East Canton oil field, in collaboration with the oil-and-gas industry, has shown promising results and could prove to be a significant catalyst for a larger-scale pilot EOR project. Results from this project will be released in mid-2011.

Over 1,500 "Clinton" penetrations have been drilled within a one-mile radius of the CO_2 No. 1 well (fig. 48). Most of these are gas wells and were drilled between 1969 and 1989. As these oil and gas wells become depleted, it may prove a good opportunity to consider the "Clinton" as a secondary CO_2 injection zone. Concern exists over the CO_2 mixing with brine to produce a weak acid and what effect this would have in contact with the surrounding well cement and casing. This is an active area of research in other areas of the United States. (e.g., Bachu and Bennion, 2009; Carey and others, 2010) and would need to be researched and addressed locally but appears to be manageable.

The specifics of this formation within the CO_2 No. 1 well were addressed under the saline formations discussion. Minor gas shows, with a maximum of 23 units above background, were encountered while drilling on air through this interval in the CO_2 No. 1 well (fig. 40).

Silurian-Devonian "Big Lime" Interval (Top of Onondaga Limestone to Base of Lockport Dolomite)

The "Big Lime" interval (top of the Onondaga Limestone to the base of the Lockport Dolomite) is also an important oil and gas producing interval in the state and throughout the Appalachian Basin. This interval includes reservoirs in the Lockport Dolomite, Bass Islands Dolomite, and the Oriskany Sandstone (fig. 3).

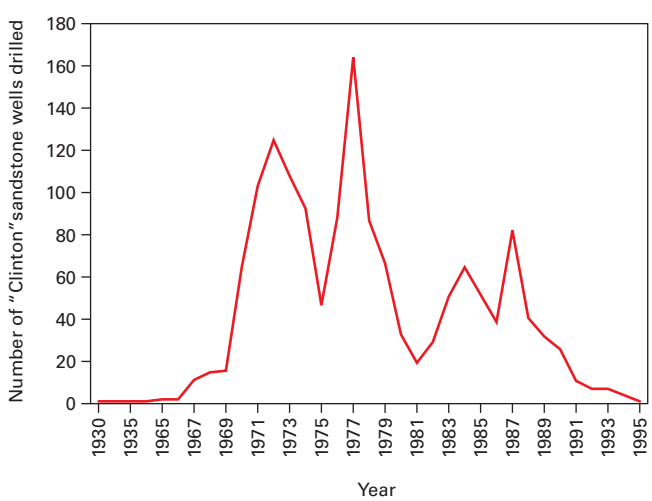


FIGURE 48.—Graph illustrating the 1,543 wells drilled for "Clinton" sandstone production within the Ohio Geological Survey CO_2 No. 1 well area of review from 1930 to 1995.

Significant hydrocarbon production from Lockport carbonates occurs in central and eastern Ohio, eastern Kentucky, western West Virginia, and northwestern Pennsylvania in the Appalachian Basin (Noger and others, 1996). There are 20 wells with production from the Lockport within the AOR. These are in the Salem North field, approximately 9 miles to the southwest of the CO_2 No. 1 well (fig. 49). The discovery well was drilled in 1926 and the field was abandoned in 1951. There is no historical production data available for this field. Only one 30-unit gas show occurred in the Lockport at a depth of 3,996 feet during drilling operations in the CO_2 No. 1 well, and no significant reservoir development was evident in the Lockport interval on wireline logs. However, proximity to the Salem North field indicates potential Lockport reservoir development in the area.

The Bass Islands Dolomite is a local oil-and-gas producing reservoir in northwestern Pennsylvania, and western New York along a narrow, 84-mile-long, structurally controlled northeast–southwest trend (Van Tyne, 1996). There are no producing Bass Islands oil-and-gas fields in Ohio; however, significant gas shows have been encountered in numerous wells in eastern Ohio. Several small gas shows with a maximum of 16 units above background were encountered while drilling through the Bass Islands in the CO_2 No.1 well.

There are four Oriskany Sandstone producing fields within the AOR (fig. 49). These are the Backus Knob, the Murphy Hollow, the Salem North, and the Toad Hollow fields. The closest Oriskany fields to the CO_2 No. 1 well are the Backus Knob and Murphy Hollow fields that are approximately 5 miles to the south. The Backus Knob field was discovered in 1930 and abandoned in 1953. The Murphy Hollow field was discovered in 1945 and abandoned in 1946. There are no available production records for these fields. Oriskany production from the Salem North field began in 1939 with wells being drilled until 1988. The last producing well for this field was abandoned in 1991. Production data is available for several of these wells but did not indicate significant volumes. The Toad Hollow field is approximately 6 miles to the east of the CO_2 No. 1 well and was discovered in 1974. Reported cumulative production through 2009 was approximately 1.9 BCFG and 6,770 BO for 18 wells in this field.

There were no significant gas shows and no significant reservoir rock encountered while drilling through the Oriskany Sandstone interval in the CO_2 No. 1 well. Proximity to producing Oriskany fields in Tuscarawas and adjacent counties indicates localized areas of potential reservoir quality rock for CO_2 sequestration or EOR in this region.

UNMINEABLE COALS

Ohio has had a long and proud history of coal mining, with the first reported production dating back to 1800. Coal production peaked in Ohio in 1970 with 50.57 million tons produced (Crowell, 1995). In 2009, the state's coal industry produced 27.32 million tons and ranked eleventh in the nation (Wolfe, 2010). Coal-bearing rocks are found in 40 eastern Ohio counties. Tuscarawas County ranks sixth in the state in all-time coal-producing counties. Much of the Tuscarawas County production was from surface mines, yet a number of underground mines were developed (fig. 18). In fact, a portion of the CO_2 No. 1 well site was strip-mined up through the mid-1990s.

Deep unmineable coals are not found directly under the CO_2 No. 1 well site. Approximately 14 miles to the east, deep (greater than 500 feet) unmineable coals five to ten feet in total thickness are present, which thicken to the east-southeast (fig. 50). Ohio is

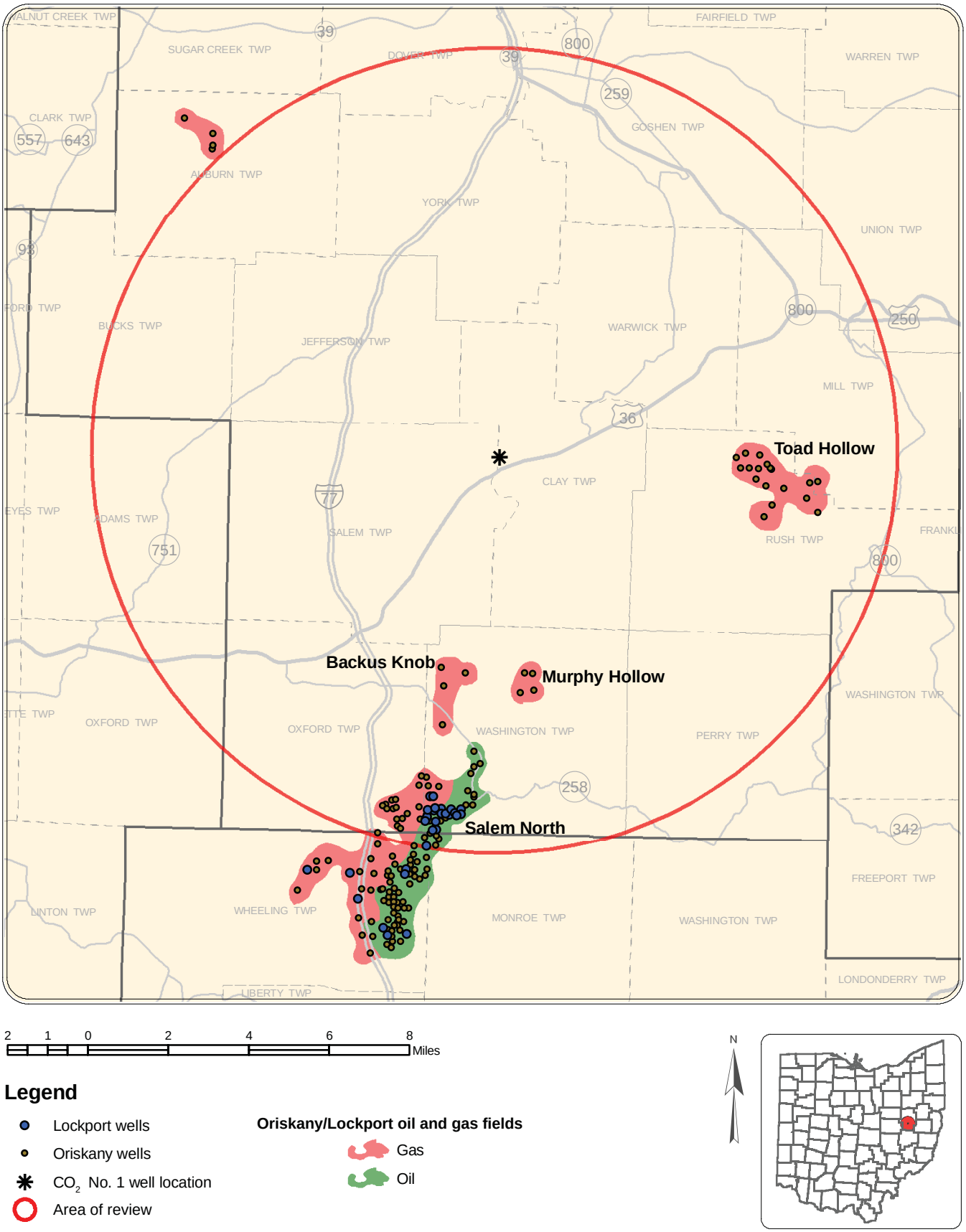


FIGURE 49.—Oriskany Sandstone and Lockport Dolomite oil and gas fields map for the Ohio Geological Survey CO_2 No. 1 well area of review and vicinity.

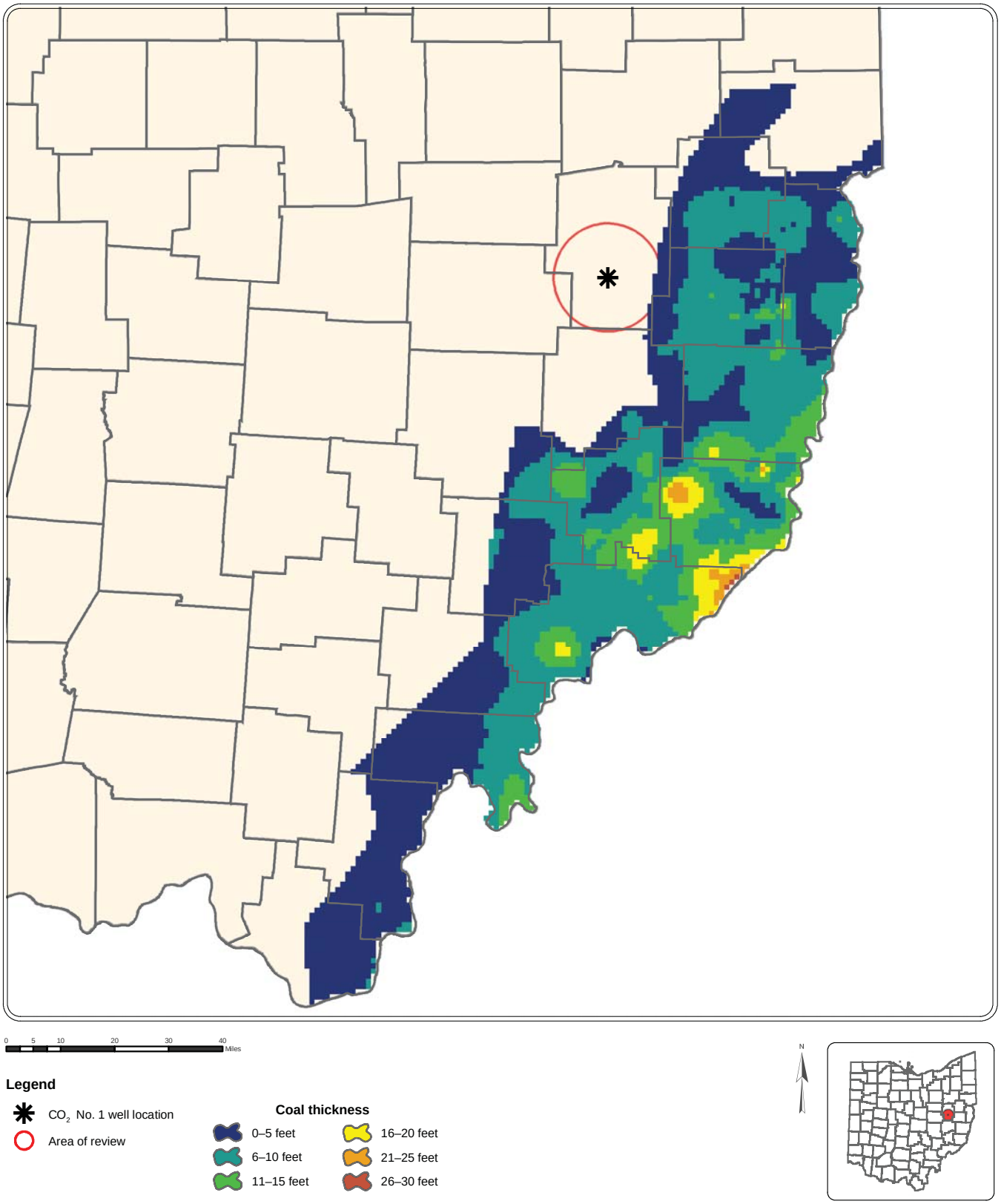


FIGURE 50.—Map showing total thickness of coals greater than 500 feet deep in the Ohio Geological Survey CO_2 No. 1 well area of review and southeastern Ohio.

lacking reliable gas-content analyses on most of the coal beds in the state. Research on this topic is a high priority at the Ohio Geological Survey. However, using conservatively low gas-content values, the Ohio Geological Survey estimates the state's coal bed methane (CBM) reserves at 2–5 trillion cubic feet of methane. Although there is currently very limited CBM production in Ohio (all from mine vents), rising natural gas prices have led to growing interest in this energy resource in the state, and CO_2-enhanced recovery of methane may provide an economic incentive for CO_2 sequestration in coalfields. Quite possibly, if EOR opportunities develop and pipelines are constructed in the region, deep coalbed sequestration (and enhanced-methane production) can be made part of the expanding portfolio of sequestration options in this region.

