CarbonSAFE Illinois – Macon County
Final Report

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EXECUTIVE SUMMARY

CarbonSAFE Illinois – Macon County established that commercial-scale geologic storage of CO_2 is highly feasible in the central portion of the Illinois Basin. The objectives of the project are to evaluate the feasibility of geologic storage of 50 million tonnes of CO_2 over a 30-year time-frame, and to generate data and establish workflows to assist the development of commercial CCS. To realize these objectives the project conducted a series of data acquisition activities including drilling a stratigraphic test well, T. R. McMillen #2 (TRM2), in Christian County, IL to collect core and cuttings samples, wireline geophysical logs, and perform vertical seismic profile surveys. In addition, a 30 mi- (48 km-) long 2D seismic survey was performed to evaluate the regional structures and lateral continuity of reservoir and containment strata.

This report summarizes an extensive work package to present key activities and findings towards evaluating sites for geologic storage of CO_2. The project was undertaken as a series of tasks that addressed risk, stakeholder engagement, business and economic issues, permitting, drilling and well testing, geologic characterization, seismic surveys, modeling, CO_2 source suitability and infrastructure development. Detailed reports associated with these tasks are included as appendices to this report. Data generated by this project have also been uploaded to the NETL EDX data exchange site.

The Mt. Simon Storage Complex was the primary target for evaluating the potential for commercial-scale storage. This complex is comprised of the Mt. Simon Sandstone as the storage unit, and the Eau Claire Formation as the seal, or confining strata. Drilling of TRM2 well began October 29, 2018 concluded on December 12, 2018, after reaching a total depth of 6,478 ft (1,975 m) and encountering over 1,600 ft (488 m) of Mt. Simon Sandstone. Excellent quality reservoir rock was observed within the Mt. Simon Sandstone strata, particularly in the Lower Mt. Simon Sandstone, but also in other intervals within the formation. The Eau Claire Formation is regionally extensive and includes a thick shale sequence near its base in TRM2 and is an excellent seal to the reservoir.

Geophysical log interpretations and core descriptions were used to characterize the reservoir quality and identify depositional environments to formulate a conceptual model for the Mt. Simon Sandstone in this part of the Illinois Basin. The 2D seismic survey trended east-west and was tied into the TRM2 well. The seismic data indicates little structure in the region with some faults in the upper Precambrian potentially being present regionally. A basement high is observed west of TRM2 that may reduce the thickness of some of the Lower Mt. Simon strata. Extensive well testing confirmed the high quality of reservoir in the Lower Mt. Simon Sandstone at this location.

Dynamic modeling of a series of injection scenarios indicates that commercial-scale storage in the area of interest is highly feasible. The modeled scenarios included single and multiple well injection schemes including to address reaching 50 million tonnes (Mt) stored over 30 years, 20 Mt over 12 years, and 150 Mt over 30 years using 3 to 4 injection wells. The simulations determined CO_2 plume extent, pressure distribution and potential Area of Reviews. Reservoir heterogeneity within the storage complex influences movement of CO_2. The CO_2 plume migrates vertically and laterally up-dip within relatively higher permeability facies due to buoyancy. Low-permeability layers, such as observed in lower strata of the Middle Mt. Simon Sandstone retard vertical migration of the CO_2 plume. Using these reservoir variations as part of an injection strategy can potentially help minimize CO_2 plume and AoR size.

Options for CO_2 sources in the region were examined along with cost estimates for compression, transportation, and storage. An evaluation of the business environment in the region indicates that CCS projects would be viewed favorably as there is experience with CCS in the area. A stakeholder analysis highlighted concerns and views in the regional and did not identify concerns with CCS. The analyses also addressed high level environmental justice issues for Macon County. The SimCCS tool kit was used to evaluate existing infrastructure and options for expansion of networks for the region.

INTRODUCTION

The main objectives of the CarbonSAFE Illinois – Macon County project are to evaluate the feasibility of geologic storage of 50 million tonnes of CO_2 over a 30-year period in the central region of the Illinois Basin, and to generate data and establish workflows to assist the development of commercial CCS. A characterization site was initially selected in Macon County, but was shifted to northern Christian County, Illinois (Figure 1), where a stratigraphic test well, T. R. McMillen #2 (TRM2), was drilled to collect site-specific data including rock cores, fluid samples, geophysical logs, vertical seismic profiles, and information regarding reservoir behavior determined by *in situ* formation testing. Additionally, about 30 mi (48 km) of 2D seismic data was collected for the study. These data were integrated with other regional data including information gathered from other CCS studies in the Illinois Basin to perform the evaluation of suitability and feasibility for commercial-scale geologic storage in the region. The Mt. Simon Sandstone was the main targeted storage reservoir, with the overlying Eau Claire Formation being the primary confinement strata; together these Cambrian-aged units form the Mt. Simon Storage Complex in the Illinois Basin.

Figure 1. Regional location of CarbonSAFE Illinois Macon County project study area within the Illinois Basin.

In addition to geological characterization, the project conducted stakeholder analyses including an examination of environmental justice for the region. The business environment for commercialization of CCS in the region was described along with an evaluation of existing regulations and policies that impact CCS development in Illinois.

An assessment of regional CO_2 sources and infrastructure was performed and investigated several sources of CO_2 in proximity to the project site including at the Archer Daniels Midland facility (approximately 1 million tonnes annually [Mta] of CO_2 from ethanol production) in Decatur, IL, the Abbott Power Plant (about 0.4 Mta CO_2 from coal) at the University of Illinois in Champaign, IL, and the City Water Light and Power plant (about 1.6 Mta CO_2 from coal) in Springfield, IL. During the project, other potential sources were identified and evaluated for the cost of transporting CO_2 to the potential storage site.

The work presented in this Final Report is derived from a number of technical reports and focused studies conducted by the project team over the course of the project. This report presents key activities, findings, and results from the various tasks within the project with reference to the fuller discussion of the work within the respective technical reports. The technical reports are included as appendices to this document.

Funding for the CarbonSAFE Macon County project was issued by the U. S. Department of Energy (U. S. DOE) under Cooperative Agreement Number DE-FE0029381. The Illinois State Geological Survey (ISGS) of the University of Illinois at Urbana-Champaign was the Prime Awardee, and project Subwardees included the Indiana Geological and Water Survey (IGWS), Pacific Northwest National Laboratory (PNNL), Richland Community College (RCC), Brigham Young University (BYU), Trimeric Corporation, Projeo Corporation, University of Wyoming (UW), and Industrial Economics (IEc). A project advisory board consisted of Archer Daniels Midland Co., the Decatur Park District, Podolsky Oil Company, and City Water Light and Power of Springfield, Illinois (Figure 2).

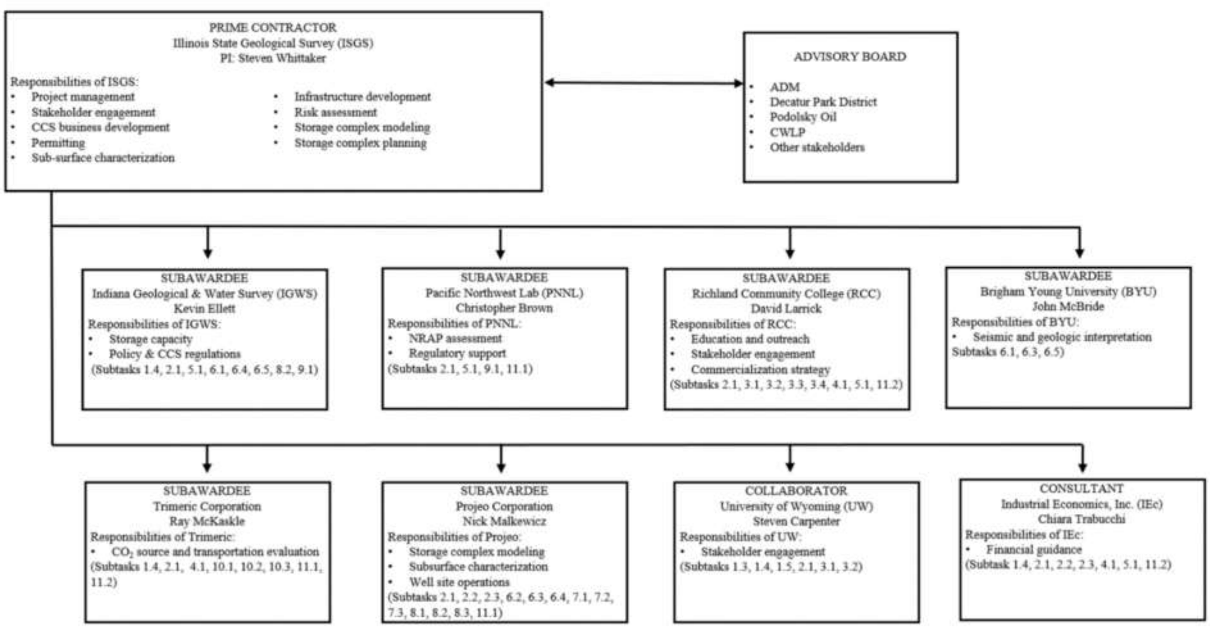

Figure 2. Organizational structure of the CarbonSAFE Illinois Macon County project.

DRILLING AND WELL DATA COLLECTION

Data was generated by the CarbonSAFE Illinois – Macon County project through the well drilling operations of TRM2 (Figure 3; Figure 4), including collection of whole core and rotary sidewall core (RSWC) in multiple key formations, acquisition of extensive geophysical logs, laboratory analysis of reservoir and caprock characteristics, geomechanical testing of both core types, fluid sampling, and *in situ* well testing. Approximately 30 mi (48 km) of 2D seismic surveys and a walkaway VSP were also conducted for the project. A detailed list of data collected by the project is provided in the *CarbonSAFE Macon County Data Catalog* (Appendix A).