CARBONACEOUS SHALES

Ohio also contains widespread, thick deposits of carbonaceous shales. These shales are interesting in that they are often multifunctional; acting as seals for underlying reservoirs, as source rocks for oil-and-gas reservoirs, and are unconventional gas reservoirs themselves. Both the Ordovician-shale and the Devonian-shale intervals within the AOR contain thick sequences of organic shale (figs. 51 and 52). While these intervals are not directly proposed as injection zones, they represent opportunities for additional research and may have potential to add to the CO_2 sequestration capacity in this region.

CONFINING UNITS FOR POTENTIAL INJECTION INTERVALS

The defined primary confining unit (seal) for both the primary injection zone (the Cambrian basal sandstone) and the deepest secondary injection zone (the Rose Run sandstone) is the Upper Ordovician-shale interval (includes the Queenston Shale, the Cincinnati group, the Utica Shale, and the Point Pleasant Formation; fig. 3). In the AOR, the thickness for this interval ranges from 1,400 to 1,650 feet (fig. 51). Within the CO_2 No. 1 well this interval has a thickness of 1,445 feet.

The secondary confining interval for these sequestration units is defined as the Devonian-shale interval (Hamilton Group through the Ohio Shale; fig. 52). This interval ranges from 1,850 to 2,550 feet in the AOR with regional basinward thickening to the east and southeast. The CO_2 No. 1 well has a thickness of 2,184 feet for the Devonian-shale interval.

In addition to the primary and secondary seals, the site also offers thousands of feet of tight (low porosity and permeability) carbonates and evaporites as additional safeguards to prevent CO_2 migration into shallower horizons or the biosphere (fig. 3). Overlying the Cambrian basal sandstone, there are approximately 2,200 feet of carbonates in the Cambrian-Ordovician interval comprising the Conasauga group, Knox Dolomite, and Trenton-Black River. Above the "Clinton" sandstone—a secondary sequestration and EOR target—there are approximately 1,200 feet of Silurian-age carbonates and evaporites (Lockport Dolomite and Salina Group). Overlying the Oriskany Sandstone (the shallowest potential secondary injection zone), the Devonian-shale interval is the primary confining unit, and there are also approximately 150 feet of Devonian-age carbonates (the Onondaga Limestone). There are approximately 2,900 feet of sedimentary rock between the Oriskany Sandstone and the deepest underground source of drinking water (the Sharon Sandstone).

STRUCTURAL GEOLOGY NEAR THE CO_2 NO. 1 WELL SITE

Depth to the Precambrian basement at the CO_2 No. 1 well is 8,628 feet below ground level (7,701 subsea), based on geophysical well logs. The Precambrian structure map does not indicate any regional faulting or folding within the AOR and displays basinward regional dip of about 90 feet per mile to the east-southeast (fig. 14). The nearest documented basement fault to the Tuscarawas County site is in Holmes County, approximately 25 miles to the west-northwest (fig. 14). The faulted feature at this location is named the Killbuck Dome and consists of a series of horst and grabens in the Precambrian surface, reactivated by later tectonic forces (Wicks, 1996). Another notable Precambrian feature is the Cambridge cross-strike structural discontinuity. This feature, also known as the Cambridge Arch, extends from Washington County in the southeast to Coshocton County, where it loses definition about 16 miles west-southwest of the CO_2 No. 1 well. Some researchers feel that the feature is a late-formed, thin-skin detachment structure with some folding (e.g., Janssens and Olds, 1993), while others believe that deep Precambrian faulting is responsible for the shallower structures (Baranoski, 1993). To the north and northeast of the AOR are the northwest–southeast trending Akron-Suffield and Highlandtown fault systems, which are both basement-related features.

Locally, based on proprietary 3-D seismic data, there is a northwest–southeast trending monoclinal feature, informally named the York-Clay feature by Artex and other operators in the area. It is approximately 3.5 miles east of the CO_2 No. 1 well. This basement feature extends up to at least the Knox interval, and the west flank contains very steeply dipping beds in the Cambrian-Ordovician interval. The western limb may be faulted or fractured, but more detailed work is required to determine the nature and extent of this feature.

OIL AND GAS WELL PENETRATIONS

Over 250,000 oil-and-gas wells have been drilled in Ohio since 1860. Most of this drilling, however, has been restricted to the "Clinton" or more shallow horizons. More recently the deeper exploration wells targeting the Knox have been drilled, and this continues today.

There are 306 wells reaching the Knox Dolomite (includes the Beekmantown, Rose Run, and Copper Ridge) within the AOR (fig. 53). The Knox is the deepest producing oil-and-gas horizon in Ohio, with an average depth of 7,300 feet in the AOR. In this area, Knox production was not pursued until 1980, and most drilling has occurred since 1990.

The "Clinton" Sandstone, the most actively drilled target in Ohio, contains 1,543 wells in the AOR with an average drilling depth of 5,040 feet (fig. 54). The majority of these "Clinton" wells have been drilled since 1969. This is significant in that Ohio's statewide oil-and-gas regulatory agency (renamed to DMRM) was created in 1965. Thus, these well locations are properly documented and cementing and plugging conditions have been enforced during this time. This situation reduces the necessity for additional activity in the proper plugging and abandonment of improperly plugged and abandoned wells.

The Oriskany Sandstone reservoirs were first discovered in the AOR in 1925 and drilling for this horizon continues today. Approximately 53 Oriskany penetrations have been drilled in the AOR (contained in fig. 54), although a number of deeper wells have been

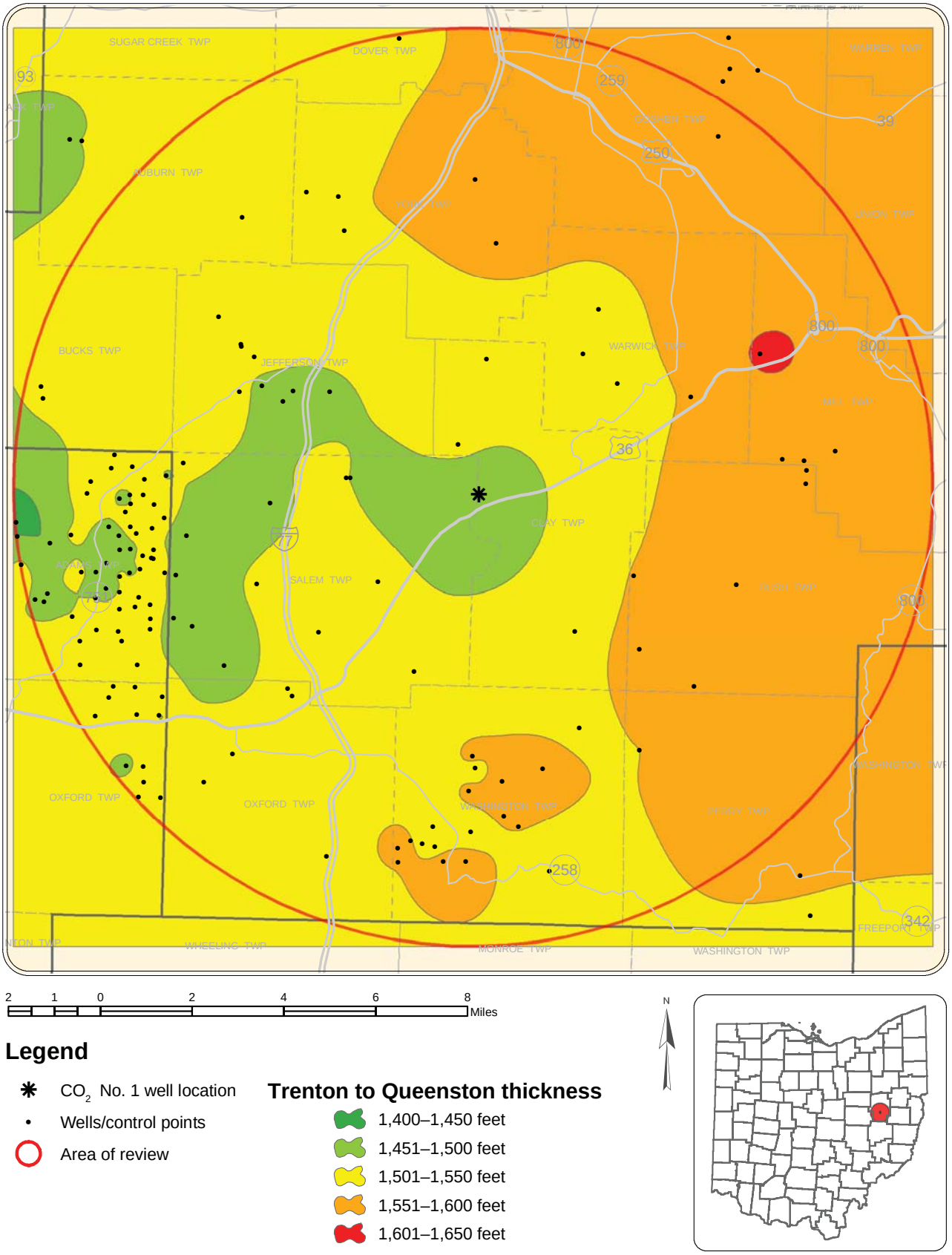


FIGURE 51.—Map of the thickness of the Ordovician Cincinnati group (top of the Trenton Limestone to top of the Queenston Shale) in the Ohio Geological Survey CO_2 No. 1 well area of review.

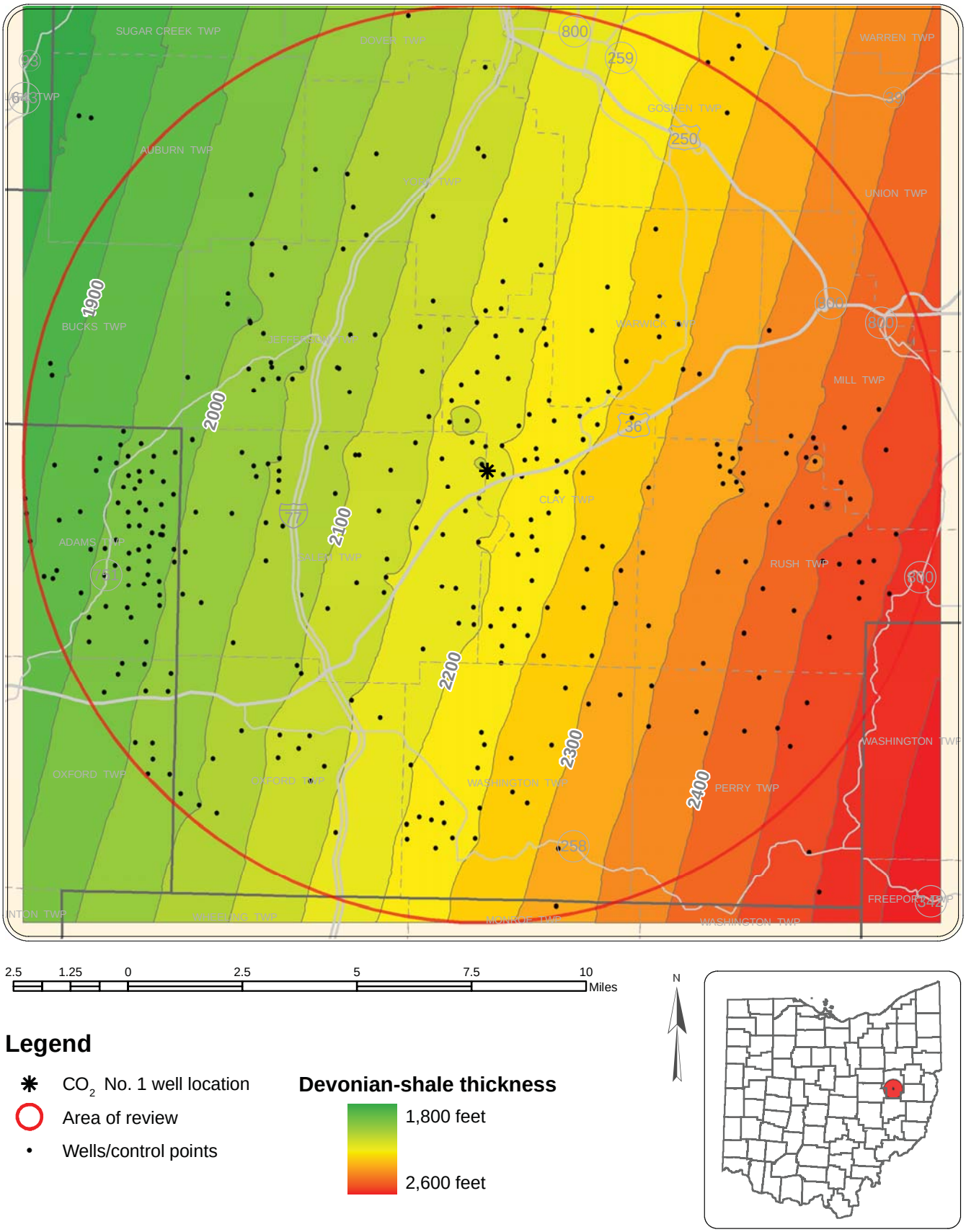


FIGURE 52.—Map of the thickness of the Devonian-shale interval in the Ohio Geological Survey CO_2 No. 1 well area of review.