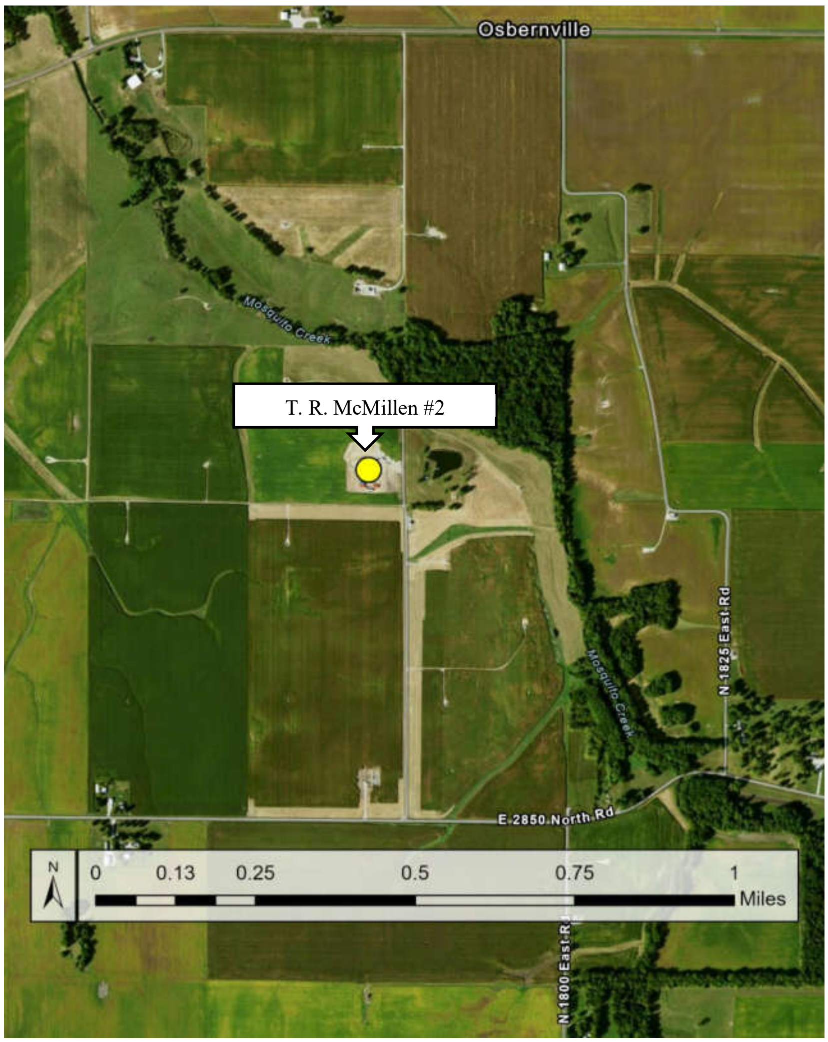

Figure 3. TRM2 well site

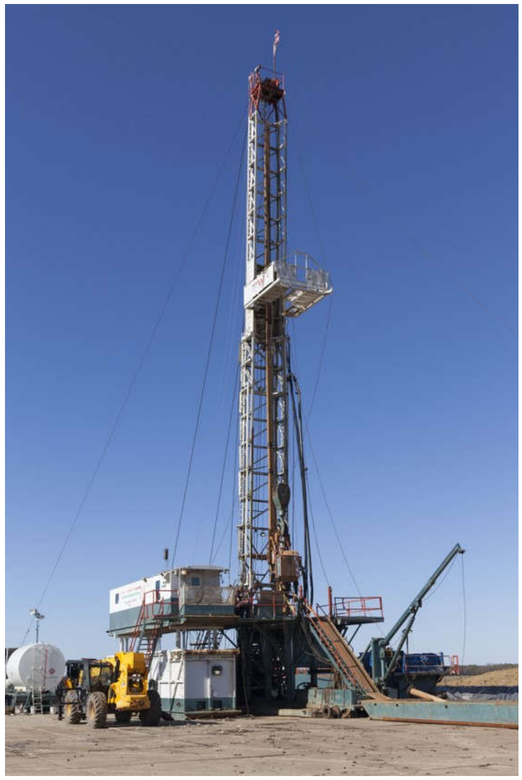

Figure 4. Drilling operations at T.R. McMillen #2

Well location and Drilling Operations

Characterization of the CarbonSAFE Macon County project area included drilling, completion, testing, of a stratigraphic test well TRM2. The well was located near the village of Mount Auburn, IL, in Section 04, Township 15, Range 01W of Christian County (Figure 5). The well was installed in a closed loop pad at latitude 39.772784°N and longitude 89.203412°W. The lower portion of the well was plugged and is being converted to an oil production well from Silurian strata.

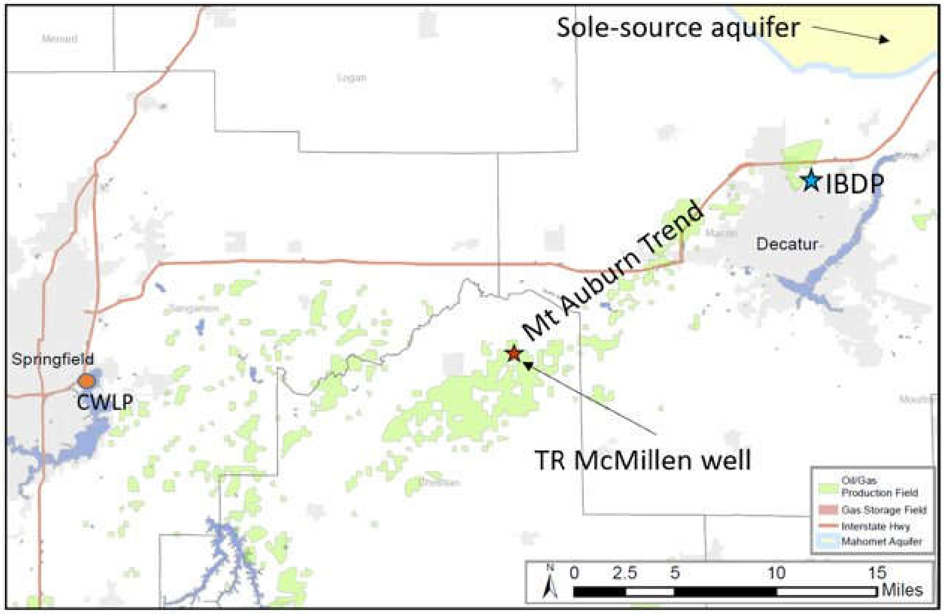

Figure 5. Sub-regional location of the TRM2 well, southwest of the Illinois Basin – Decatur Project (IBDP) carbon storage site in Decatur, Illinois

The TRM2 drilling permit was issued by the Illinois Department of Natural Resources (IDNR) Division of Oil and Gas on August 17, 2018 (API 120212565). Site preparation for drilling activities began on September 26, 2018, and drilling operations commenced on October 29, 2018. Surface, Intermediate, and Production casings were set at depths of 257 ft (78 m); 4,353 (1,327 m); and 6,477 ft (1,975 m), respectively. Well drilling and completion operations were concluded on December 12, 2018, after reaching a total depth of 6,478 ft (1,975 m). Time vs Depth for drilling TRM2 is shown in Figure 6.

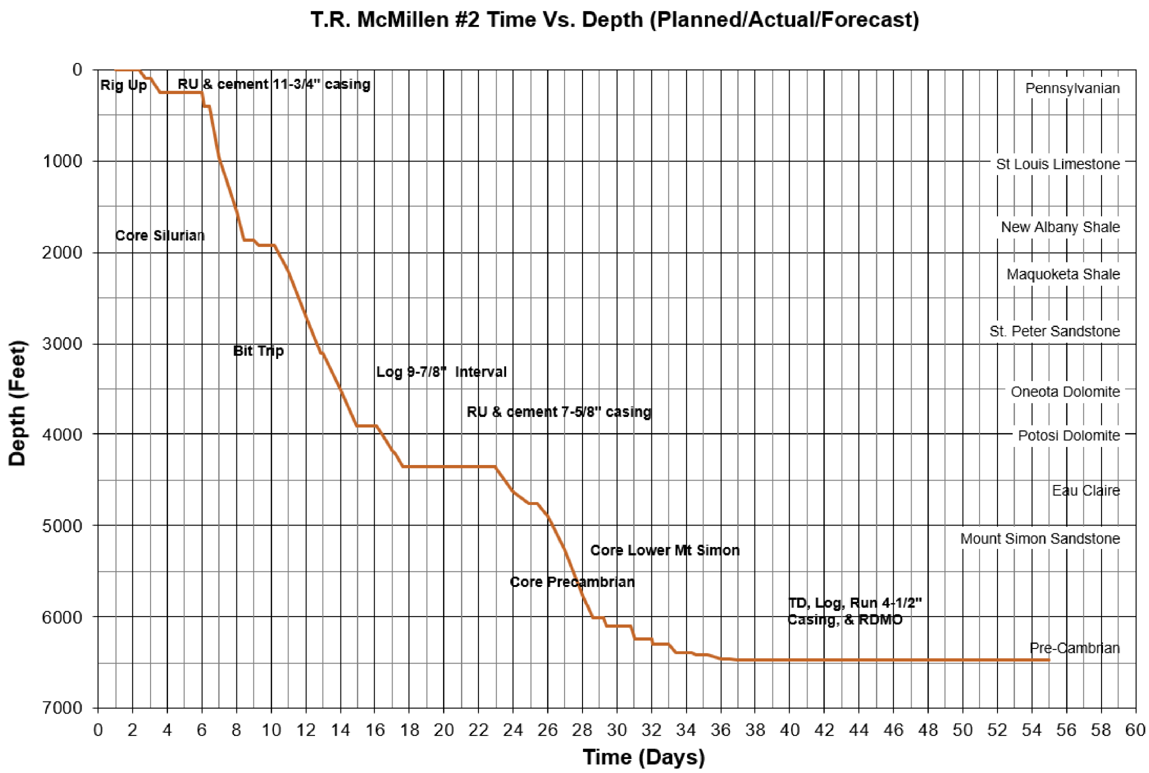

Figure 6. Drilling operations timeline at the TRM2 well

A full description of well drilling and data collection operations is detailed in Appendix B, *Drilling and Completion Report TR McMillen Well #2: from CarbonSAFE Illinois – Macon County* (Armstrong and Habel, 2020).

Core Samples and Geophysical Logging

During drilling, cuttings collection and mudlogging on the TRM2 well commenced at a depth of 1,500 ft (547 m) MD and continued to well TD. The formation tops are presented in Table 1. Three intervals were cored for full diameter core and are listed in Table 2. In addition to whole core, 108 one-inch diameter rotary sidewall cores (RSWC) were recovered during post-drilling logging operations from the Potosi Dolomite through the Precambrian basement.

Table 1. Selected tops and measured depths (MD, ft) from the TRM2 well, Christian County, IL.

Formation	Top (MD ft)
Pennsylvanian	365
Barlow Limestone	729
Paint Creek	810
Aux Vases Sandstone	871
St Louis Limestone	996
Warsaw Shale	1,202
Chouteau Limestone	1,700
New Albany Shale	1,710
Devonian	1,863
Racine	1,873
Joliet	2,012
Maquoketa Shale	2,209
Trenton Limestone	2,395
St. Peter Sandstone	2,832
Shakopee Dolomite	3,054
New Richmond Sandstone	3,584
Oneota Dolomite	3,598
Eminence Dolomite	3,904
Potosi Dolomite	4,029
Franconia Dolomite	4,292
Ironton-Galesville	4,576
Eau Claire	4,694
Mount Simon Sandstone	5,200
Pre-Cambrian	6,814

Table 2. Full diameter core recovered during drilling of the TRM2 stratigraphic test well

Formation Name	Depth From (ft)	Depth To (ft)	Core Recovered (ft)	Run Order No.
New Albany/Racine	1,863	1,924.8	61.80	1
Mt. Simon (Lower A)	6,240	6,300	61.00	2
Precambrian	6,391	6,410	19.43	3
Precambrian	6,462	6,468	7.15	4

The ISGS and Core Laboratories performed routine analyses on whole core and rotary sidewall core (RSWC) recovered from TRM2 to characterize and evaluate the site-specific reservoir and seal properties of the Mt. Simon Storage Complex and augment regional characterization of those units. These analyses included testing for porosity, horizontal permeability, vertical permeability, bulk density, X-Ray Diffraction (XRD), net confining stress, pressure decay profile permeameter testing, and grain density. Schlumberger Reservoir Laboratory performed geomechanical testing on selected sample from TRM2, including Brazil Tensile Strength, Triaxial Compression, and Ultrasonic Velocity Measurement tests (3) (Table 3). The Department of Civil Engineering and Environmental Engineering at the University of Illinois at Urbana-Champaign performed additional geomechanical tests for index properties, hydromechanical properties, ultrasonic velocities, and uniaxial and conventional triaxial compression. Detailed results of laboratory testing are available in the *CarbonSAFE Macon County Data Catalog*, Appendix A.

A full suite of geophysical logs were collected at the TRM2 well and are presented in Table 4. Further details on well logging are found in Appendix C, *Report of Geology from the T. R. McMillen #2 Well Drilled for CarbonSAFE Illinois – Macon County* (Freiburg et al., 2022). A panel of selected geophysical logs collected is shown along with depths of core analyses in Figure 7.