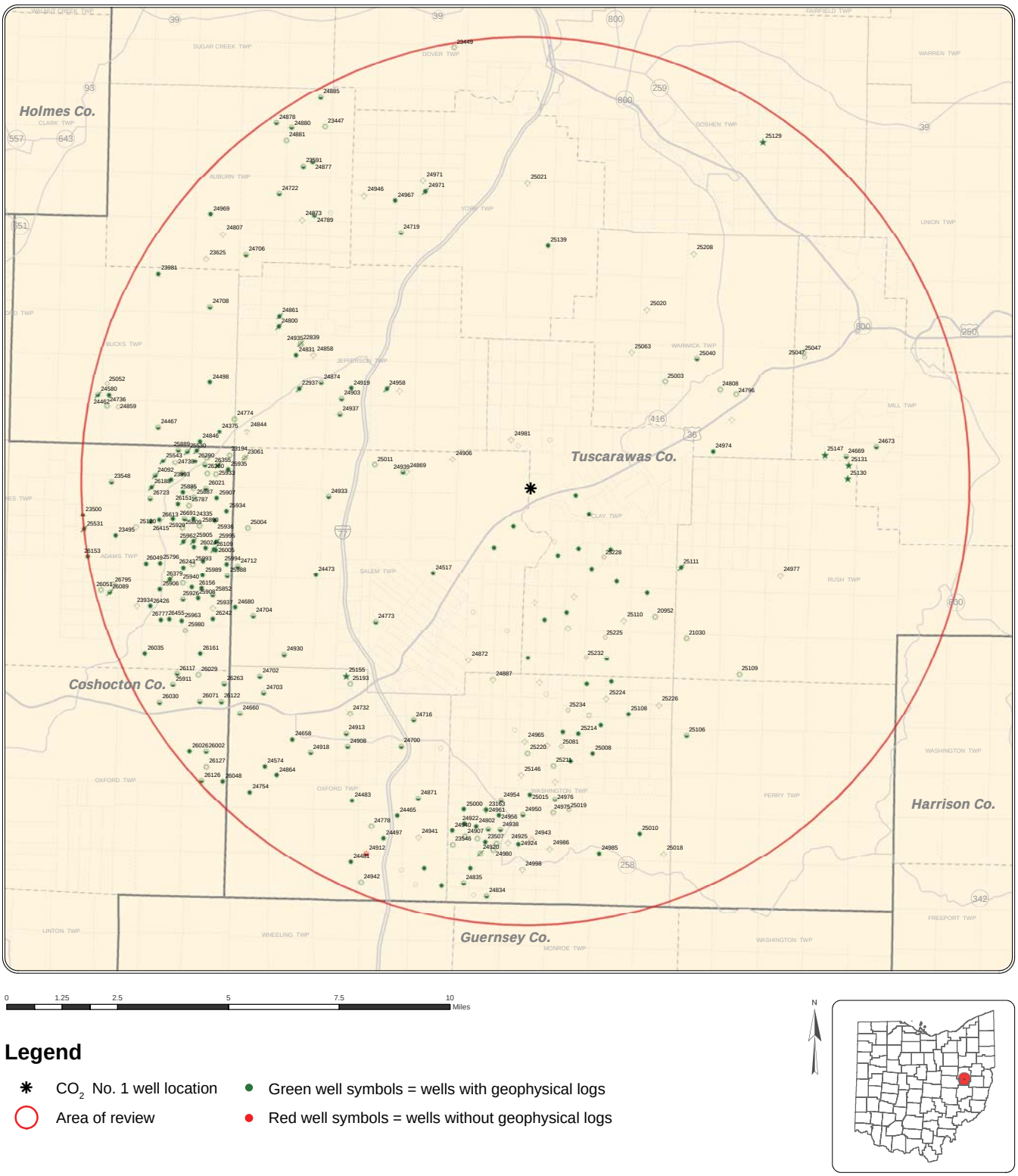


FIGURE 53.—Map of wells that penetrate the Beekmantown dolomite or deeper within the Ohio Geological Survey CO_2 No. 1 well area of review. Also shown are wells with geophysical logs.

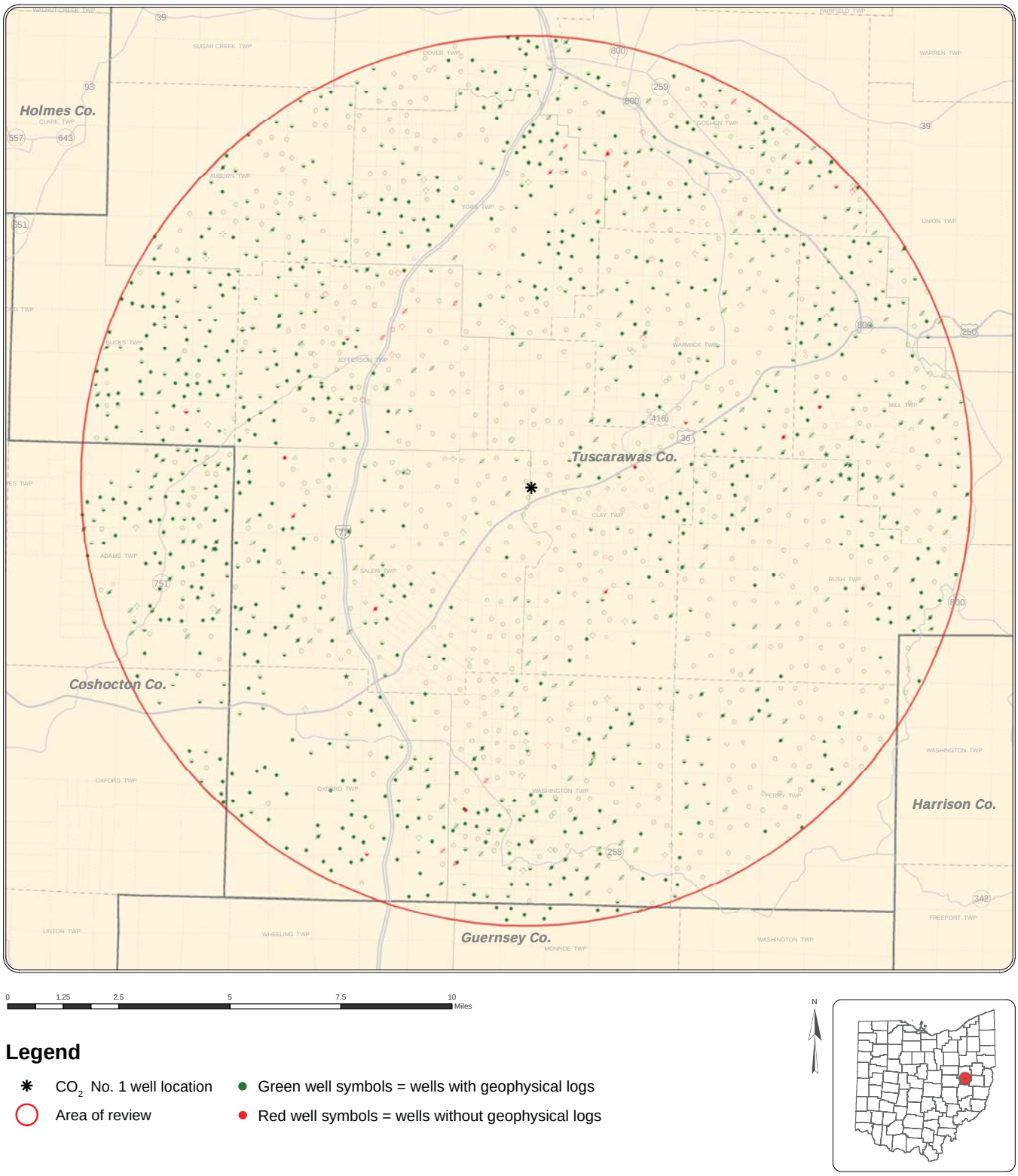


FIGURE 54.—Map of wells that penetrate the "Clinton" sandstone or deeper within the Ohio Geological Survey CO_2 No. 1 well area of review. Also shown are wells with geophysical logs.

plugged back to the Oriskany. Average depth to the Oriskany in the AOR is 3,945 feet.

Within the AOR most of the earliest drilling for oil and gas targeted the Berea Sandstone at depths ranging from about 800 to 1,800 feet, with an average of about 1,230 feet. Drilling for Berea production started in 1901 within the AOR, and there are currently 156 Berea-targeted wells.

SEISMIC REFLECTION DATA

The nearest public domain seismic reflection data to the Tuscarawas County site is the Ohio COCORP line (fig. 14), an east–west profile acquired in 1989. The COCORP acquisition parameters were designed to look at geologic features within Earth's crust that are 10 to 30 miles deep. Thus the upper few seconds of Paleozoic and shallow Precambrian reflection data are not specifically processed for standard structural and stratigraphic interpretations of these shallow horizons.

There are several oil-and-gas industry reflection 2-D seismic lines that have been acquired in the vicinity, and a 25-mi^2 3-D seismic survey is present within and adjacent to the AOR, but these are held proprietary by the companies. Some seismic reflection data may be available for licensed purchasing but were not obtained for the drilling of this well because of cost and time limitations.

SEISMICITY

The Ohio Geological Survey operates a statewide array of seismic monitors, with all data reported to and collected at our central facility, the Horace R. Collins Laboratory near Delaware, Ohio. The Ohio Geological Survey also cooperates closely with the U.S. Geological Survey National Earthquake Information Center in Colorado, and operates one of the USGS strong-motion sensors at its Delaware facility. Lastly, in the event of a strong event within the state, the Ohio Geological Survey cooperates with the USGS and the Lamont-Doherty Observatory to quickly place portable sensors around the area of the event to closely monitor any aftershocks. Close-spaced monitoring of aftershocks allows very precise placement of the epicenter and better solutions for the geometry of the fault plane involved. (Figure 55 is a map showing all recorded earthquake locations and relative magnitudes [Ohio Division of Geological Survey, 2007]. Updates to this map and detailed information on most previous seismic events can be found on the OhioSeis website at: **http://www.dnr.state.oh.us/OhioSeis**.)

The CO_2 No. 1 well site lies within the eastern Ohio aseismic zone, where there has never been a documented earthquake epicenter. The nearest significant earthquakes are the January 31, 1986, 5.0-magnitude (mbLg) in southern Lake County, at a distance of 90 miles (145 km) from the site, and the September 28, 1998, 5.2-magnitude (mbLg) Pymatuning earthquake in western Pennsylvania, at a distance of 66 miles (107 km) from the site. Both earthquakes generated Modified Mercalli Intensities of III in Tuscarawas County. The nearest earthquake epicenter to the site is a 3.0-magnitude (mbLg) event on August 7, 2000, in southern Portage County, at a distance of 28 miles (46 km) from the site.

The U.S. Geological Survey Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years map (USGS, 2002) indicates that the site is within the less-than-6-percent g zone. These data suggest very high seismic stability at the Tuscarawas County site.

CLASS I AND II INJECTION WELLS

There are no Class I (hazardous and industrial waste) injection wells within the AOR. The nearest Class I injection facility is located in Lake County, approximately 96 miles from the proposed site.

Only four Class II (brine injection) wells are located within the AOR (fig. 56). The three closest wells (about 2 miles southeast of the CO_2 No. 1 well site) inject into the Berea Sandstone at depths of approximately 900 feet, which is approximately 2,300 feet above the Oriskany Sandstone, the most shallow sequestration target. The remaining brine injection well is located 9 miles from the site and injects into the "Clinton" sandstone at approximately 5,500 feet. This well is approximately 9 miles southeast and down-dip from the CO_2 No. 1 well and outside of the projected CO_2 plume modeled during the FutureGen project.

HYDRAULIC TESTING

Reservoir testing conducted within the Ohio Geological Survey CO_2 No. 1 Well provided additional information on hydraulic and storage properties for test horizons within the Cambrian basal sandstone (8,526 to 8,613 ft) and Rose Run sandstone (7,377 to 7,509 ft). This work is described in detail in Appendix 4 and is summarized here.

The principal hydraulic/storage parameters quantified during testing include transmissivity (T), hydraulic conductivity (K), permeability (k; intrinsic), and storativity (S). The field-test activities were completed using a hydrologic-test sequence approach that included short-duration, slug-injection/DST recovery tests, used in conjunction with longer duration injection test and injection-test recovery characterizations. Hydrologic tests were analyzed individually using standard analytical methods and collectively using a combined-test history matching approach.

The perforated test intervals were isolated within the cemented well casing using a lower bridge-plug packer and an overlying tubing string packer. Downhole memory gauges were used to monitor downhole pressures within the isolated test interval and well interval below the bridge-plug packer. Testing complexities identified for some of the zones during the characterization phase include:

1. High test system/formation fluid compressibility due to the assumed presence of gas (basal sandstone, Rose Run #3) and moderate well-skin effects (Rose Run #2). Of note is that no gas shows were noted by the mudlogger's gas chromatograph through the basal sandstone interval.
2. Multilayer, commingled reservoir conditions (composite Rose Run).
3. Transitional, non-radial flow conditions possibly imposed by the partial penetration/perforation well completion (Rose Run #1 and #2).

Six discrete, perforated-depth intervals within the basal sandstone (8,526–8,531 ft; 8,536–8,542 ft; 8,554–8,576 ft; 8,578–8,587 ft; 8,602–8,604 ft; and 8,608–8,613 ft) were hydrologically tested. Collectively, the basal sandstone perforated intervals exhibited relatively low hydraulic properties: T = 0.073 ft^2/day, K = 0.0015 ft/day, and k = 0.5 mD. The high storativity value of S = 2.8E-2 is an indication of the presence of gas within the test system or surrounding formation.

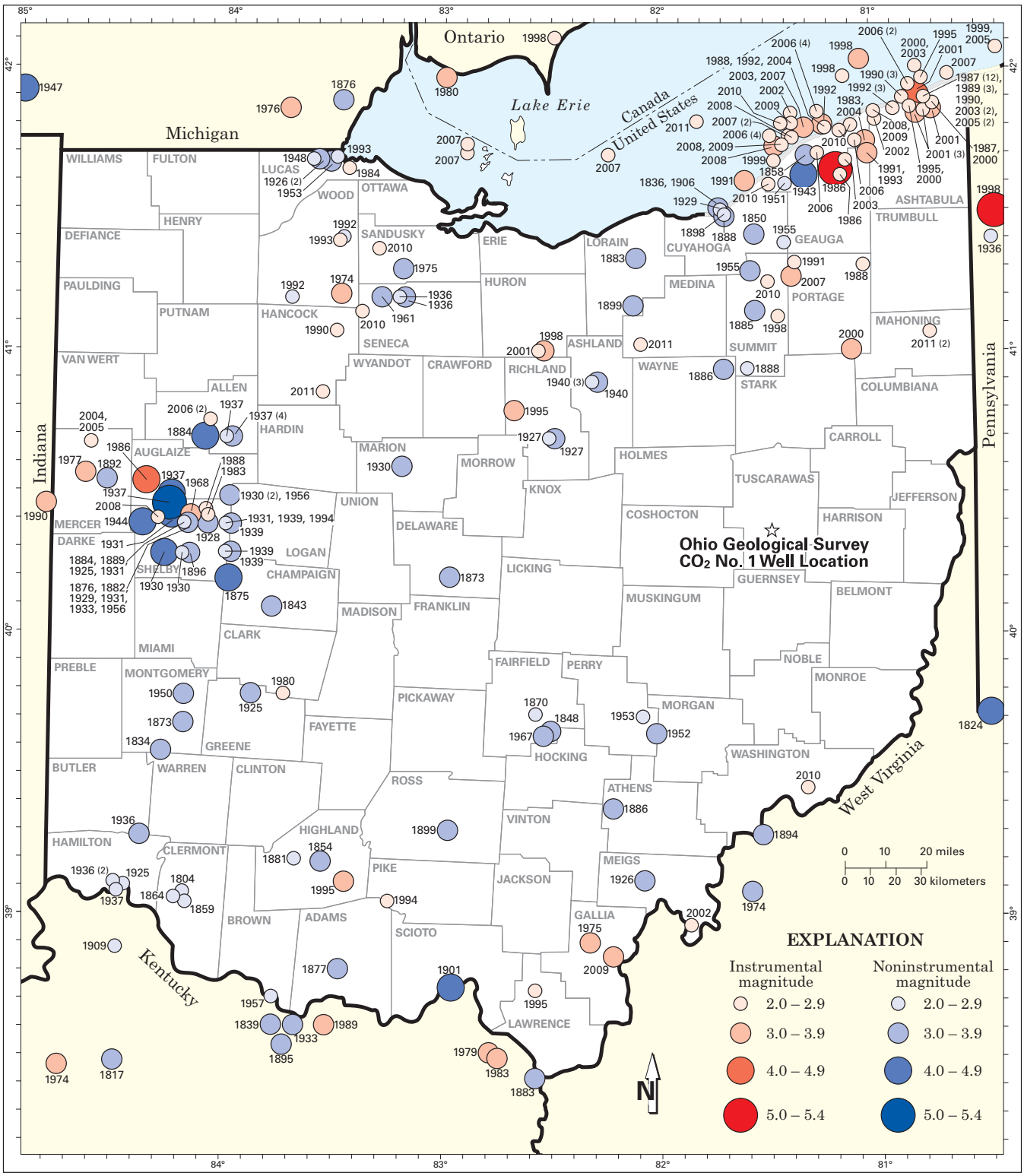


FIGURE 55.—Map showing all known earthquake locations and relative magnitude in and adjacent to Ohio. From Ohio Division of Geological Survey (2007).

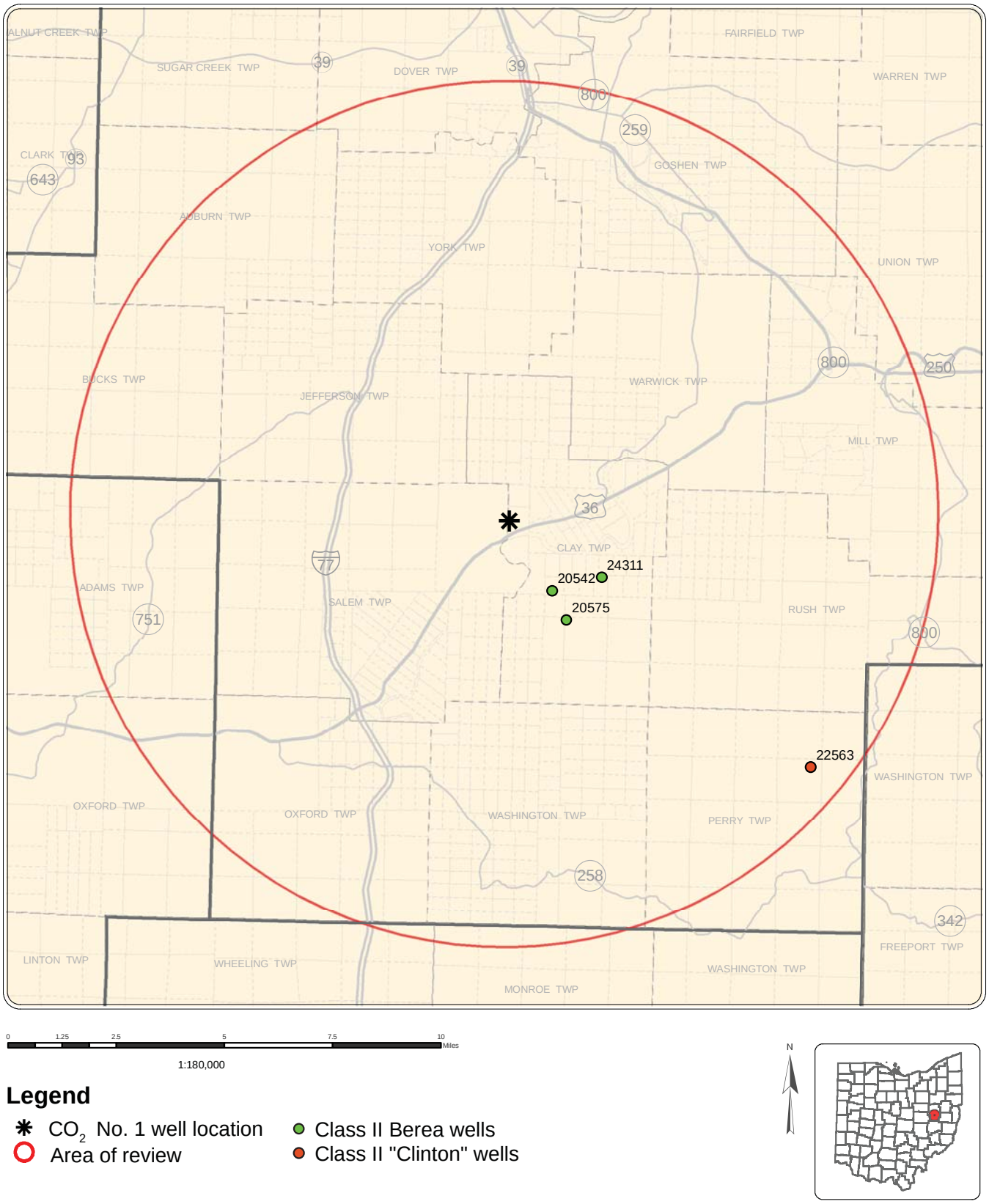


FIGURE 56.—Map showing the locations of Class II injection wells designated by injection formation within the Ohio Geological Survey CO_2 No. 1 well area of review.

The Ohio Geological Survey derived a comparison of the average field-test-derived k estimate (0.5 mD) as it relates to the range of small-scale k values, obtained from the wireline CMR and the PressureXpress survey test results and discrete sidewall cores that were obtained over the entire basal sandstone unit (table 2). As indicated, the average field-test k value falls within the k range obtained for four discrete sidewall core permeability measurements (0.0052 to 0.84 mD) obtained within the perforated test interval. The wireline CMR survey results for the perforated test interval average 2.6 mD (range: 1E- 5 to 17.7 mD), which is a factor of 5 greater than the field-test-derived value of 0.5 mD. The wireline PressureXpress test results for six discrete depth intervals within the basal sandstone ranged from 0.01 to 0.06 mD, which is significantly lower than the field-test-derived average estimate.

Three perforated test zones in the Rose Run were individually hydrologically tested: Rose Run #1 (7,506–7,509 ft), Rose Run #2 (7,416–7,418 ft and 7,435–7,446 ft), and Rose Run #3 (7,377–7,380 ft and 7,387–7,396 ft). Based on the results of these tests, ~95 percent of the composite transmissivity is contained within the middle Rose Run test interval (Rose Run #2). The composite summation transmissivity value for the perforated Rose Run test intervals was estimated at 0.93 ft^2/day.

Table 2 presents a comparison of the average field-test-derived k estimate values for the three Rose Run test zones as they compare to the range of small-scale k values obtained from wireline CMR and PressureXpress survey results, and discrete sidewall cores obtained over the entire Rose Run formation. As indicated, the average field-test k value for the lower and middle Rose Run test zones (i.e., Rose Run #1 and #2) generally fall within the upper or slightly above the k range obtained from discrete sidewall core permeability measurements and wireline CMR and PressureXpress survey results.

For Rose Run #1 (with a average field-test-derived k estimate of 2.6 mD), the one sidewall core permeability measurement and one PressureXpress test result available for the perforated interval provided a value of 1.4 and 0.22 mD, respectively. The CMR survey results for the tested interval ranged from 0.02 to 1.8 mD and averaged 0.7 mD.

For Rose Run #2 (with an average field-test-derived k estimate of 22.1 mD), the two sidewall core permeability measurements and two PressureXpress test results available for or within proximity to the perforated interval provided a k estimate range of 0.8 and 26.6 mD, and 3.86 and 5.67 mD, respectively. The CMR survey results for the tested interval ranged from 0.05 to 16.3 mD and averaged 5.1 mD.

The reason for the slightly higher average-k estimate for the field tests in comparison to the averaged CMR survey and PressureXpress results is not known. The lower-k values from the small-scale CMR survey and PressureXpress test results, however, may be attributed to the presence of low-to-moderate skin effects that were detected during the field-test characterization.

For Rose Run #3, the three sidewall core permeability measurements and two PressureXpress test results available for the perforated interval provided a wide range, varying between 0.004 and 13.8 mD and less than 0.01 mD, respectively. The CMR results for the tested interval ranged more narrowly between 0.1 and 3.1 mD and averaged 0.7 mD. The average CMR-derived k value of 0.7 mD for the Rose Run #3 perforated-test interval is nearly identical to the average field-test-derived k estimate of 0.6 mD.

The relative correspondence between the average-k wireline CMR values and the larger-scale average-field-test k estimates for the various Rose Run test intervals suggests that there is little scale dependence between these two test-methods, and it suggests that the test intervals are relatively homogeneous away from the test well over the test radius-of-investigation. The relative correspondence of average-k values for field tests and wireline CMR surveys suggests that the CMR may be a viable reconnaissance borehole indicator for identifying the distribution and presence of permeability within the targeted sandstone reservoir formations.

SUMMARY

The region surrounding the Ohio Geological Survey CO_2 No. 1 well has a long history of oil, gas, and coal extraction; yet the older wells are relatively shallow (less than 5,000 feet) and well

TABLE 2.—*Intrinsic permeability test zone comparison by characterization method for the Ohio Geological Survey CO_2 No. 1 well*

Stratigraphic Unit	Test Zone[a]	Perforated Interval (ft)	Characterization Method Permeability (mD)			
			Packer Tests[b]	CMR Survey[c]	PressureXpress Survey[d]	Sidewall Core Lab Tests[e]
Rose Run	Rose Run #3	7,377–7,380 7,387–7,396	0.6	0.7 (0.1–3.1)	<0.01 (two tests)	0.004–0.8 (three core tests)
	Rose Run #2	7,416–7,418 7,435–7,446	22.1	5.1 (0.05–16.3)	3.86–5.67 (two tests)	0.8–26.6* (two core tests)
	Rose Run #1	7,506–7,509	2.6	0.7 (0.02–1.8)	0.22 (one test)	1.4 (one core test)
Cambrian basal sandstone	(total)	8,526–8,531 8,536–8,542 8,554–8,576 8,578–8,587 8,602–8,604 8,608–8,613	0.5	2.6 (1E-5–17.7)	0.01–0.06 (six tests)	0.0052–0.84 (four core tests)

[a] Relative position within stratigraphic unit indicated in parentheses.
[b] k = K (μ/γ); K = T/b; assumed contributing thickness, b; assigned equal to the perforated interval length, L.
[c] k = determinations every 0.5 feet; range and average value calculated just over perforated interval.
[d] k calculated from discrete PressureXpress survey mobility measurements using an assumed formation fluid dynamic viscosity value of 0.878 cp (see Section 2.3.5).
[e] k = Klinkenberg laboratory measurements; * indicated core value for Rose Run #2 located 1 foot above a test zone perforated interval.

protected with thick confining intervals above the deep-injection operations. The sedimentary rock assemblage provides numerous, vertically-stacked reservoir rocks for research and characterization of injection operations in sandstone and carbonate reservoirs, as well as coal and organic-rich shales. CO_2-assisted EOR has not yet occurred in this region. However, within 10 miles of the AOR are three large oil fields, producing from three different horizons, capable of producing hundreds of millions of barrels of incremental oil using CO_2-assisted EOR. Active exploration, within and near the AOR, targeting the Beekmantown dolomite provides an opportunity to work with the oil-and-gas industry to utilize CO_2 in current operations. This deep stratigraphic test has provided detailed geologic and injection data that can help foster the research necessary to initiate widespread EOR operations in the Midwest and the eastern portion of the nation, which could translate into additional billions of barrels of oil being produced over the coming decades. The information collected and interpreted from this site and any sequestration or EOR benefits gained is widely applicable to the entire Appalachian Basin region.

Available published literature, oil and gas well data, core descriptions and analyses, coal information, and Class II (brine injection) data were compiled and analyzed within the AOR (a 10-mile radius of the CO_2 No. 1 well) during the FutureGen project[7] proposal. Data collected and analyzed from the CO_2 No. 1 well was integrated with the FutureGen data for mapping purposes. A total of 3,368 oil and gas well records, stratigraphic core tests, and brine-injection wells are contained in the public archives within the AOR. The nearest public-domain seismic reflection data is the east–west trending COCORP line, which is located several miles south of the AOR. There are several proprietary 2-D seismic reflection lines and a proprietary 25-square mile 3-D seismic survey present in the AOR.

Maps of oil and gas fields in the AOR are provided to assist in understanding the potential impact on sequestration. There are 19 oil and gas fields within the AOR (fig. 45), which includes hydrocarbon production from the Cambrian-Ordovician Knox Dolomite (Rose Run sandstone and Beekmantown dolomite), the Silurian "Clinton" sandstone and Lockport Dolomite, and the Devonian Oriskany Sandstone and Berea Sandstone. Within the AOR, there also exists hydrocarbon potential in the Ordovician Trenton-Black River interval and the Silurian Bass Islands Dolomite. Existing oil and gas data provide geologic analogues and are useful for evaluation of prospective saline reservoirs. There have been at least 1,850 oil and gas wells drilled within the AOR, of which 306 are Knox penetrations and 1,543 are "Clinton" penetrations (including the Lockport, Bass Islands, and Oriskany). These range in depth from approximately 3,600 (Oriskany) to 7,500 (Knox) feet below the surface. The CO_2 No. 1 well is the first Precambrian test in the AOR and in Tuscarawas County. Prior to this test well, the closest Precambrian well to the site was approximately 18 miles to the west in Coshocton County.