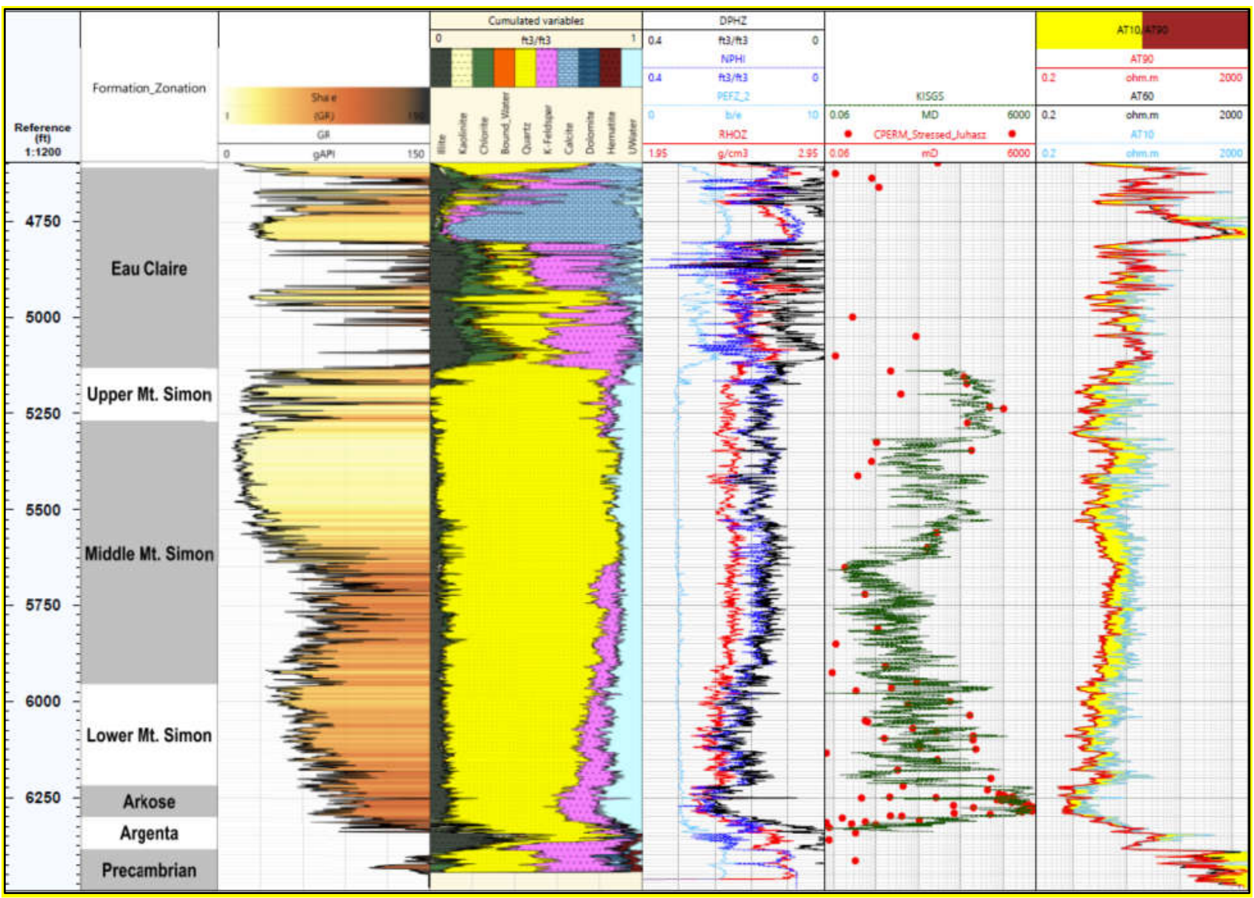

Figure 7. Geophysical log traces over the Mt. Simon Storage Complex. Traces shown include gamma ray, mineral content, neutron porosity and density, calculated permeability with core analyses (red dots), and resistivity. Interpreted stratigraphic zonation is listed on the left column.

Table 3. Reference table for rock mechanical tests performed by Schlumberger Reservoir Laboratory for TRM2

Sample ID	Sample Depth (ft)	Orientation	Bulk Density as received (g/cc)	TEST TYPE	Test Type Reference
5189-1	5190.04	Load applied normal to bedding	2.197	Brazil	Unconfined Compression Test (UCS)
6133-1	6133.97	Load applied normal to bedding	2.226	Brazil	Triaxial Compression Test (TXC)
6240-1	6240.00	Vertical	1.912	MTXC; UV	Ultrasonic Velocity Measurement (UV)
6248-1	6248.00	Vertical	2.175	MTXC; UV	Multiple Stress-path Compression Test (MSC)
*6250-1	6250.00	Vertical	1.901	MTXC; UV	Multi-stage Triaxial Compression Test (MTXC)
6319-1	6320.07	Load applied normal to bedding	2.313	Brazil	Brazilian/Indirect Tensile Strength Test (BRAZIL)
					Fracture Toughness Model (FT)

Table 4. Well logs collected for TRM2

Well Section	Log Type	Bottom Depth (ft)	Top Depth (ft)	Company
Surface	None	-	-	N/A
Intermediate	Triple Combo (Induction, Neutron, Density, Gamma Ray, Microlog, Spontaneous Potential, Mud Resistivity)	3904.5	257	Schlumberger
	Directional Survey	3904.5	257	Schlumberger
	Formation Images	3904.5	257	Schlumberger
	Caliper (1 axis and 2 axis)	3904.5	257	Schlumberger
	Dipole Sonic (Compressional and Shear)	3904.5	257	Schlumberger
	Temperature	3904.5	257	Schlumberger
	Cement Bond Log / Variable Density Log	0.0	4,331	Wayne County
	Casing Collar Locator	0.0	4,331	Wayne County
	Ultrasonic Cement Bond Log	100	2,100	Weatherford
	Cement Bond Log / Variable Density Log	17	2,100	Weatherford
TD	Triple Combo (Induction, Neutron, Density, Gamma Ray, Microlog, Spontaneous Potential, Mud Resistivity)			
	Directional Survey	4,353	6,475	Schlumberger
	Formation Images	4,353	6,475	Schlumberger
	Caliper (1 axis and 2 axis)	4,353	6,475	Schlumberger
	Dipole Sonic (Compressional and Shear)	4,353	6,475	Schlumberger
	Sonic Cased Hole		6,475	Schlumberger
	Sonic Mechanical Properties	4,353	6,475	Schlumberger
	Temperature	3,750	6,475	Schlumberger
	Cement Bond Log / Variable Density Log	0	6,434	Wayne County
	Casing Collar Locator	0	6,434	Wayne County
	Magnetic Resonance	4,353	6,475	Schlumberger
	Elemental Capture Spectroscopy	3,900	6,475	Schlumberger
	Natural Gamma Ray Spectroscopy	3,900	6,475	Schlumberger
	Sidewall Cores (108)	4,353	6,475	Schlumberger
	Zero Offset Vertical Seismic Profile	1.6	6,350	Exoduas / Sigma Cubed
	Walkaway Vertical Seismic Profile	493.7	6,350	Exoduas / Sigma Cubed
	Ultrasonic Cement Bond Log	4,000	6,430	Weatherford
	Cement Bond Log / Variable Density Log	5,000	6,430	Weatherford
	Elemental Analysis Processing	4,353	6,475	Schlumberger
	1D Mechanical Earth Model	4,353	6,475	Schlumberger

VSP

A Vertical Seismic Profile (VSP) was conducted on the well using geophones set at 60 levels with a crane hoisting the cable and geophones from February 19 to 21, 2019. Two vibroseis trucks were used during the survey.

Well Testing and Completion Operations

In Situ Formation Testing

As part of TRM2 drilling and completion program the ISGS designed, conducted, and analyzed production and injection testing of the Eau Claire, Mt. Simon, and Precambrian formations (Table 5). Multiple single-well, multirate well tests of TRM2 were conducted between June 7, 2019, and October 31, 2019. These included Step Rate Tests (SRT), Vertical Interference Tests (VIT) or Pulse Tests (PT), Pressure Falloff Tests (PFO), and Pressure Buildup Tests (PBU). Minifrac Tests (MFT) were attempted but either failed or gave no results differing from other tests and were not included in the final well testing report.

Multiple single-well, multirate well tests of the TRM2 were conducted between June 7, 2019, and October 31, 2019. These included Step Rate Tests (SRT), Vertical Interference Tests (VIT) (or Pulse Tests, PT), Pressure Falloff Tests (PFO), and Pressure Buildup Tests (PBU). (Minifrac tests [MFT] were attempted but either failed or gave no results differing from other tests and are not included in this report.) The pre-frac steps of each SRT can be analyzed as a Multirate test (MRT) but are representative of very near-wellbore characteristics. All analyses require formation pressure (i.e., bottomhole pressure, bhp) and flow rate (injection and production) data measurements.

The test program was designed for permeability, initial pressure, fracture gradient, and any large-scale geologic features affecting rate and pressure. VITs were used to determine vertical communication and vertical permeability between perforated intervals above (AZ) and/or below (BZ) the injection zone (IZ). SRTs were used to determine fracture gradient. PFO tests were used for permeability, initial pressure, and large-scale geologic features. Multirate tests (MRT) were used for permeability when other analyses were inconclusive.

Porous and permeable test intervals were chosen based on project interest, porosity logs, permeability estimates (from core and permeability transform), cement bond logs, and formation microimager (FMI) logs. Small, 5-ft (1.5 m) perforated intervals were chosen for all tests; this allowed use of smaller volume pumps that were lower in cost and afforded week-long tests for each injection test interval. Moreover, a 5-ft (1.5 m) perforated interval into a much larger test interval causes a partial penetration pressure transient effect that can be analyzed for vertical permeability within the test interval (Table 5). (Note that vertical interference testing was designed to record data that could be analyzed for vertical permeability between perforated intervals.)

Table 5. Summary of test intervals. Because of uncertainty in well log measurements in crystalline basement rock, the perforated interval and test interval were equal.

Formation Name	Abbreviation	Perforation interval, ft	Test interval depth and thickness, ft	Average porosity from log (%)
Eau Claire	EC	5,098-5,103 5.0	5,098-5,103 5	8.0
Mt. Simon E	MtSE	5,190-5,195 5.0	5,175-5,219 44	13.4
Mt. Simon A2	MtSA2	6,219-6,224 5.0	6,193-6,250 47	20.2
Mt. Simon A1	MtSA1	6,260-6,265 5.0	6,252-6,300 48	23.8
Precambrian 2	PC2	6,370-6,375 5.0	6,363-6,386 23	~5
Precambrian 1	PC1	6,415-6,420 5.0	6,387-6,420 33	~3

After the test interval was perforated, so that each test could start at near initial pressure, no swabbing (i.e., fluid production) was done. Consequently, the first injection into each perforated interval was expected to have low communication initially with the test interval. The exception was MtSA2, which first had a production (or flowing) test before its injection test. For short-term tests (SRT and VIT), a liquid-filled tubing string was desirable to reduce wellbore storage (WBS) effects and increase discernable reservoir pressure response from each test. As such, for test intervals that could not support test brine to surface following overnight or longer shut-ins, additional test brine was added to the tubing under no direct pressure, so that the bottomhole pressure increase was due to increase in hydrostatic head of test brine and not increase in pressure due to resistance of test fluid entering the perforated interval. The addition of test brine to fill the injection tubing is identifiable on pressure-time graph as a linear increase in pressure vs. time, as the hydrostatic head of test brine increases pressure without additional increase due to resistance of the test interval.

A mixture of Mt. Simon brine (9.3 lb/gal) and freshwater (8.3 lb/gal) was used as the test brine. The mixed density was measured as 8.6 lb/gal. The Mt. Simon brine density and salinity were 9.3 lb/gal and salinity of 180,000 ppm, respectively. Using measured density of each fluid, a 30-70 mixture of brine-freshwater was calculated. Based on this mixture, a salinity of 54,300 ppm was estimated. All injection tests used a mixture of freshwater and Mt. Simon brine.

To acquire VIT data during each injection test, memory gauges were placed outside of the tubing string for AZ testing and below a retrievable bridge plug for BZ testing. The IZ test data was from surface readout electric line gauge and an IZ memory gauge placed outside of the tubing string (Figure 8).

Because the testing program for each test interval included an SRT and/or MFT that was designed to induce a small vertical fracture, it is possible that VITs for adjacent perforated intervals may not follow the principle of reciprocity. In other words, the k_v/k_h between two intervals may be different because for the first VIT, the fracture may not exist, and for the second VIT, the fracture may exist. Therefore, the chronological order of the intervals tested is important (Table 6).

Table 6. Chronological order of TRM2 well testing

Testing order	Test Intervals	Injection / Production
1	MtSA2	Production
2	MtSE	Injection
3	EC	Injection
4	MtSA1	Injection
5	MtSA2	Injection
6	PC2	Injection
7	MtSA1-A2	Test fluid disposal (injection)

A detailed description of the testing operations is provided in Appendix D, *Well Testing Operations for T. R. McMillen #2 Drilled in CarbonSAFE Illinois – Macon County* (Malkewicz, 2020) and a discussion of the analyses is presented in Appendix E, *Analyses of Well Testing at TR McMillen#2 Drilled in CarbonSAFE Illinois – Macon County* (Frailey, 2021). A summary of the results and petrophysical properties for each test interval is shown in Table 7.

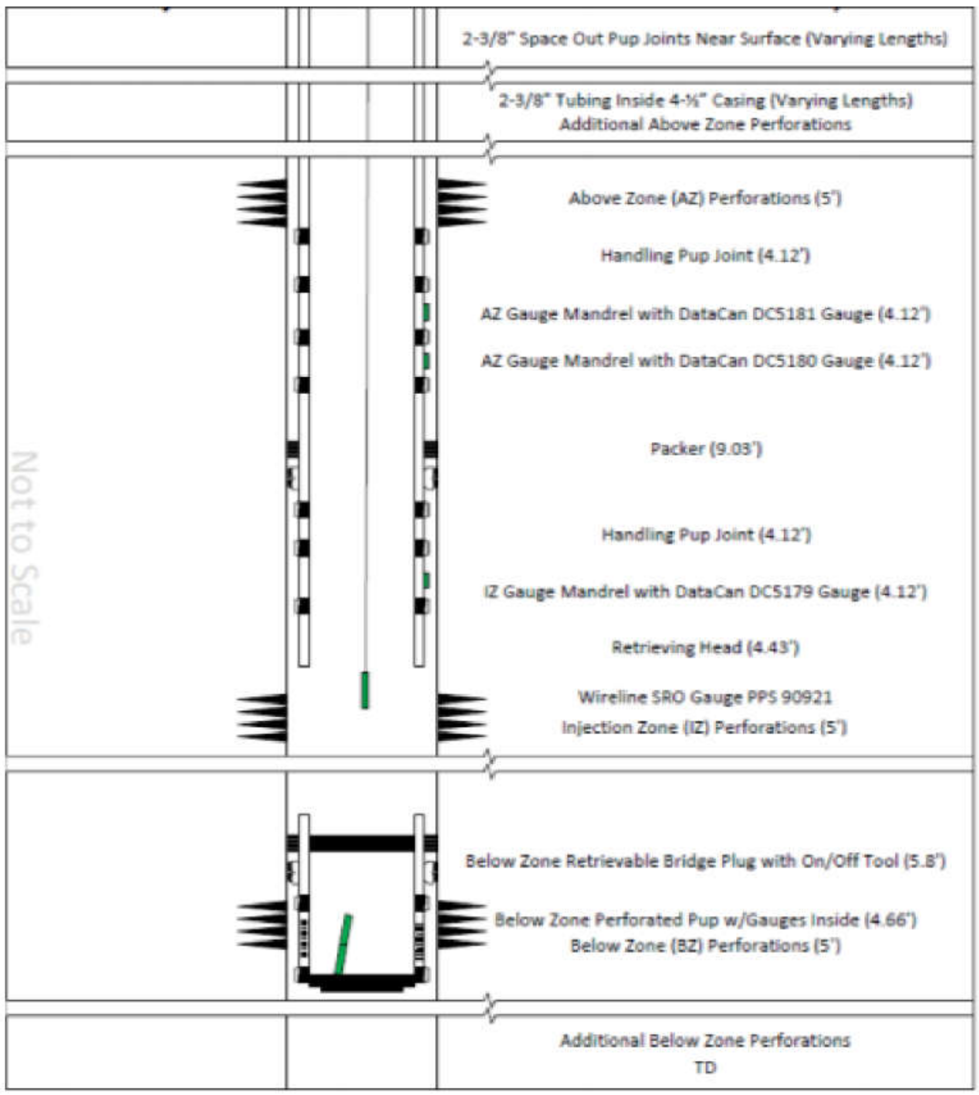

Figure 8. General description of the pressure gauge and packer locations for IZ, BZ, and ZA.

Table 7. Tabulation of petrophysical properties for each test interval.

Attribute	MtSA2-Prod	EC	MtSE	MtSA2	MtSA1	PC2	MtSA1-A2
Initial Pressure/ Fluid Gradient (psi/ft)	-	2483 (0.487)	2319 (0.444)	2809 (0.449)	2872 (0.456)	2948 (0.460)	-
Fracture Gradient (psi/ft)	-	1.00 - 1.19	0.712	0.783	0.769	1.27	0.69
k-h*, md-ft	2,400-5,400 (flowing) 4,900 (pumping)	11-16	10,000 (280-420)	4,200 (2000-2200)	14,700 - 10,000 (200-400)	0.13-0.20	4,600
k_v/k_h	0.0061-0.030 (flowing) - (pumping)	-	-	0.0084-0.017	0.000016-0.00028	-	0.0019

SUBSURFACE CHARACTERIZATION AND STORAGE COMPLEX MODELING

Regional Geology and Site Setting

The characterization site was chosen within the central Illinois Basin area as this region has demonstrated potential for carbon storage. The Illinois Basin is a geological feature that covers approximately 110,039 mi^2 (285,000 km^2), from western Illinois to western Indiana, and from southern Wisconsin to northwestern Kentucky and northern Tennessee (Kolata and Nelson, 2010). At least four tectonic-eustatic cycles linked to the Precambrian and Paleozoic tectonic evolution of the Laurentia continent (McBride et al., 2003) controlled deposition of the Paleozoic sediments that now form the strata of the Illinois Basin. The strata have been subsequently influenced by the three major tectonic structures that crosscut the Illinois Basin: the LaSalle Anticlinal Belt, the DuQuoin-Louden Anticlinal Belt, and the Rough Creek-Shawneetown Fault Zone (Willman et al., 1975; Treworgy et al., 1991), with regional contributions to sedimentation by minor tectonic structures such as the Sandwich Fault Zone. The Paleozoic bedrock is covered by Late Cenozoic and Quaternary sediments that directly underlie the surface of nearly all of Illinois. The regional geological setting of the project and its impact on sedimentation and reservoir character at the evaluation site is discussed more fully in Freiburg et al. (2022) and in Appendix C.

The project evaluation site in Christian County, IL, was chosen to leverage information previously gathered during other carbon storage investigations in the Illinois Basin including a demonstration of storage by the Illinois Basin – Decatur Project at the Archer Daniels Midland (ADM) ethanol facility in Decatur, IL. Initially, the project site was just north of Decatur at the Forsyth Oil Field in Macon County, and which is why the project bears the name CarbonSAFE Illinois – Macon County. This location was only about 4 mi (6.5 km) from the IBDP demonstration and the now ongoing commercial operation at ADM known as the Illinois Industrial Carbon Capture and Storage (IL-ICCS) project. The Macon County CarbonSAFE location was moved early into the project about 20 mi (32 km) south-west from its original site to the Mt. Auburn Oil Field in Christian County, IL (Figure 5). This move was considered advantageous for several reasons including land availability, but perhaps most importantly this alternate location would better develop understanding about the regional distribution of reservoir characteristics and storage complexes in the central basin.

Although the project was interested in evaluating stacked storage potential, the main target for characterization was the Mt. Simon Sandstone (reservoir) and the Eau Claire Shale (caprock seal) that comprise the Mt. Simon Storage Complex (Figure 9). The Mt. Simon Storage Complex was used by the IBDP and currently by IL-ICCS at ADM in Decatur, Illinois (Figure 5). Situated below the Mt. Simon Sandstone and above the crystalline Precambrian basement is the Argenta Formation, consisting of sandstone and conglomerate with rare interbedded mudstone, but with generally poor reservoir characteristics and it is not considered a storage target.

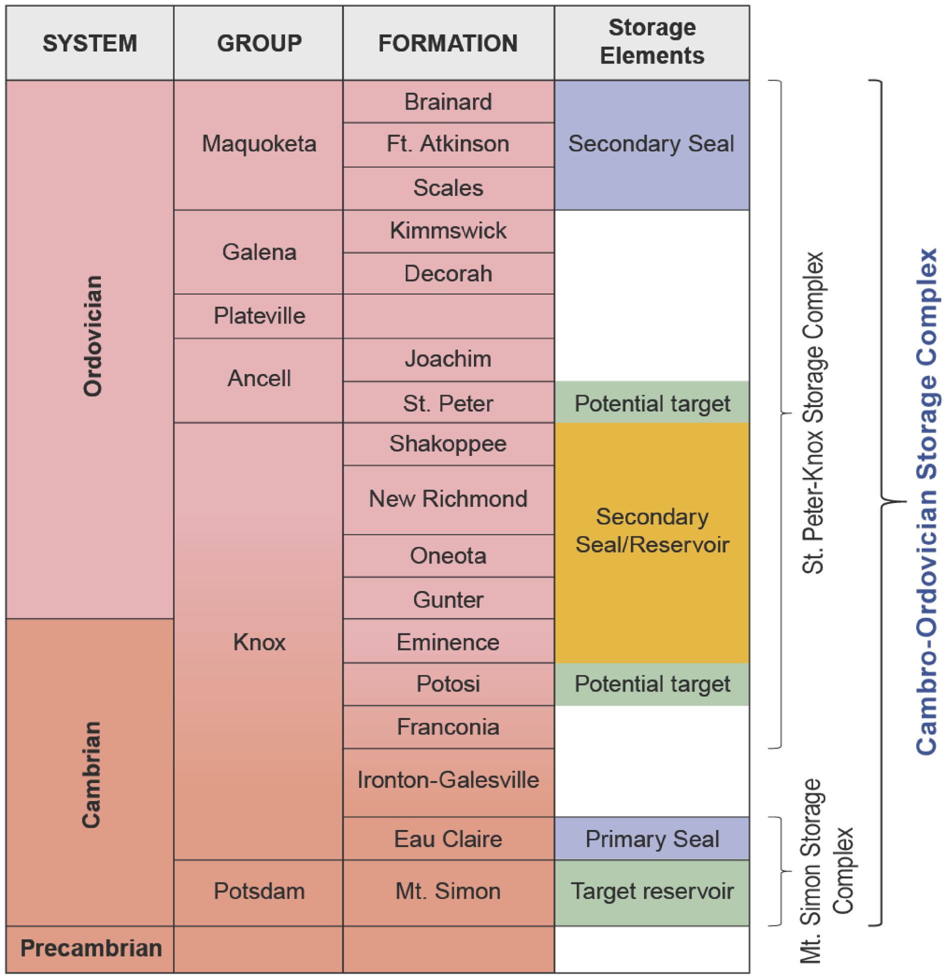

Figure 9. Generalized geologic column of the Illinois Basin (thickness not to scale). The Mt. Simon Storage Complex is at the base of the sedimentary column in the Illinois Basin. Other potential storage units and seals are also present in the sedimentary section.