A minimum depth of approximately 2,500 feet is necessary for injected CO_2 to remain in the supercritical state. At the CO_2 No. 1 site and most of eastern Ohio, this will eliminate the Berea Sandstone as a sequestration target. However, injection into unmineable coal beds and perhaps organic-rich Devonian shale may have sequestration potential, since these do not require this depth constraint. CO_2 is adsorbed in organic-rich zones rather than being stored in pore spaces. Sequestration of CO_2 in carbonaceous shales has not been demonstrated and still requires further research.

[7] See footnote 1, p. 9.

Figure 57 summarizes the well construction, the stratigraphic section penetrated, sidewall core points, and gas shows in the CO_2 No. 1 well. This diagram also indicates the depths of stratigraphic intervals encountered and identifies both confining units and potential sequestration target zones in the test well. Eighty-two sidewall cores were taken in both sequestration targets and confining intervals. Nine deep-saline injection horizons, both carbonates and sandstones, were evaluated for sequestration potential at the CO_2 No. 1 well site; these include the following in ascending stratigraphic order: the Cambrian basal sandstone, the Copper Ridge dolomite (includes vuggy carbonate zones and the "B-zone" clastic interval), the Rose Run sandstone, the Ordovician Beekmantown dolomite, the Silurian Cataract Group ("Clinton" sandstone), the Lockport Dolomite, the Bass Islands Dolomite, and the Devonian Oriskany Sandstone (fig. 57).

The test well contains 80 feet of net sandstone (greater than 6 percent porosity) combined in the Cambrian basal sandstone and Rose Run sandstone intervals. The Cambrian basal sandstone has 56 feet of net sandstone with an average porosity of 10 percent and a maximum of 15 percent. Core analyses indicate low permeabilities that are generally less than 0.1 mD and a maximum of 1.0 mD. The Rose Run sandstone contains 24 feet of net sandstone with an average porosity of 9.0 percent and a maximum of 13.5 percent. Permeabilities in the Rose Run are more promising than the basal sandstone, with multiple values above 1.0 mD and a maximum of 31.1 mD. The Copper Ridge did not contain any appreciable reservoir development in either vuggy carbonates or the clastic "B-zone." Overlying the Cambrian basal sandstone there are approximately 1,020 feet of carbonate and shale in the Conasauga and overlying Copper Ridge that would provide good confining units. There also are over 2,300 feet of Trenton-Black River carbonates and Cincinnati group shales overlying the Knox, which would provide additional confining units for the Cambrian basal sandstone and the Rose Run.

The CO_2 No.1 well contains approximately 24 feet of net sandstone (greater than 50 percent shale free) in the "Clinton" interval. Core porosities in this interval range from 3.6 to 8.6 percent and permeabilities are very low with all measured values of 0.01 mD or less. These values indicate a low-sequestration capacity in this horizon; however, gas shows in the test well and producing "Clinton" gas wells within the AOR indicate the potential to store and mobilize CO_2. There were no significant zones of porosity development within the Lockport. However, localized porosity development from Lockport reefal zones may be present in the area. Five gas shows were encountered in this horizon while drilling on air, with a maximum of 72 units above background. The Bass Islands contains no significant reservoir quality rock (greater than 4 percent porosity). Although sequestration potential is not favorable at this site in the Bass Islands Dolomite, zones of fractured and brecciated Bass Islands Dolomite are promising in localized areas of the state. In the CO_2 No. 1 well, the Oriskany Sandstone is 23 feet in thickness with no significant porosity development greater than 4 percent. Proximity to producing Oriskany fields in Tuscarawas and adjacent counties indicates localized areas of potential reservoir quality rock for CO_2 sequestration in this region. At this site, there are approximately 2,900 feet of confining interval (including the Onondaga Limestone, Devonian shale and Cuyahoga Formation) between the Oriskany Sandstone and the deepest underground source of drinking water (Sharon Sandstone).

Comparing the projected injectivity of this well to some existing Class II brine injection wells that are located geographically near it provides some additional insight into potential for injectivity in this area of Ohio. The Guernsey County brine injection well

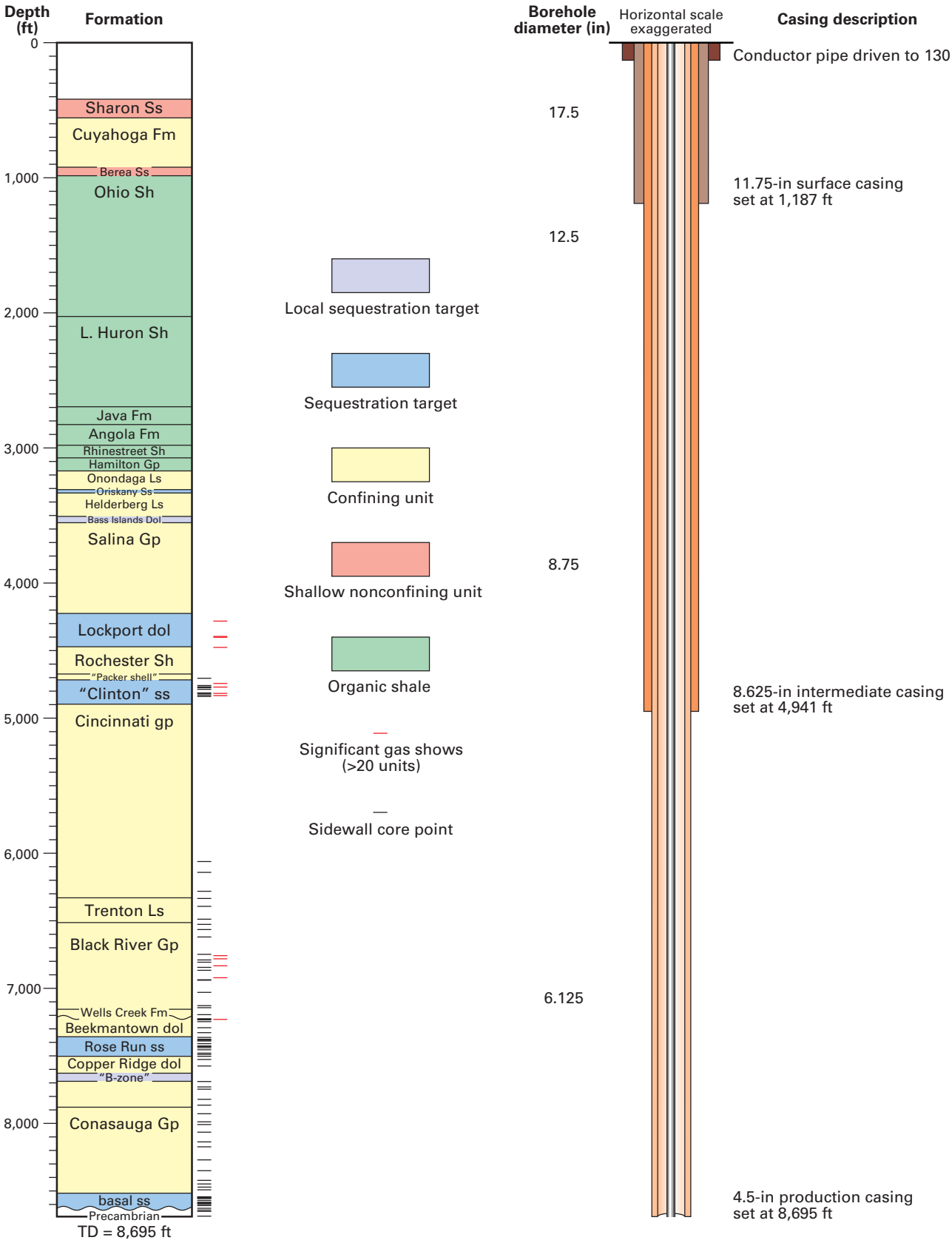


FIGURE 57.—Diagram showing the well construction of the Ohio Geological Survey CO_2 No. 1 well and the primary stratigraphic units and depth encountered. Also shown are the sidewall core points and significant gas shows.

is noteworthy, as this is a fairly new well with good geophysical logs and reliable injection volume data (table 3). This well has fairly similar stratigraphy and geophysical log signatures to that found for the CO_2 No. 1 well. In 24 months, the Guernsey County well has injected approximately 500,000 barrels of brine and well treatment fluids—an amount much higher than projected for the CO_2 No. 1 well from the limited testing conducted.

While the CO_2 No. 1 well did not reveal any high injectivity zones through the attempted tests, the well has certainly added vast amounts of information to our understanding of the geology of eastern Ohio. The Ohio Geological Survey, industry, academia, and many others will be analyzing and learning from this well for many years to come. Defining deep geology and economic potential—for extractive purposes or injection—is a scientific exploration effort. To define eastern Ohio's deep sequestration options will require a concerted effort spanning a number of years, using multiple exploration techniques, and a number of deep-test wells such as the CO_2 No. 1. The Ohio legislature, the Ohio Coal Development Office, and the U.S. DOE are to be commended for the foresight of funding this and other similar efforts, for without them, our knowledge does not progress.

LESSONS LEARNED

While the Ohio Geological Survey CO_2 No. 1 well in Tuscarawas County, Ohio, has provided much useful data on sequestration potential for a key part of the state, this first exploratory well drilled by the state for this purpose has provided a number of lessons that should be considered in any future efforts.

At the time this well was drilled (May through June 2007), service companies operating in the Appalachian Basin were not well-prepared for the type of logging, sidewall coring, and well testing operations attempted in this project. For example, the logging contractor had to ship tools into the region from the western United States. When one of these failed to work properly, they had no backup tools in the region, resulting in downtime at the drilling site while attempting repairs. This resulted in both increased time and cost. A similar situation occurred in the use of the sidewall cutting assembly on the uphole section ("Clinton" and shallower), resulting in the project team obtaining only nine of the planned 29 cores for that section, since the company could not get the tool working after $1^1/_2$ days and had no backup tool accessible (in all, 82 cores were obtained on the overall column). With the recent Marcellus Shale and Utica/Point Pleasant Shale plays taking place in the Appalachian Basin, additional service companies are now working in the region and this problem has abated somewhat. Nevertheless, the availability of service providers and equipment in the region needs to be considered in any well planning effort. To the extent possible, backup service providers should be included in the team to mitigate tool and equipment difficulties.

Drilling, logging, and testing operations are complex operations with inherent uncertainties given the exploratory nature of the work. Budgeting for such projects is a challenge especially when considering that for government-funded projects, budgets must be committed far ahead of beginning operations. Typically, government-funded projects do not allow for contingency funds to cover cost increases in services that occur between the time of original proposal and actual vendor procurement or the need for additional funds should delays in schedule arise. For example, prices for drilling and supplies almost doubled from the time funding for this project was originally proposed and actual purchase orders were placed with vendors. This increase was due to high market demand for such services during

TABLE 3.— *List of class II (brine) deep-injection wells, injection zone depths, and injection rates near the Ohio Geological Survey CO_2 No. 1 well*

Permit No.	County	Twp.	Injection Zone	Injection Zone Depths	Injection Dates	Cumulative Brine Injection Volumes (through 2009)	Average Daily Injection Rates	Calculated Cumulative CO_2 Injection Volumes*	Calculated Average Daily CO_2 Injection Rates*
4067	Guernsey	Westland	Rose Run to basal sandstone	7,216–8,902 feet (open hole)	Since October of 2008	364,705 barrels	1,054 barrels (32,088 gallons)	1,000,000–2,400,000 bbl (81,000,000–102,000,000 gal) (0.23–0.28 Mt)	5,500–7,000 bbl (230,000–290,000 gal) (643–811 t)
4527	Holmes	Killbuck	basal sandstone	6,402–6,500 feet (perforated)	Since 1985	5,009,920 barrels	987 barrels (41,202 gallons)	26,000,000–33,000,000 bbl (1,100,000,000–1,400,000,000 gal) (3.1–3.9 Mt)	5,200–6,600 bbl (218,000–276,000 gal) (610–772 t)
7350	Muskingum	Falls	Rose Run	5,721–5,795 feet (perforated)	Since 1986	1,953,561 barrels	232 barrels (9,324 gallons)	10,000,000–13,000,000 bbl (430,000,000–550,000,000 gal) (1.2–1.5 Mt)	1,200–1,500 bbl (51,000–65,000 gal) (143–182 t)
6595	Perry	Jackson	basal sandstone	6,168–6,248 feet (perforated)	Since 1985	4,069,021 barrels	586 barrels (24,612 gallons)	21,000,000–27,000,000 bbl (900,000,000–1,100,000,000 gal) (2.5–3.1 Mt)	3,000–3,900 bbl (130,000–164,000 gal) (364–459 t)

*The range in CO_2 volumes is based on calculations using depths of 5,000 and 8,000 feet. Conversion charts for CO_2 density were not available between these depths.

a period of unprecedented, high oil prices worldwide. Down time for repairs and tool failures further exacerbated the budget shortfall. Planned full-hole coring of multiple intervals had to be abandoned early on, and injection testing was cut short because of this problem. Often, the only recourse left once a project starts is to cut back planned testing and other activities to stay within budget. The lessons learned here would be to provide for some budget contingency for uncertainty, if at all possible; be prepared to make tradeoffs between the testing and the drilling program to assure that results obtained are as meaningful as possible; and communicate as clearly as possible among the project team and management what effect cutbacks in the testing are expected to have on the results.