Characterization of the Mt. Simon Storage Complex

Site characterization activities within the CarbonSAFE Macon County project were designed to establish the feasibility of geologically storing commercial quantities of CO_2 (~50 Mt over 30 years) within a storage complex. The workflow comprises an initial evaluation and analyses of the various types of data collected from the TRM2 well, establishing lithological and petrophysical parameters for reservoir and confining strata, their integration with what is known of regional geological settings, determining depositional settings and facies, identifying structural features, development of a conceptual geological model, construction of static geocellular and geomechanical models, and dynamic simulation of a suite of potential injection and development scenarios to evaluate the injectivity, capacity and containment performance of the Mt. Simon Storage Complex

Core Interpretation and Lithological Analyses

Freiburg et al. (2022) and Appendix C provide detailed description of core, lithofacies associations, depositional setting and sequence stratigraphy. The Argenta Formation and the Mount Simon Sandstone are identified at 6,299-6,386 ft (1,920-1,946 m) and 5,130-6,299 ft (1,564-1,920 m), respectively. The Precambrian crystalline basement is granite and rhyolite and the contact with the Argenta Formation is sharp and unconformable.

The lithology of the Argenta Formation is defined using geophysical logs (FMI) and core plugs, and consists dominantly of medium- to very coarse-grained, moderately sorted, sandstone, locally pebbly, with thin dark maroon mudstone partings. The lower part of this formation dominantly fine- to medium-grained sandstone (6,325-6,386 ft [1,928-1,946 m] in depth) and the upper part is largely composed of medium- to pebbly-grained sandstone and conglomerate (6,299-6,325 ft [1,920-1,928 m] in depth).

The Mount Simon Sandstone is divided into: (1) the lower Mount Simon Sandstone that includes units A and B, (2) the middle Mount Simon Sandstone that includes the units C and D, and (3) the upper Mount Simon Sandstone that is entirely Unit E.

- Unit A occurs from 6,129 to 6,299 ft (1,868 to 1,920 m) in depth and is fine- to coarse-grained, moderately to well sorted, sandstone with thin dark maroon mudstone partings Subangular to subrounded sand-sized grains of quartz and feldspar are the dominant fraction. Lithic fragments are also recognized. The grains are consolidated with a maroon to brown hematitic clay matrix. Sedimentary features such as planar, low angle and crossed stratifications are common. This unit is commonly referred to as the Arkosic zone and often has excellent reservoir qualities and interpreted depositional environments are shown in Figure 10 and Figure 11. A lithostratigraphic interpretation is shown in Figure 12.
- Unit B from 5,955 and 6,129 ft (1,815 to 1,868 m) consists of dark to light maroon to red, fine- to coarse-grained, moderately to well sorted, sandstone.
- Unit C from 5,541 and 5,955 ft (1,689 to 1,815 m) in depth consists of dark to light maroon to red, fine- to coarse-grained, moderately sorted, sandstone. Thin dark marron to dark red mudstone partings are common in the upper part of the unit. Planar to cross-stratifications are identified in the FMI log.
- Unit D from 5,270 and 5,541 ft (1,606 to 1,689 m) is fine- to medium-grained, moderately sorted, sandstone and massive and planar stratification are the dominant sedimentary features as recognized in the FMI log.
- Unit E from 5,130 and 5,270 ft (1,564 to 1,606 m) consists of light maroon to red, light tan to pink when altered, fine- to medium-grained, moderately to very well sorted, sandstone. Mudstone and fine-grained sandstone are abundant between 5,130 and 5,172 ft (1,564 and 1,576 m) in depth.

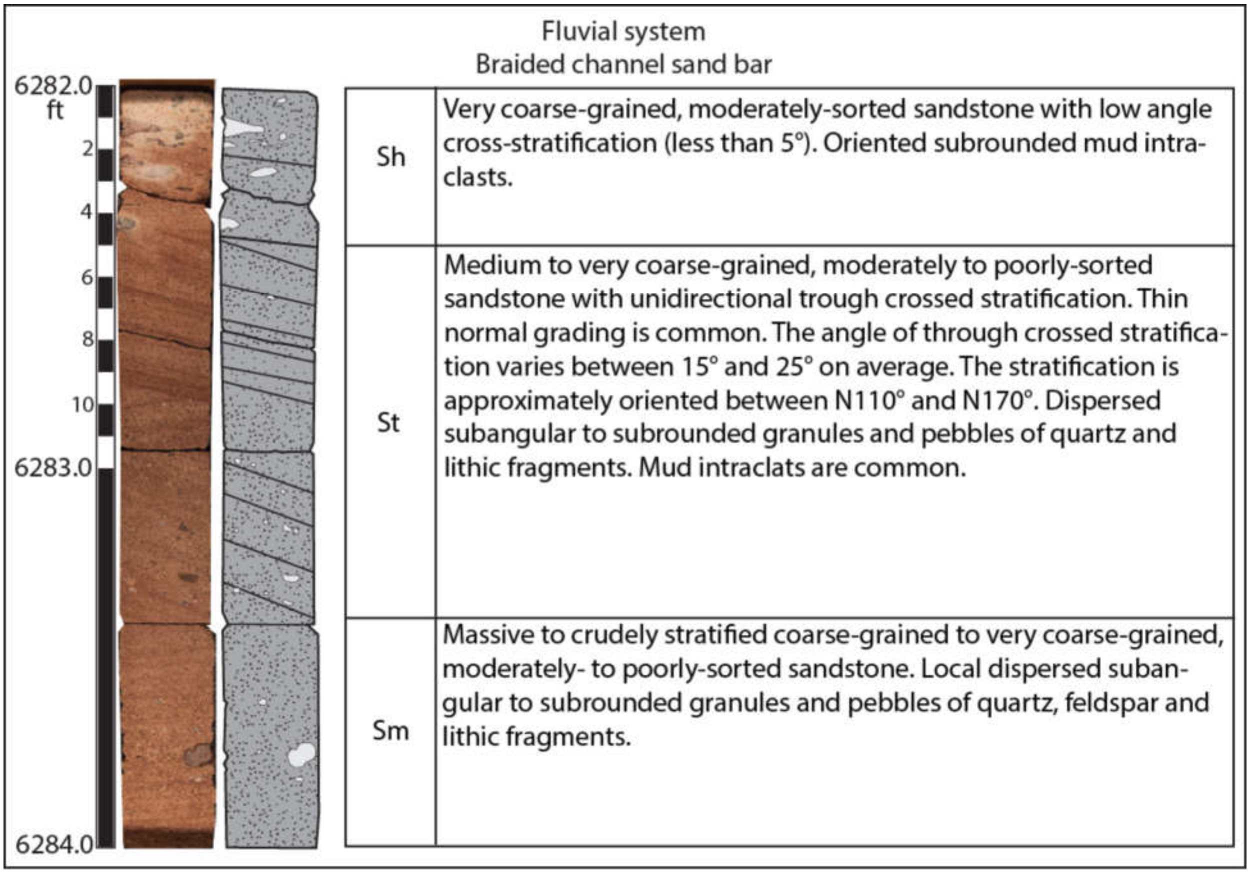

Figure 10. Cores from the T.R. McMillen#2 borehole showing coarse-grained sandstone with massive structure, faintly horizontal, low-angle- and crossed stratification in the unit A (Arkose) of the Lower Mount Simon Sandstone. The sandstone is interpreted as a braided sand channel fill and bar in a fluvial river system.

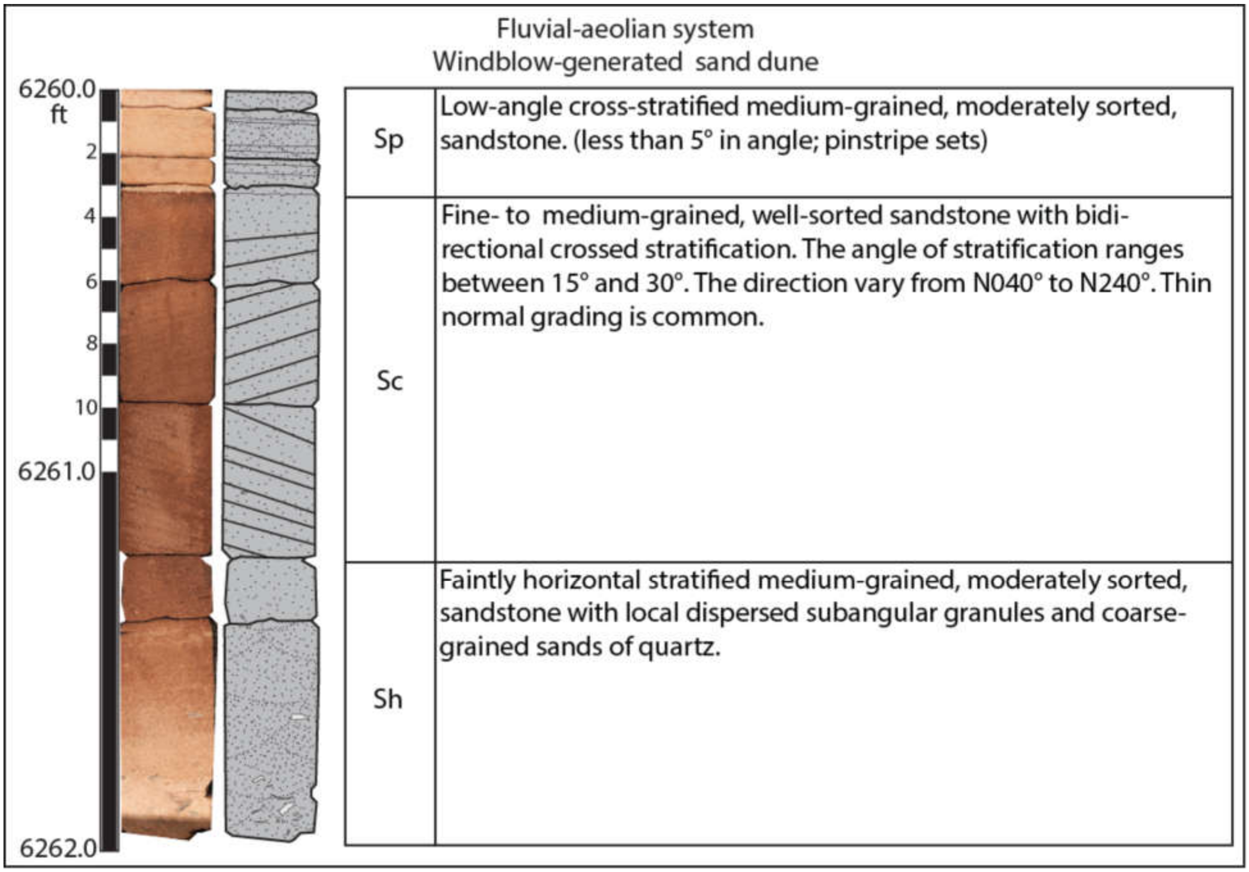

Figure 11. Cores from the T.R. McMillen#2 borehole showing medium- to fine-grained sandstone with large-scale trough crossed stratification in the unit A (Arkose) of the Lower Mount Simon Sandstone. The sandstone is interpreted as a sand dune in an aeolian plain system.

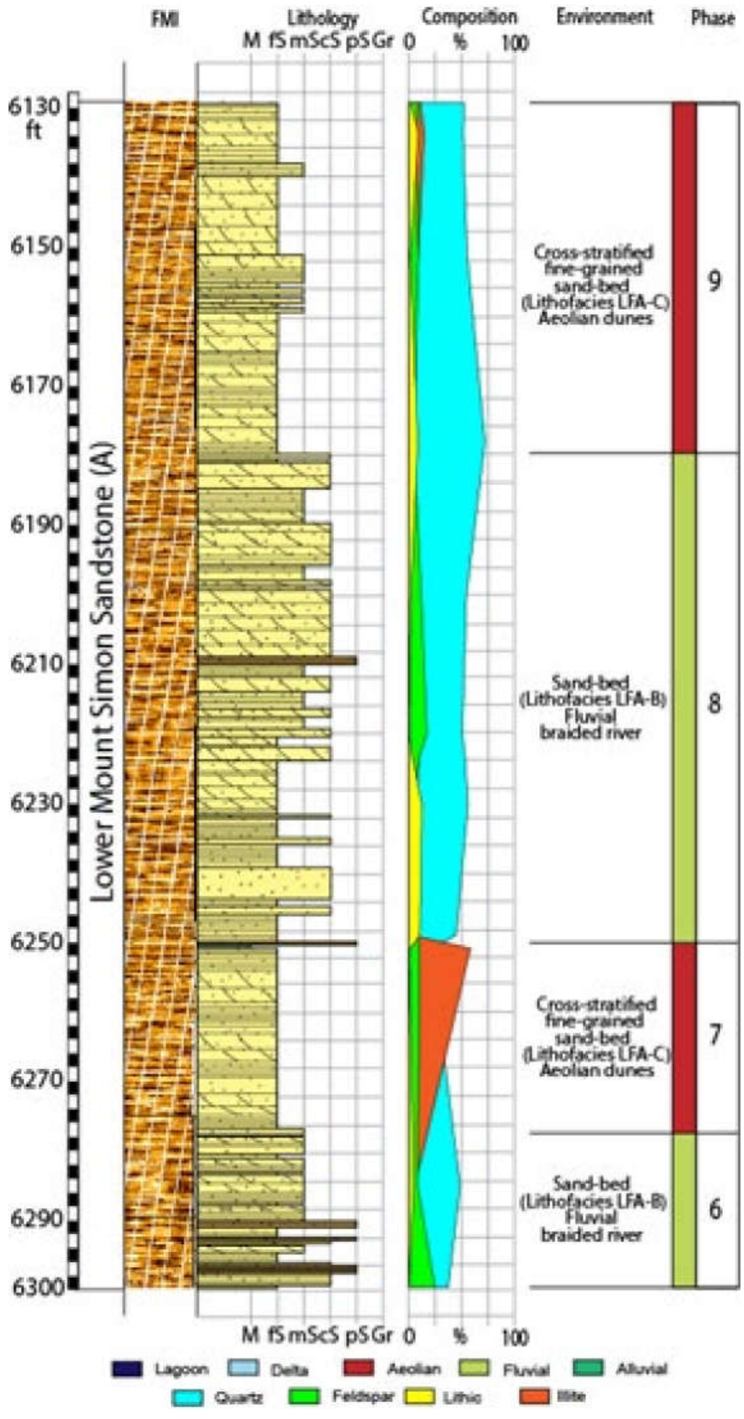

Figure 12. Lithostratigraphic column, FMI log and composition of the Unit A (Arkose) of the Lower Mt. Simon Sandstone showing lithofacies associations and paleoenvironmental interpretation.

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Sedimentological Analyses and Depositional Model

Sedimentological analyses were performed based on core examination and interpretation of gamma-ray and FMI logs. Borehole data and seismic reflection data provide a large-scale picture of the distribution of strata that were controlled by an incised valley-monadnock paleo-geomorphology.

Argenta Formation

The Argenta Formation overlies a boundary surface (SU) at the contact with the Precambrian crystalline basement that represents erosion or a depositional hiatus. Sedimentary sequences were deposited during a lowstand system tract (LST) stage that is delimited at the base by SU and at the top by a transgressive surface (TS-1). This normal regression forms a coarsening-up succession that is divided into two cycles composed of sandy conglomerates and pebbly sandstones separated by a distinctive muddy sandstone unit. The lithofacies are interpreted as the vertical evolution from alluvial waterlain fan deposits to delta distributary channel rivers at the transition between a fluvial plain and a possible ephemeral lake.

With the increase of sediment supply, (i.e., coarser materials composed of very coarse-grained sands, granules, and pebbles) the accommodation space progressively decreased, causing initial alluvial fan surface incision during the expansion of the drainage basin (Figure 13). Channel-lag pebble fill deposits were accumulated under high-energy subaqueous traction regime in a waterlain alluvial-fluvial fan system complex. Due to widening of the flow into a braided river, the flood spreads out from the channels. This flow deposited sheet flood sediments such as gravel- to sand-sized dunes and antidunes (Reineck and Singh, 1986). Multiple waterlain flows occurred in the alluvial fan system that produced the truncation (e.g., scour- and fill-structures) of dunes and antidunes. The waterlain alluvial fan corresponds to base and midfan parts of an alluvial fan system complex. The fanhead part of the alluvial fan system accumulates debris flow deposits able to form fan-shaped bodies deposited on the slope toe of paleo-highs (e.g., monadnocks) or mountainous regions (Blissenbach, 1954; Reineck and Singh, 1986). The top of this coarser material unit is inferred to be a minor maximum regressive surface that marked a phase of retrogradation before the progradation of the overlapping of a fluvio-deltaic system complex.

A rapid differential subsidence occurred through the basin with the progradation of a delta front facies that transitioned eastward into lacustrine sediments. Wave-related reversal currents created bidirectional trough crossed-stratification by the migration of distributary channel dunes in a transition between fluvial and delta-front lobe system complexes. The distributary channel dunes vertically graded to mouth bar deposits. The top of this sequence is inferred to be a local or regional minor erosion surface that marked the beginning of the second depositional sequence.

Because the drainage of the basin became dominant, a probable proximal source of sediments (e.g., monadnocks) nourished the alluvial plain system by the deposition of the second coarsening-up cycle. This phase is inferred to be a minor retrogradation that is marked by a minor maximum regressive surface. The source area denudation significantly decreases with the decrease of coarse-grained material supply and the transition with a new episode of progradation of fluvial-delta front sediments.

Mt. Simon Sandstone

The transition between alluvial fan and braided river sedimentation is encountered at the base of the Lower Mt. Simon. This transition marked an early stage of transgressive system tract (TST) though the basin (Figure 14; Figure 15). This change can be explained by the increase of fluvial style sedimentation, when the rate of sediment supply exceeds that of accommodation space creation. Periodic reactivation of proximal source area denudation increased coarser-grained lithic sediment supply in the fluvial braided river system, as shown by the deposition of horizontally layered or dispersed granules and pebbles of quartz, feldspar, and lithic rocks. The unit A (Arkose) was dominated by extensive vertically and laterally amalgamated channel-fill and channel bar complexes that were formed by the bedload-related migration of sand dunes under high-energy flow regime. During the deposition of the units A and B, the fluvial braided river system spread vertically and laterally with the deposition of aeolian dunes. These dunes developed on the overbanks of a floodplain that was not preserved because of the cannibalistic nature of the braided channels. With the absence of core samples and the lack of surface recognition in the FMI log, the transition between the units B and C is informally inferred to be a minor TS that is the base of a second stage of TST (Figure 15).

The fluvial stream sedimentation was optimal during the deposition of the Middle Mt. Simon Sandstone (units C and D). The paleo-topography of the Precambrian crystalline basement was mostly flat, which decreases the supply of course-grained materials. Consequently, composition of the units C and D decreased in feldspars and lithic materials through the basin. Because the rate of sediment supply exceeded the accommodation space, the fluvial river sediments developed a wide area of fluvial plain system during a moderate to rapid subsidence. Up to 683-ft- (208-m-) thick braided river sandstones and aeolian dune sandstones of the units C and D were deposited in newly created accommodation spaces by the differential subsidence movements. The unit C dominantly deposited braided river system, while the unit D was marked by the development of aeolian dunes in a fluvial plain environment. The sediments of the unit C pinched out the paleo-highs (e.g., monadnocks, hills, mountains), while the unit D vertically overlapped the previously unit C. Both units can be inferred to be the early phase of the late TST stage (Figure 15).

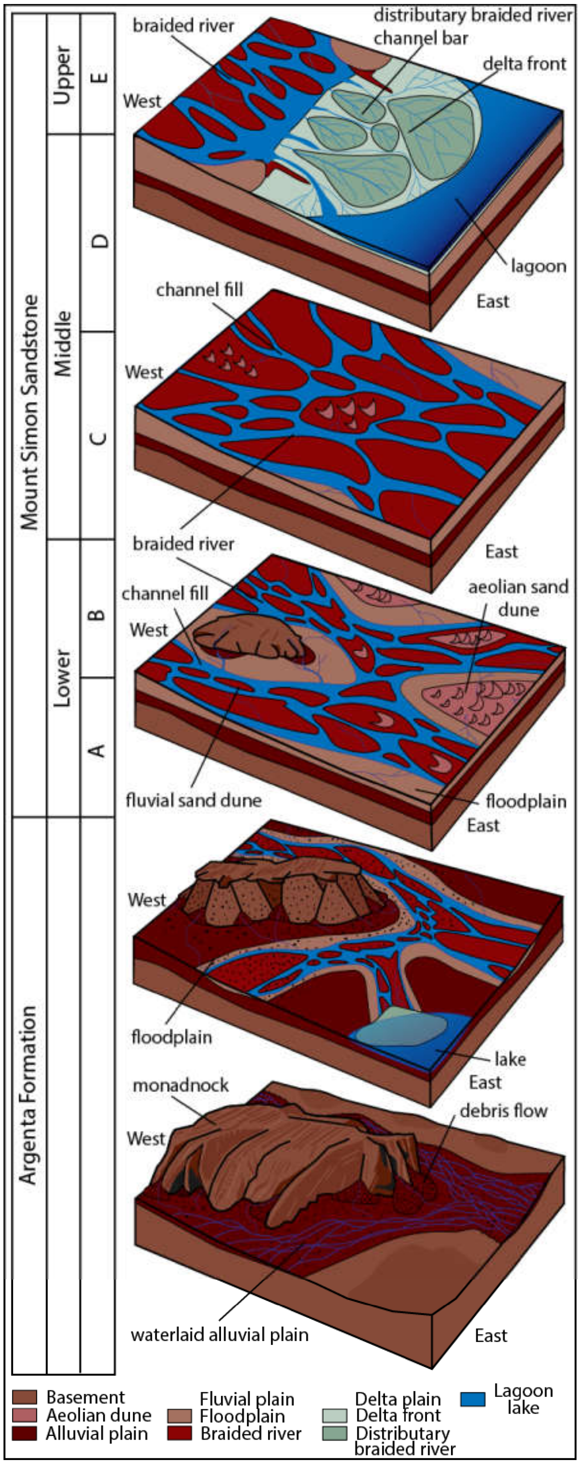

Figure 13. 3D depositional models for the T.R. McMillen #2 well showing the paleoenvironmental evolution of the Argenta Formation and Mt. Simon Sandstone.

Argenta Formation: (1) Waterlain alluvial fan deposits were accumulated around a Precambrian crystalline paleo-high, here interpreted as a monadnock, in an incised valley. (2) An alluvial-fluvial stream sedimentation developed with local deposition of proximal delta distributary braided channels. Coarser-grained materials were transported from the near source area.

Mt. Simon Sandstone: (1) The units A and B of the Lower Mt. Simon Sandstone: The drainage basin expanded, increasing the volume of sediment supply in the fluvial braided river. Aeolian dunes were deposited in the overbanks of the floodplain. The paleo-high was one of the source areas of coarser-grained materials. (2) The units C and D of the Middle Mt. Simon Sandstone: The rate of subsidence decreases through the basin that laterally increased the fluvial plain system. Locally aeolian dunes were deposited in the overbanks of the floodplain. The paleo-high was denudated and flat. (3) The unit E of the Upper Mt. Simon Sandstone: Delta fan prograded through the basin with the deposition of distributary braided channels and mouth bars in a relatively high-energy, wave-generated flow regime.