Performing hydraulic testing in a cased wellbore, such as done in this project, is challenging in that the casing must be perforated over carefully selected intervals and then acid must be used to dissolve the cement and other debris across the perforations to achieve a representative flow between the reservoir and the wellbore. The selection of perforation intervals based on log interpretations can lead to exclusion of some potentially attractive zones, and the resulting reservoir analysis may not be fully representative of the hydraulic parameters. Based on discussions with oil-and-gas industry representatives, it is possible that the perforation intervals used in this project may have been too narrow, thus not allowing access to a large enough portion of the prospective reservoirs. It should also be noted that it was not possible to conduct hydraulic tests on the Beekmantown interval due to the presence of natural gas in this zone. Comments also were received from industry representatives that the acidizing treatment was not allowed to "soak" for a long enough time to ensure any remaining cement (skin) was cleared from behind the casing. Finally, higher pressures should have been run in the hydraulic testing to get a wider range of flows and, thus, a more accurate assessment of the maximum allowable flow rates that could be achieved in the reservoirs tested. The use of real-time down-hole pressure gauges would also have helped in this respect to assure that fracture pressures were not being exceeded and that the tests were run for a sufficient period. To some extent, the ability to expand the hydraulic testing as indicated above (i.e., wider injection intervals, more time for acidizing, wider pressure ranges, and use of real time gages) was limited by the budget constraints described above and availability of all proper equipment from vendors. Consequently, the final injectivity testing results on this well are believed to be somewhat questionable. For instance, we cannot be sure the perforations were completely open; the injection pressures used were inadequate for the depths being tested; and the duration of the testing was not long enough to be sure we had penetrated deep enough into the formations. Nevertheless, we believe that the permeability values calculated and presented in this report and the accompanying appendix are reasonably representative of the tested intervals.

As an alternative to the cased-hole testing conducted in the CO_2 No. 1 well, open-hole testing should be considered for future injection testing. The problems with perforations and acidizing previously cited can be eliminated by performing the injection testing in an open-hole environment rather than through casing and cement. In a well such as the CO_2 No. 1, it would have been very difficult to isolate the upper zones using open-hole packers and still sufficiently protect the potential gas-bearing zones from damage. However, alternative casing programs that allowed for limited testing of upper zones before setting casing across these and then testing the deeper basal sandstone zones in open-hole setting could have been considered. Also, many of the better-performing brine injection wells, including the Guernsey County well cited earlier, were completed open hole even for the operational phase and, thus, had more complete access to the entire length of available injection interval. Furthermore, open-hole testing allowed for identification of the lower Copper Ridge injection zones that were difficult to identify through logs alone in the AEP-1 well at the Mountaineer Plant in West Virginia.

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Tuscarawas County Site - Dip 1

Dip 1

34075214170000 — YODER LEVI N
N. & A.L. YODER 1

12484 ft

34075249260000 — LAKE REGION OIL INC
JOHN E RABER UNIT 2

22134 ft

34157247050000 — RED HILL DEVELOPMENT
BAAB-HERCHBERGER 2

55990 ft

34157245170000 — RANGE OPERATING COMP
J.STOCKER ETAL UNIT 1

26878 ft

34157209520000 — CGAS EXPLORATION
HARDING 1

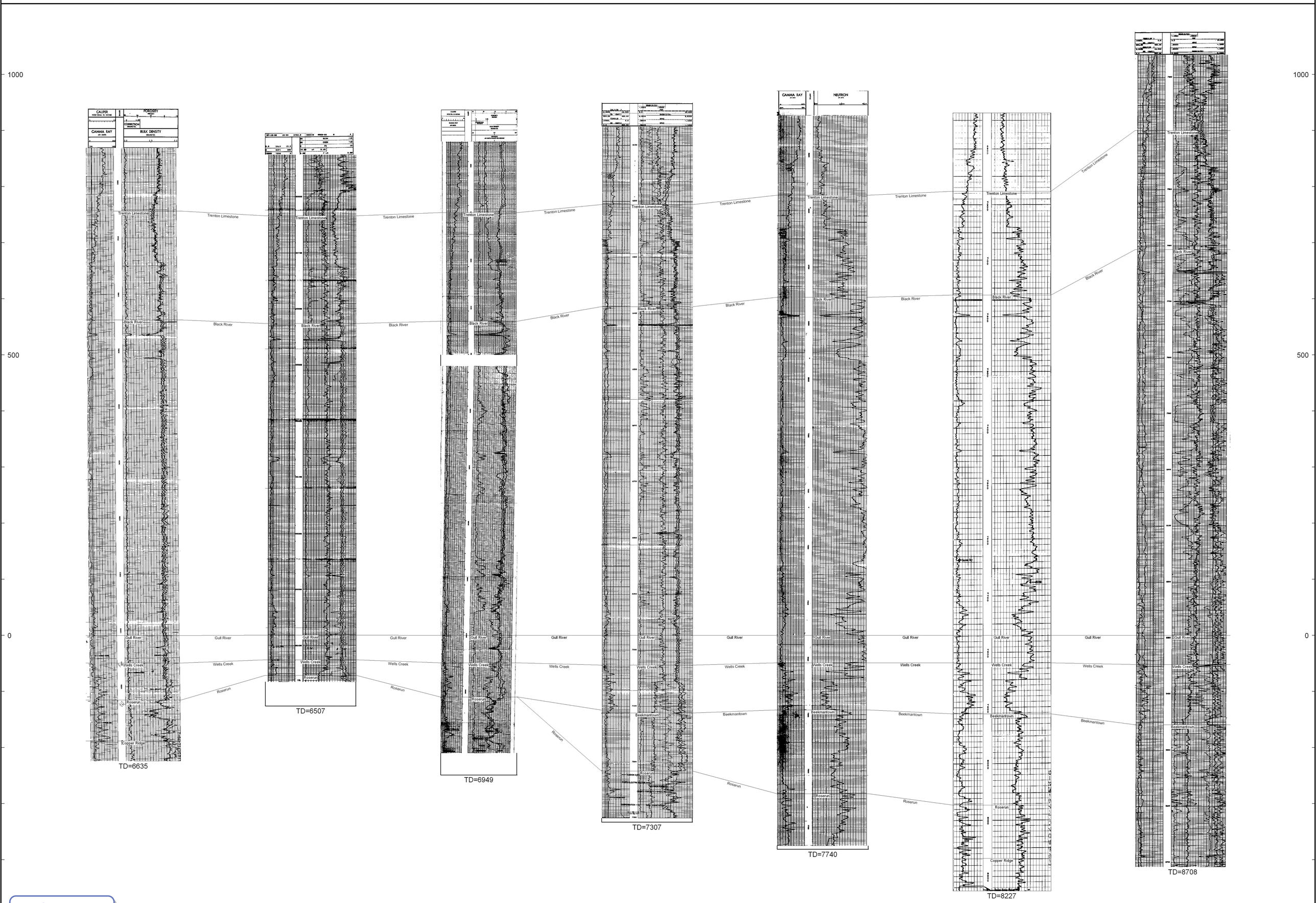
4546 ft

34157210300000 — STOCKER & SITLER INC
HUEBNER 2

50535 ft

34067208600000 — RED HILL DEVELOPMENT
PERKOWSI-BOND 2

Dip 1'



Go back

Tuscarawas County Site - Dip 2

Dip 2

34157211450000
XIT DIV. ALLIANCE MACHING CO
G.R. & T. ROWE 1

23337 ft

34157234470000
RED HILL DEVELOPMENT
E. C. BAHLER 1

15551 ft

34157247190000
RED HILL DEVELOPMENT
O. HUMERICKHOUSE 2

22087 ft

34157209550000
STOCKER & SITLER INC
MIZER UNIT 1

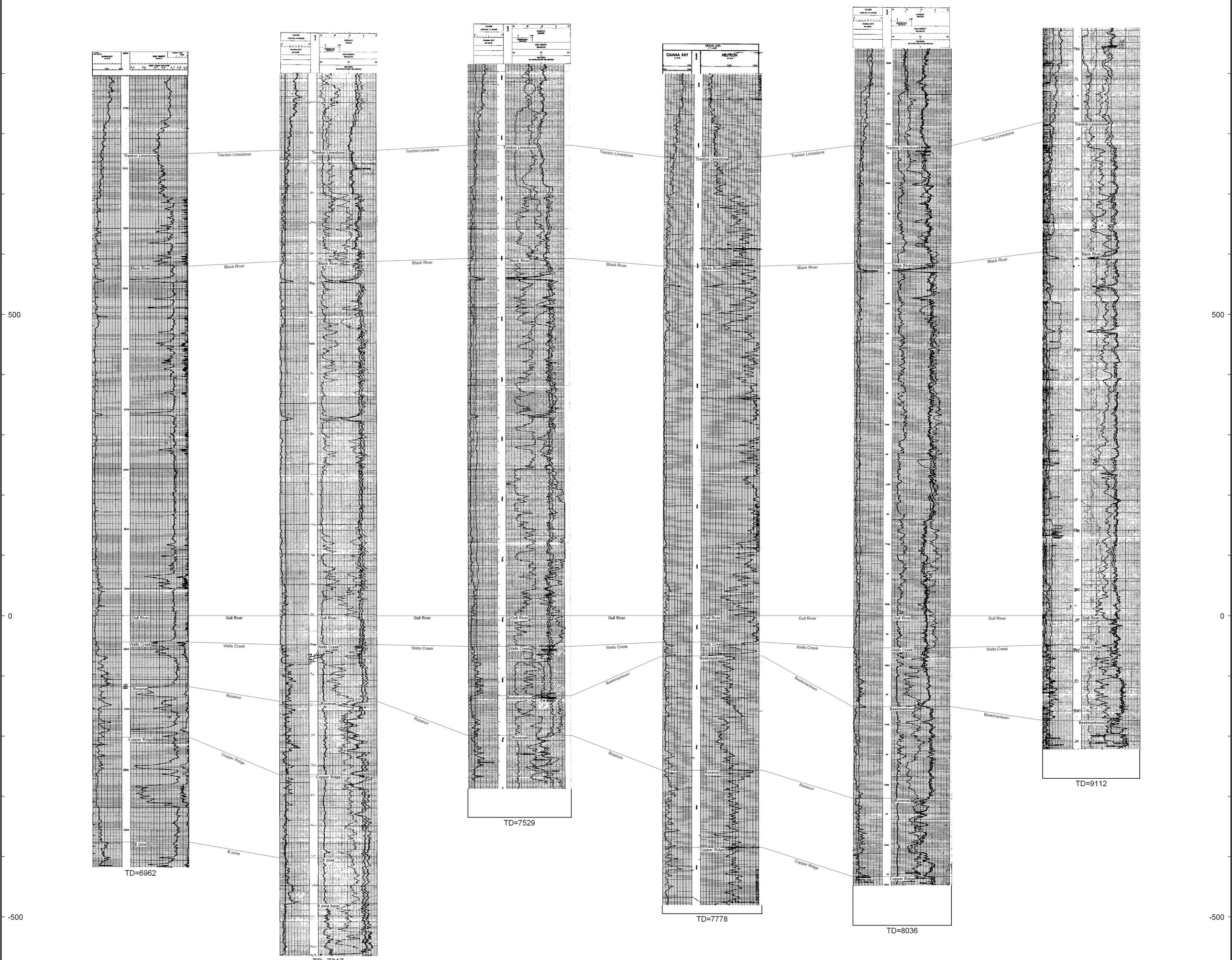
38406 ft

34157246690000
RED HILL DEVELOPMENT
INDUSTRIAL INVESTORS INC. 2

63975 ft

34067207770000
RED HILL DEVELOPMENT
D.C.JONES 7

Dip 2'



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Tuscarawas County Site - Dip 3

Dip 3

34031262530000
EASTERN STATES OIL & MYRON SCHEETZ UNIT 1

23587 ft

34031262010000
RED HILL DEVELOPMENT D.YODER 2

24886 ft

34031234950000
NGO DEVELOPMENT CORP L.T.REISS 1

23969 ft

34157247020000
RED HILL DEVELOPMENT E. FENTON 1

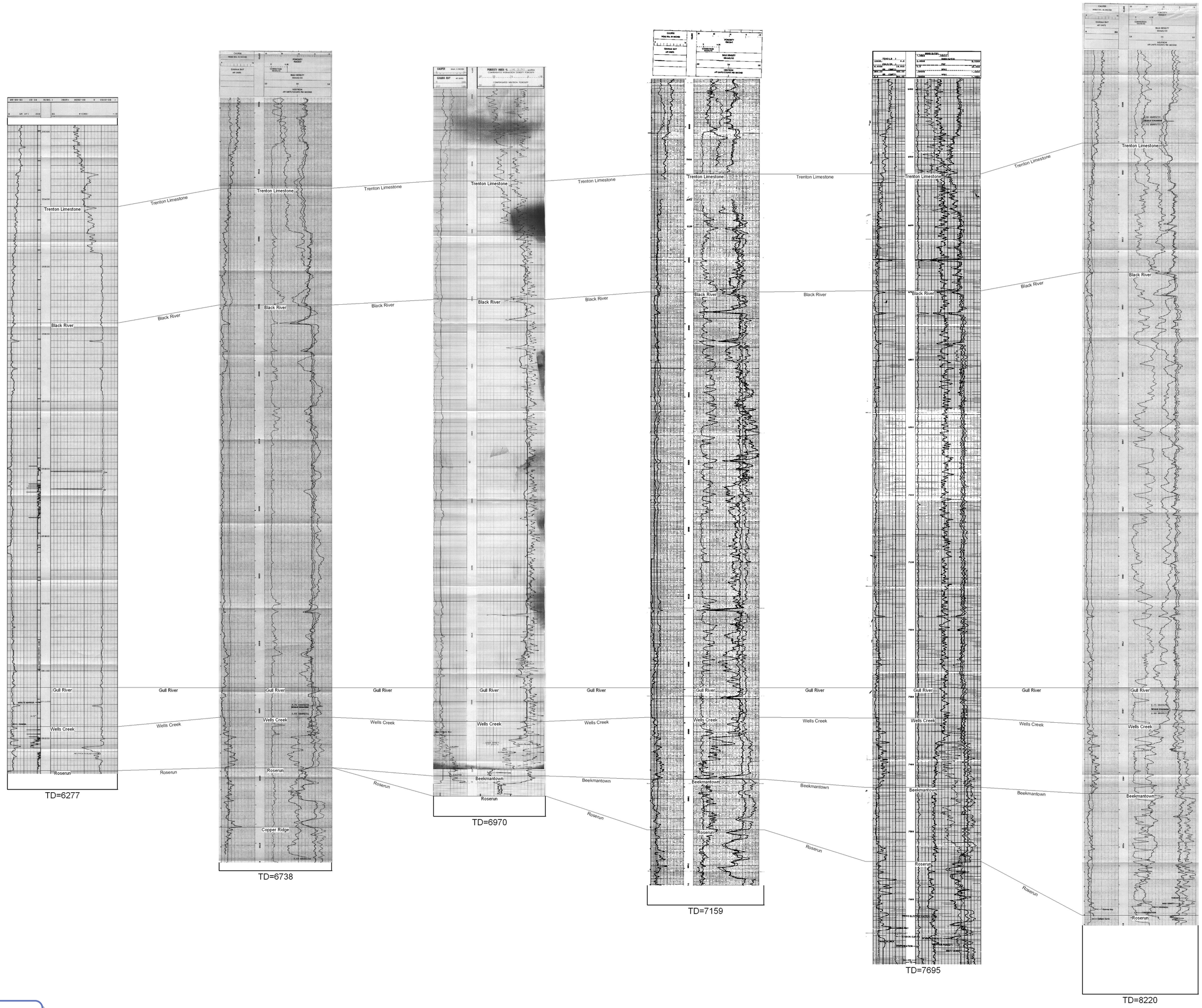
23255 ft

34157244650000
RESOURCE AMERICA INC K.WOLFF 1

36844 ft

34059237920000
RED HILL DEVELOPMENT GERALD LARRICK 1

Dip 3'