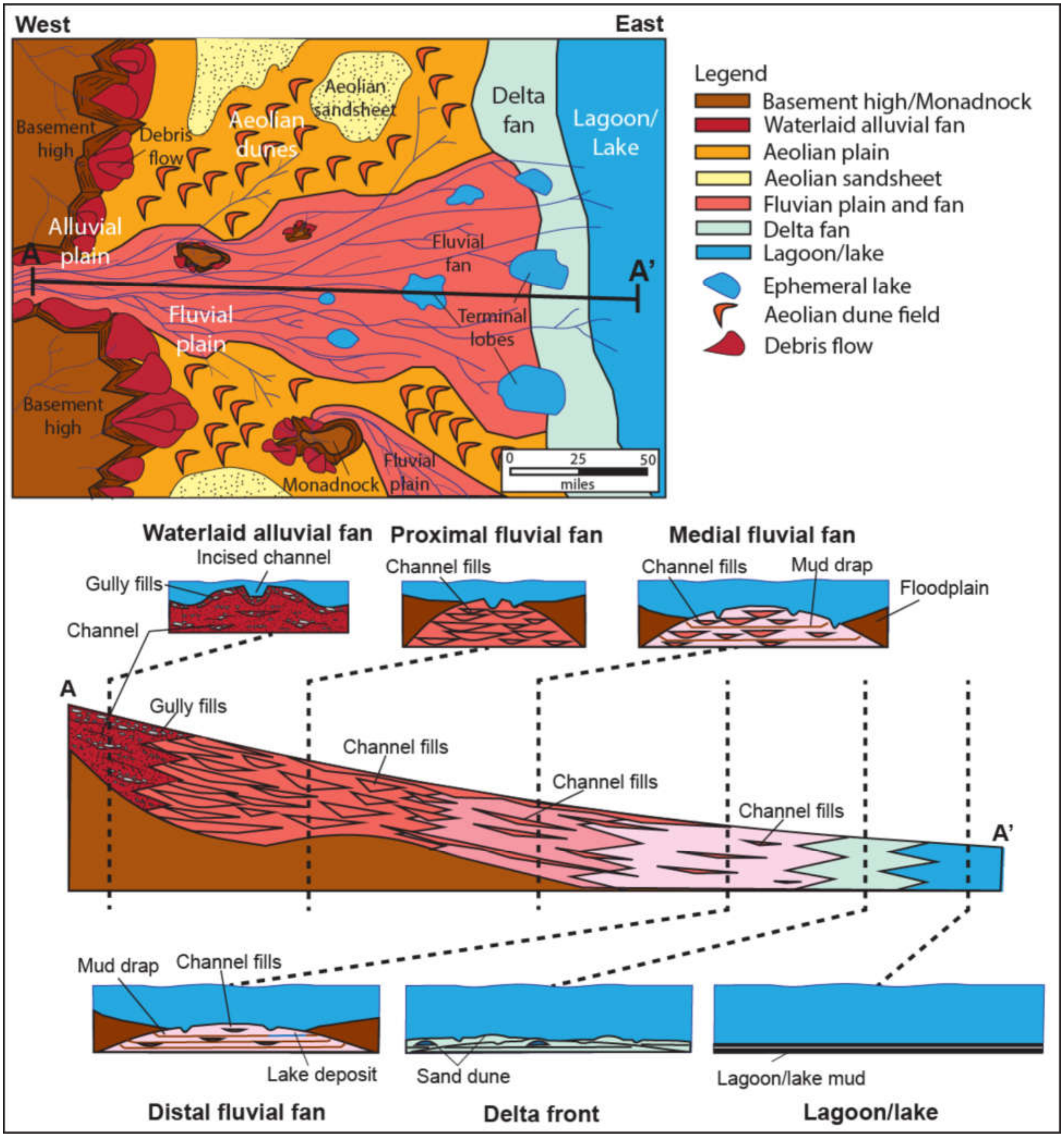

Figure 14. Large-scale depositional model for the Argenta Formation and Mt. Simon Sandstone showing the interaction from alluvial fan to delta front environments. Fluvial plain is bordered by a floodplain that accumulated aeolian dune field. Cross-sections of the alluvial and fluvial plains with details of the waterlain alluvial fan, fluvial plain, and delta fan (modified from Moscariello, 2018).

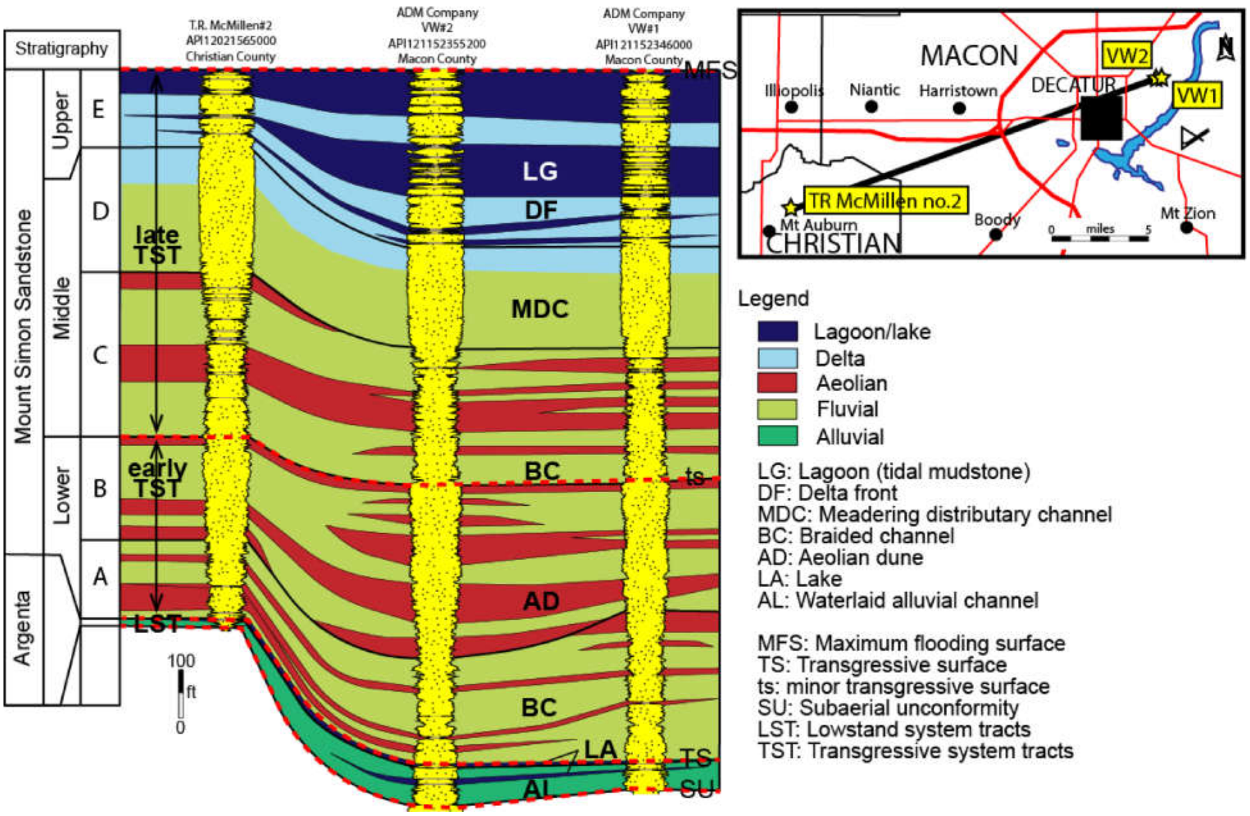

Figure 15. Profile of lithostratigraphic correlation between the T.R. McMillen #2 well, Christian County, and VW #1 and VW #2 boreholes, Macon County. Sequence stratigraphy shows that the sedimentary succession of the Argenta Formation and Mt. Simon Sandstone begins by a lowstand system tract (LST) stage over a subaerial unconformity (SU) over the Precambrian crystalline basement. LST is bounded by a transgressive surface (TS) that marked the progradation of the fluvial system through the basin. Two phases produced a fluvial-dominated and delta-dominated deposition for the Lower-Middle and Middle-Upper Mt. Simon Sandstone, respectively. The boundary with the Eau Claire Formation is marked by a maximum flooding surface (MFS).

At the end of the late TST stage, a major change occurred at the transition between the unit D and the unit E of the Upper Mt. Simon Sandstone that was marked by the progradation of braided river delta system through the basin (Figure 13; Figure 14). This event recorded the transition between fluvial-dominated to delta front-dominated systems. Amalgamated distributary braided channels and the low content of mouth bar deposits indicate a high discharge of river supply in a high-energy delta fan system. The progradation of the delta fan system gradually progressed with pure mudstones, here interpreted to be of lagoonal origin, that covered a large area across the proto-Illinois Basin. The transition from mouth bar to lagoon deposits can be inferred to be a maximum flooding surface (MFS) at the base of the Eau Claire Formation as published by Ostrom (1970) and Runkel et al. (2007) (Figure 15).

The sedimentary sequence evolution model shows that the depositional processes were likely controlled by eroded paleo-uplift of the Precambrian crystalline basement, which generated differential tectonic movements through the proto-Illinois Basin. An active tectonic subsidence enhanced the deposition of the Argenta Formation by the coarser-grained sediment supply that gradually filled the incised valley and paleo-high (e.g., monadnock) paleogeomorphology. With the decrease of the tectonic subsidence and the expansion of the drainage basin, the paleo-uplift areas began to flatten in the Lower Mt. Simon Sandstone, and the paleo-highs were totally inundated by fluvio-deltaic sediments in the Middle and Upper Mt. Simon Sandstone.

As part of the characterization work extensive petrographic analyses was also conducted that included thin section point count analysis for mineralogical (detrital and diagenetic) and pore space quantification (including grain size analysis, annotated thin section photomicrographs (Figure 16), scanning electron microscopy (SEM) (Figure 17; Figure 18) with energy dispersive X-ray spectroscopy (EDS), X-ray powder diffraction (XRD) analysis, and routine analysis of full diameter core and rotary sidewall core for porosity and permeability calculations discussed later in this report. Additional information on the petrographic analysis performed by the project team is available in Chapter 5 of Appendix C (Freiburg et al., 2022).