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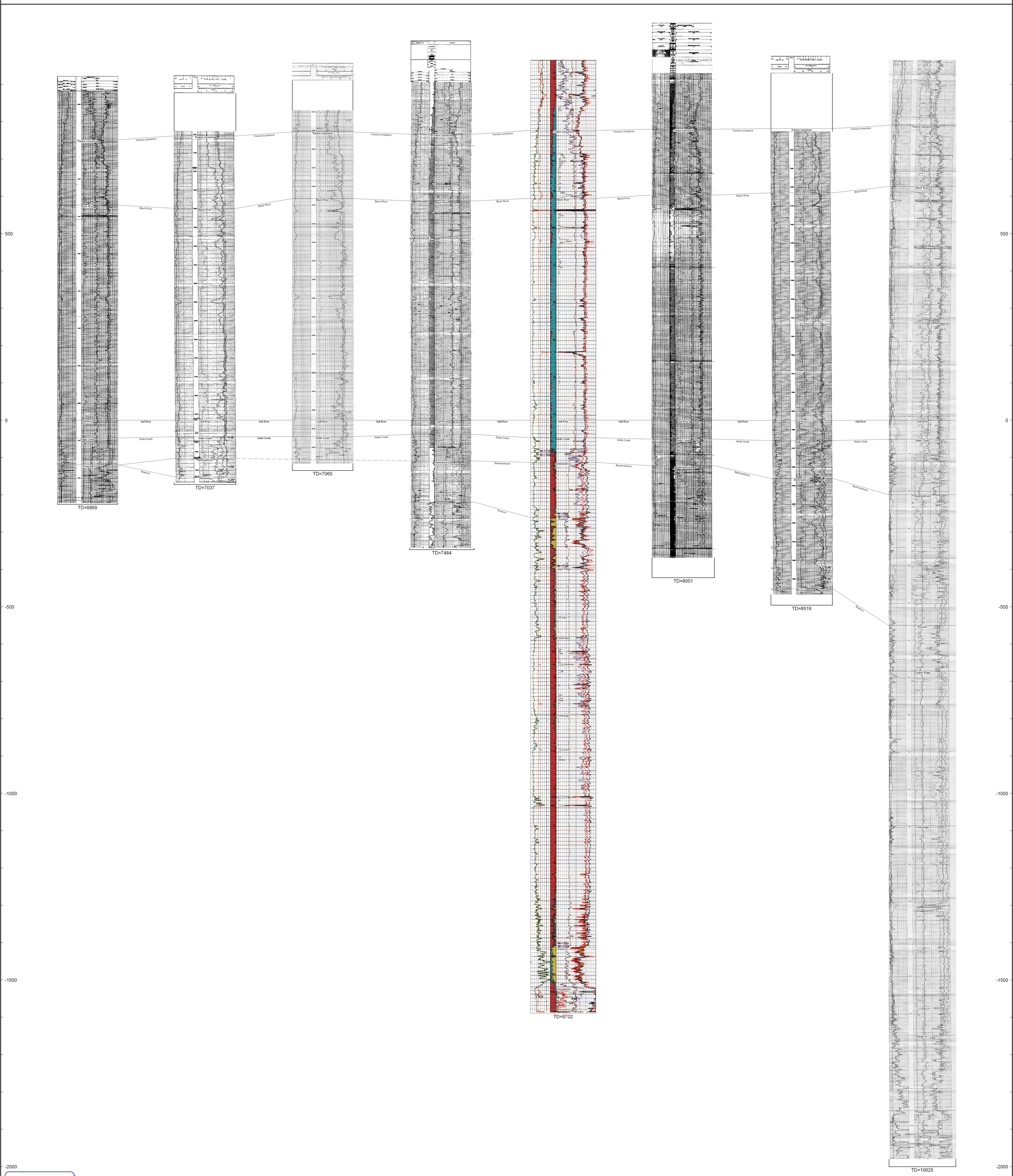
Tuscarawas County Site - Dip 4

Dip 4 — Dip 4'

34075247160000	15197 ft	34157249690000	18729 ft	34157228390000	11599 ft	34157249580000	20796 ft	34157253340000	31472 ft	34157249770000	29666 ft	34067209430000	43401 ft	34067207370000
ATWOOD RESOURCES INC L.HERSHBERGER 3		STOCKER & SITLER INC A YOUNGEN 1		TIPKA AW OIL & GAS I W.BEITZEL # 1 1		CGAS EXPLORATION W SCHUPP UNIT 3		BATTELLE OHIO GEOLOGICAL SURVEY CO2		KENOIL MCMILLEN JOHN # 1 1		KENOIL STEWART UNIT 5		RED HILL DEVELOPMENT T.ZECHMAN 1



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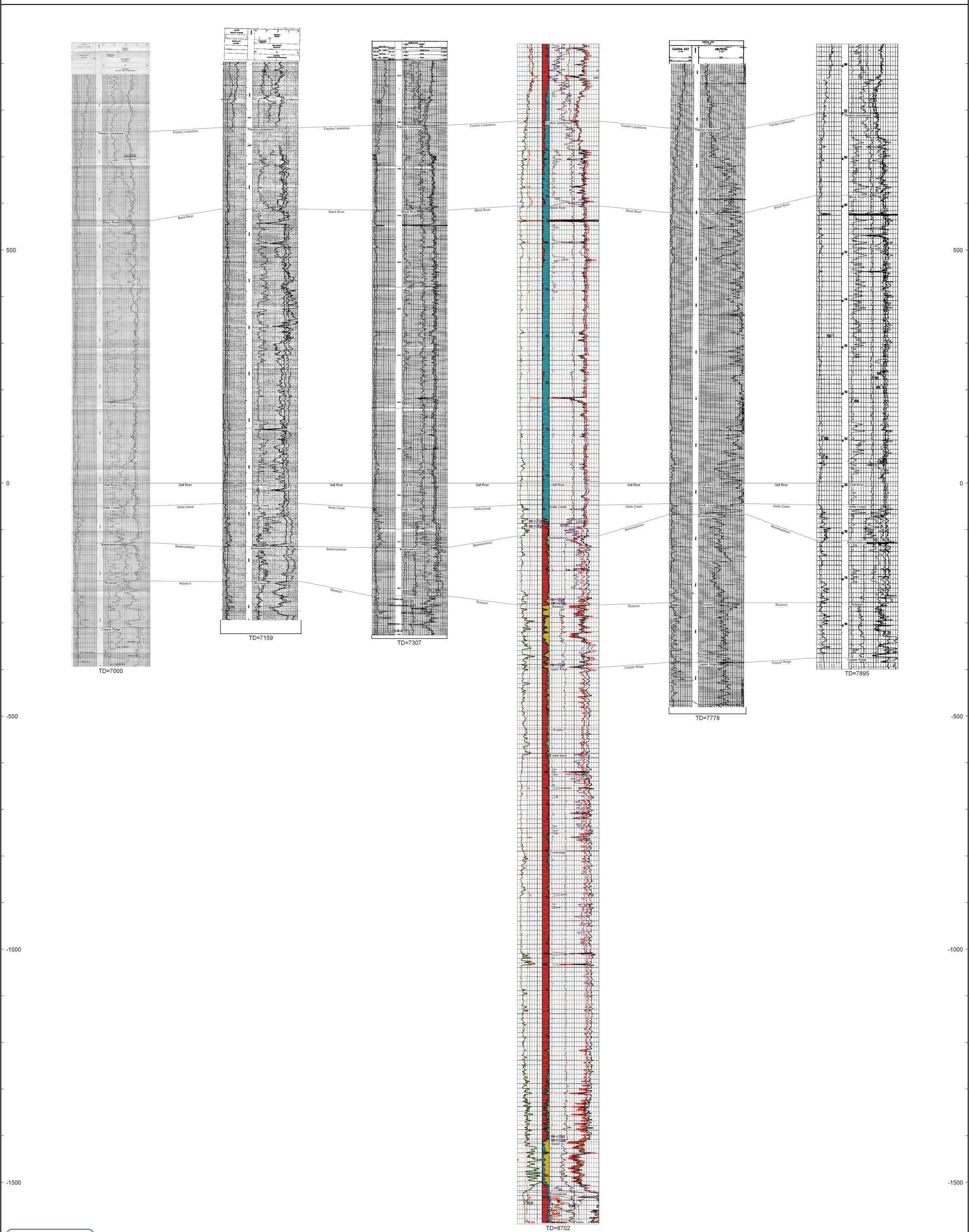
Tuscarawas County Site - Strike 1

Strike 1 — Strike 1'

34031260140000	20285 ft	34157247020000	24007 ft	34157245170000	15344 ft	34157253340000	15582 ft	34157209550000	43560 ft	34157250160000
RED HILL DEVELOPMENT J.WENTZ 3		RED HILL DEVELOPMENT E. FENTON 1		RANGE OPERATING COMP J.STOCKER ETAL UNIT 1		BATTELLE OHIO GEOLOGICAL SURVEY CO2		STOCKER & SITLER INC MIZER UNIT 1		EASTERN MOUNTAIN FUE SEIKEL 1



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Tuscarawas County Site - Shallow Dip 1

Dip 1

34075214170000 — YODER LEVI N N. & A.L. YODER 1

12484 ft

34075249260000 — LAKE REGION OIL INC JOHN E RABER UNIT 2

22134 ft

34157247050000 — RED HILL DEVELOPMENT BAAB-HERCHBERGER 2

55990 ft

34157245170000 — RANGE OPERATING COMP J.STOCKER ETAL UNIT 1

33848 ft

34157226400000 — NORTH COAST ENERGY INC CLUM ET AL UNIT

17366 ft

34157232250000 — LESLIE OIL & GAS CO., INC. GARDNER-TIDRICK

29208 ft

34067208600000 — RED HILL DEVELOPMENT PERKOWSI-BOND 2

Dip 1'

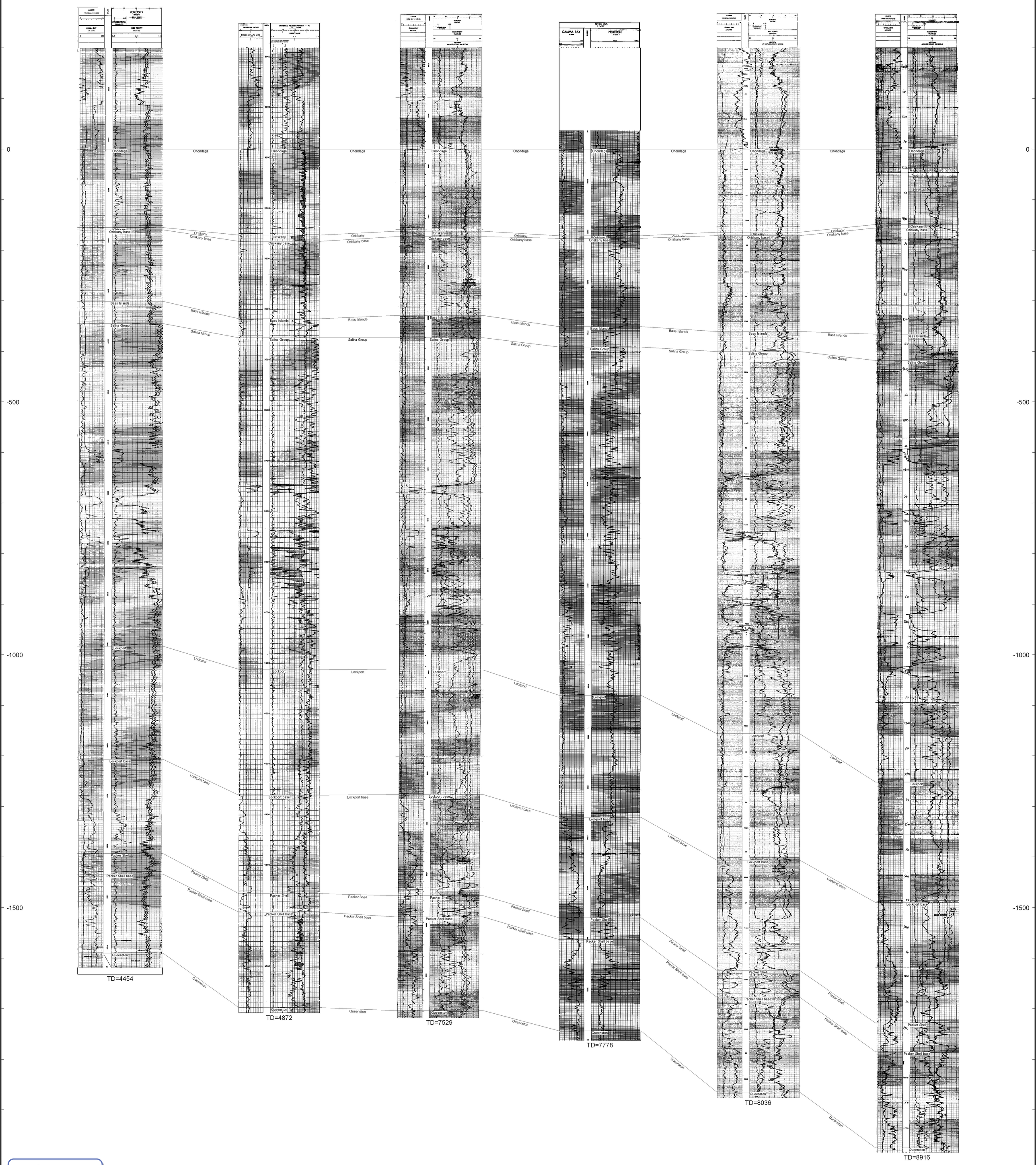
Go back

Tuscarawas County Site - Shallow Dip 2

Dip 2

34157219290000	23931 ft	34157240520000	13869 ft	34157247190000	22087 ft	34157209550000	38406 ft	34157246690000	44257 ft	34067207640000
BELDEN BRICK CO. BELDEN BRICK CO.		KNOX ENERGY INC. SECKEL		RED HILL DEVELOPMENT O. HUMERICKHOUSE 2		STOCKER & SITLER INC MIZER UNIT 1		RED HILL DEVELOPMENT INDUSTRIAL INVESTORS INC. 2		RED HILL DEVELOPMENT CLYDE VAN HORN 1

Dip 2



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Tuscarawas County Site - Shallow Dip 3

Dip 3 — Dip 3'

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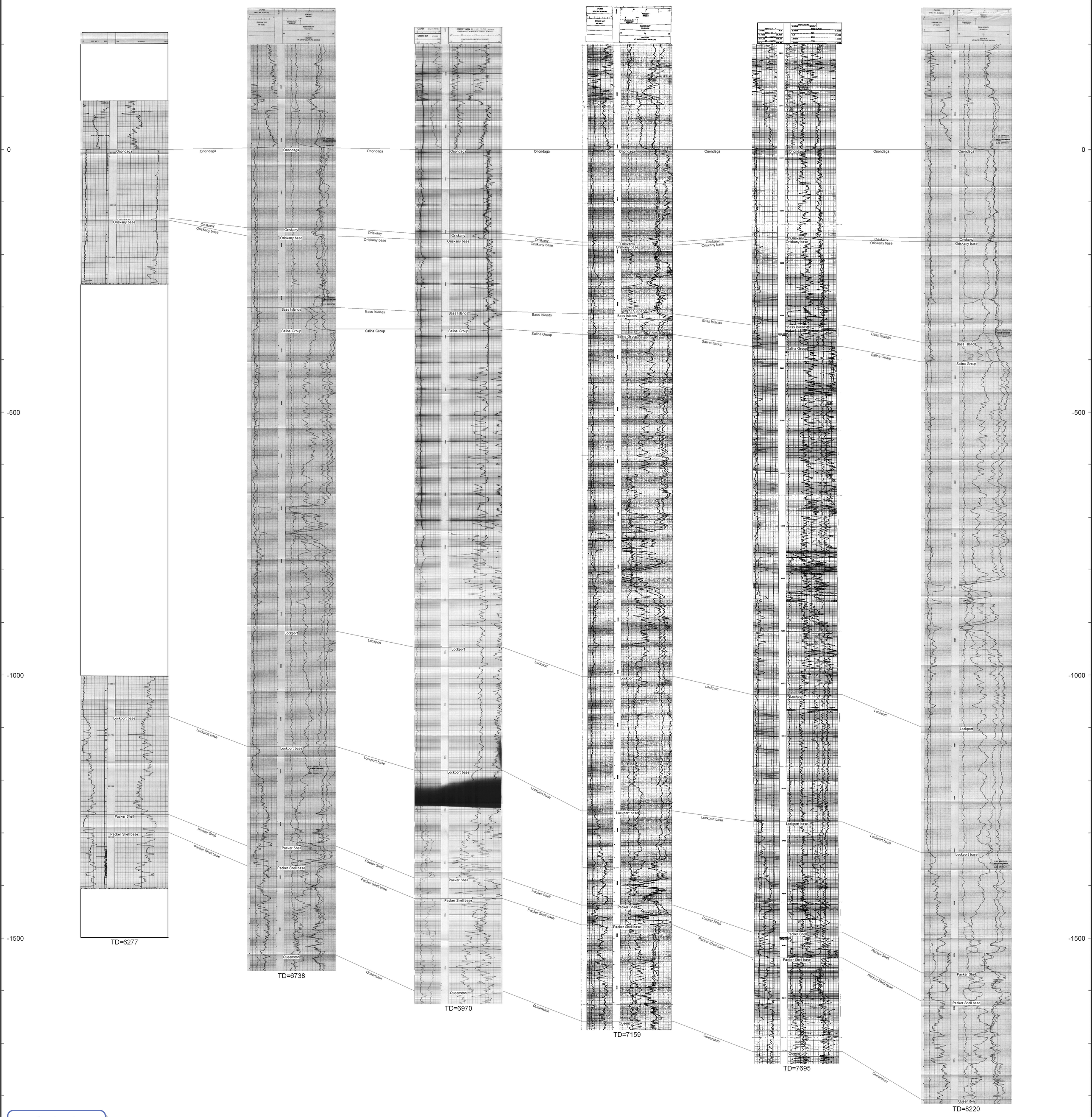
EASTERN STATES OIL & MYRON SCHEETZ UNIT 1		RED HILL DEVELOPMENT D.YODER 2		NGO DEVELOPMENT CORP L.T.REISS 1		RED HILL DEVELOPMENT E. FENTON 1		RESOURCE AMERICA INC K.WOLFF 1		RED HILL DEVELOPMENT GERALD LARRICK 1



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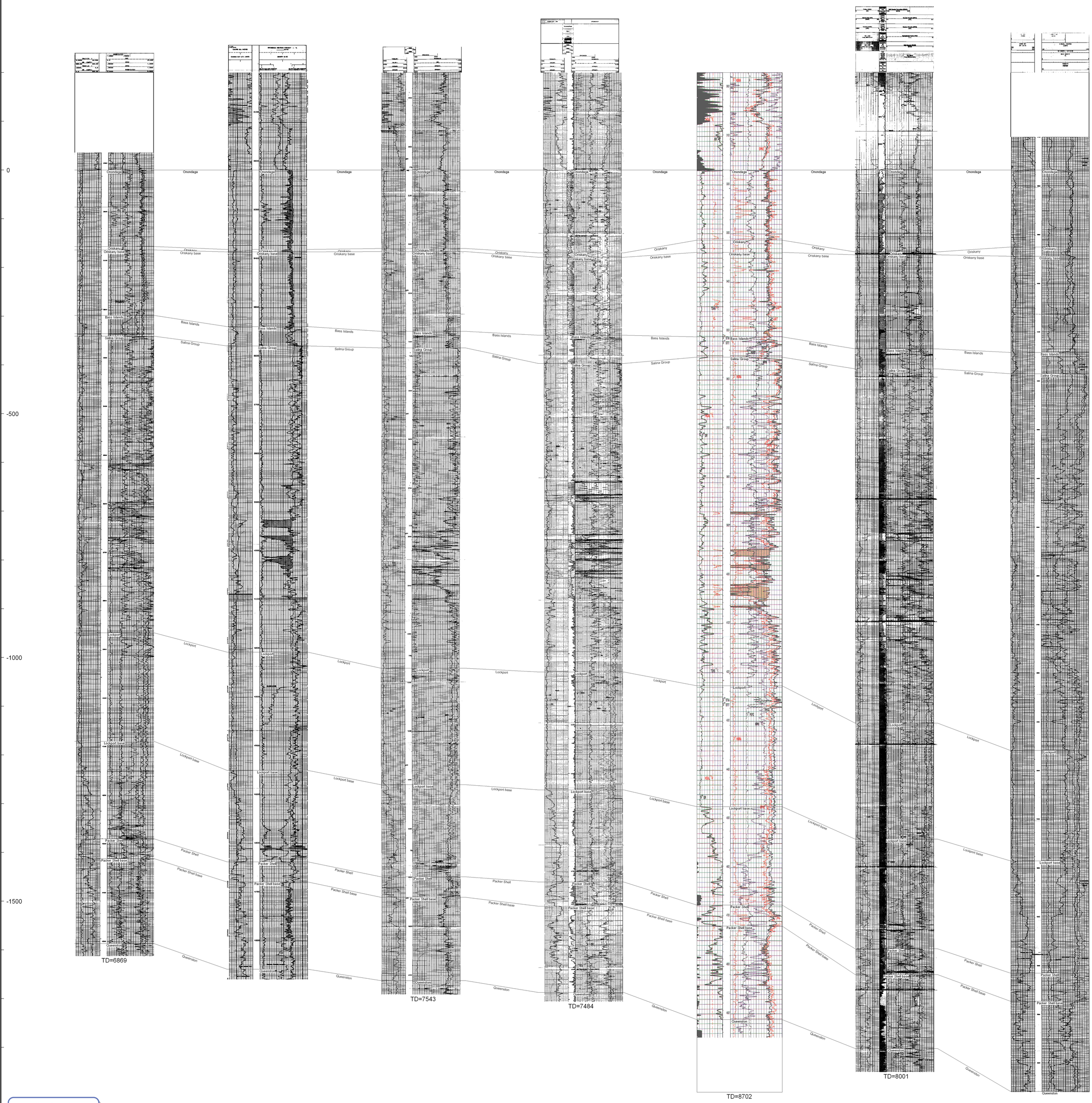
Tuscarawas County Site - Shallow Dip 4

Dip 4

34075247160000	18175 ft	34157235190000	21704 ft	34157248740000	7854 ft	34157249580000	20796 ft	34157253340000	31472 ft	34157249770000	21999 ft	34067208460000
ATWOOD RESOURCES INC L.HERSHBERGER 3		KNOX ENERGY DUMMERMUTH		SCION ENERGY, Inc. R & P LORENZ UNIT 2		CGAS EXPLORATION W SCHUPP UNIT 3		BATTELLE OHIO GEOLOGICAL SURVEY CO2		KENOIL MCMILLEN JOHN # 1 1		LANGASCO KIMBERLIN

Dip 4'



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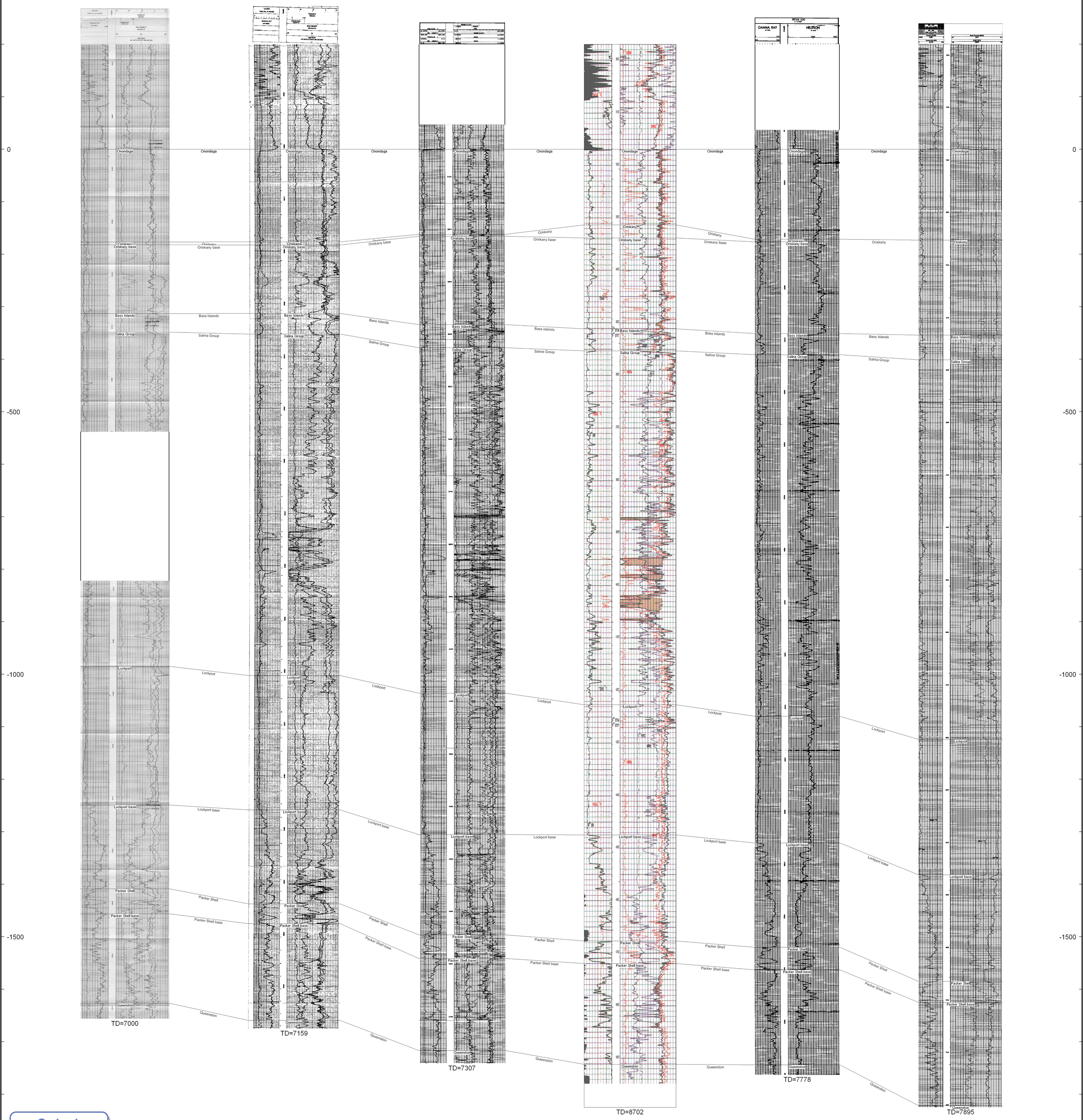
Tuscarawas County Site - Shallow Strike 1

Strike 1 — Strike 1'

34031260140000	20285 ft	34157247020000	24007 ft	34157245170000	15344 ft	34157253340000	15582 ft	34157209550000	43560 ft	34157250160000
RED HILL DEVELOPMENT J.WENTZ 3		RED HILL DEVELOPMENT E. FENTON 1		RANGE OPERATING COMP J.STOCKER ETAL UNIT 1		BATTELLE OHIO GEOLOGICAL SURVEY CO2		STOCKER & SITLER INC MIZER UNIT 1		EASTERN MOUNTAIN FUE SEIKEL 1



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