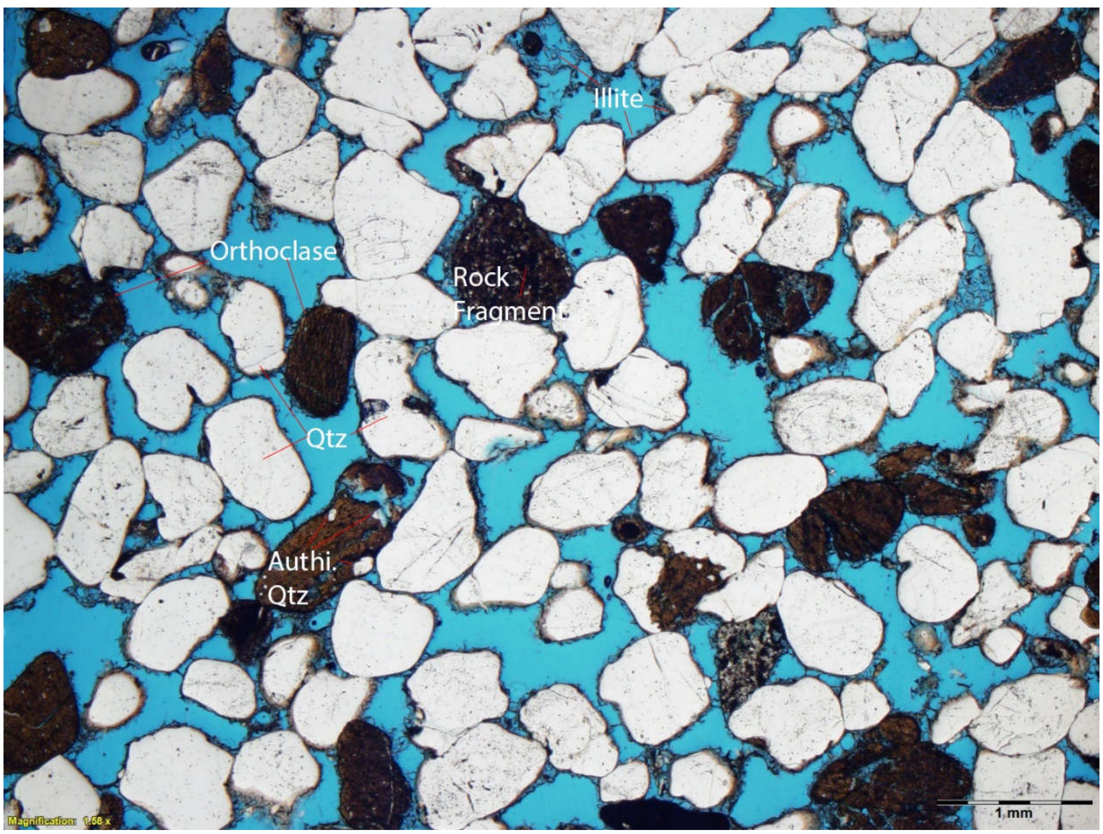

Figure 16. Thin section photomicrograph of the Lower Mt. Simon Sandstone at depth of 6,124.07 ft. Note the pore and grain lining illite and the spherical pore shape, implying possible complete grain dissolution porosity. Numerous curved illite bridges also imply secondary porosity from complete grain dissolution.

Figure 17. SEM photomicrograph of the Lower Mt. Simon Sandstone at depth of 6,249.99 ft. Abundant hairy illite lines grains, preventing pervasive authigenic quartz nucleation. Authigenic quartz is localized on small openings to the quartz grain surface between hairy illite.

Figure 18. SEM photomicrograph of the Lower Mt. Simon Sandstone at depth of 6,285.70 ft. Clays often form pore bridges between grains.

Core and Petrophysical Analyses

Confinement Strata

The Eau Claire Formation is the primary seal for the storage complex and is 608 ft (185 m) thick in the TRM2 well and can be divided at this location, and regionally, into two members. The upper member of the Eau Claire is 523 ft (159 m) thick and has a clastic-dominated mixed lithology near its base and transitions upwards into a carbonate-dominated succession near its top. The lower member is known as the Eau Claire Shale and is 85 ft (26 m) thick and dominated by clay minerals as indicated by gamma ray and PE logs as shown in Figure 19.

Nine rotary sidewall core samples were taken from the Eau Claire Formation with four of those taken from the Eau Claire Shale (Table 8; Table 9). The average porosity of 9.8% for the Eau Claire and 12.5% for the Eau Claire Shale and the median permeability of the Eau Claire Formation of 2.08 mD fall within expected values. The median permeability of the Eau Claire Shale of 11.2 mD is higher than expected; it is probably a product of sampling bias/low sample numbers.

Table 8. Rotary sidewall core porosity statistics for the Eau Claire

Unit	n	Avg	St. Dev	Median	Max	Min
Eau Claire shale	4	0.125	0.0413	0.135	0.171	0.0615
Eau Claire	9	0.0980	0.0571	0.106	0.177	0.0204

Table 9. Rotary sidewall core permeability statistics for the Eau Claire

	Permeability (mD)						Log_{10} (Permeability)				
Unit	**n**	**Avg**	**St. Dev**	**Median**	**Max**	**Min**	**Avg**	**St. Dev**	**Median**	**Max**	**Min**
Eau Claire shale	4	26.3	32.9	11.2	82.5	0.390	0.886	0.841	1.02	1.92	-0.409
Eau Claire	9	12.5	25.2	2.08	82.5	0.00516	0.184	1.1	0.318	1.92	-2.29

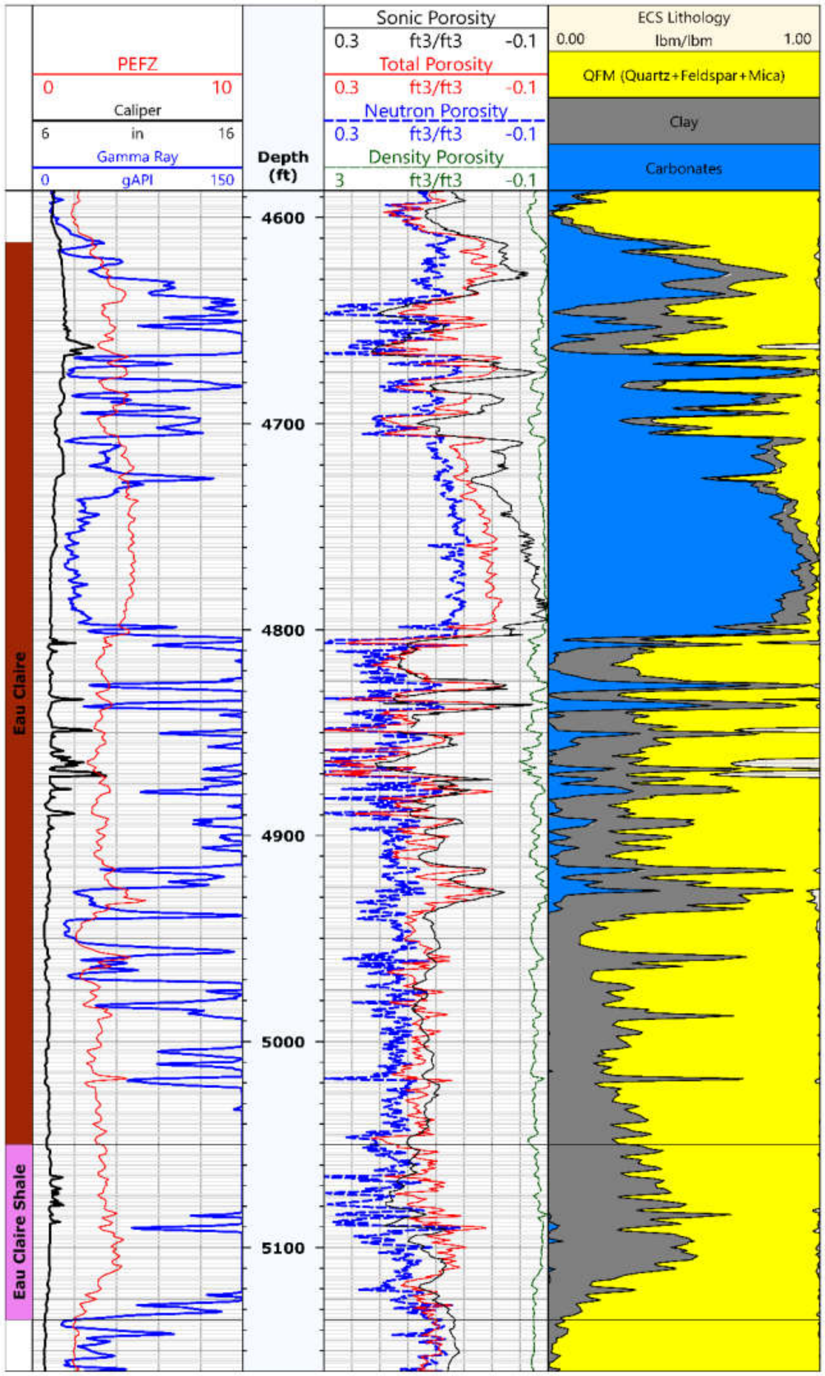

Figure 19. Porosity and lithology logs of the Eau Claire

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Reservoir Strata

A total of 64 rotary sidewall core samples were taken in the Mt. Simon Sandstone and subjected to routine testing. See Table 10 for a summary. The highest average porosity amongst the major division of the Mt. Simon (Upper, Middle, and Lower) is the Lower Mt. Simon at 21.0%, followed by the Middle Mt. Simon at 14.8% and the Upper Mt. Simon at 13.7%. The overall average of the Mt. Simon is 18.6%, whereas for the Argenta Formation it is 14.5%.

Table 10. Rotary sidewall core porosity statistics for the reservoir

Unit	n	Avg	St. Dev	Median	Max	Min
UPPER-E	7	0.137	0.0278	0.149	0.163	0.0745
Middle-D	7	0.145	0.0308	0.141	0.206	0.0978
Middle-C	6	0.151	0.0197	0.155	0.168	0.1088
MIDDLE	13	0.148	0.0265	0.152	0.206	0.0978
Lower-B	25	0.218	0.0594	0.224	0.333	0.1090
Lower-A	10	0.188	0.0616	0.196	0.279	0.0374
LOWER	35	0.210	0.0616	0.210	0.333	0.0374
MTSIMON	55	0.186	0.0607	0.168	0.333	0.0374
ARGENTA	9	0.145	0.0287	0.147	0.205	0.101

In addition to sidewall core, 60 ft (18 m) of whole core was taken from depths of 6,246 to 6,306 ft (1,904 to 1,922 m), with most of the samples taken predominantly from the Lower Mt. Simon Unit A and a small portion from the Argenta. The core was sampled at regular intervals, resulting in 24 total measurements, which were subjected to routine testing. See Table 11 for a summary. The Lower Mt. Simon Unit A average porosity is 22.5%, while the Argenta Formation is 16.7%.

Table 11. Whole core porosity statistics

Unit	n	Avg	St. Dev	Median	Max	Min
LOWER MT. SIMON A	21	0.225	0.0218	0.227	0.254	0.160
ARGENTA	3	0.167	0.0295	0.145	0.202	0.138

The enhanced thermal neutron porosity (curve mnemonic: NPOR) from the platform express tool was selected and used with the standard resolution density porosity (curve mnemonic: DPHZ) to create the cross-plot porosity (PHIT), which is representative of the formation's total porosity. The porosity logs are displayed graphically in Figure 20, with core measurements overlain, and Table 12 contains a summary of porosity statistics.

The highest average porosity amongst the major divisions of the Mt. Simon Sandstone (Upper, Middle, and Lower) is the Lower Mt. Simon at 19.8%, followed by the Middle Mt. Simon at 13.8% and the Upper Mt. Simon at 12.8%. The overall average of the Mt. Simon is 15.4%, whereas the average of the Argenta is 13.3%. Overall, comparing the cross-plot porosity to the rotary sidewall core samples, the log values are lower than the sidewall core samples, but the agreement between the log values and rotary sidewall core sample measurements is acceptable, given sampling bias that exists in coring. The average of the whole core samples for the Mt. Simon Unit A and the Argenta are higher than both the log and the sidewall core samples.

Table 12. Geophysical log porosity statistics

Unit	Density Porosity				Neutron Porosity				Cross-Plot Porosity			
	Avg	**St Dev**	**Max**	**Min**	**Avg**	**St Dev**	**Max**	**Min**	**Avg**	**St Dev**	**Max**	**Min**
UPPER-E	0.126	0.0232	0.169	0.0516	0.130	0.0306	0.287	0.0714	0.128	0.0207	0.195	0.0770
Middle-D	0.138	0.0251	0.210	0.0818	0.139	0.0291	0.229	0.0808	0.139	0.0263	0.216	0.0813
Middle-C	0.130	0.0217	0.197	0.0649	0.146	0.0259	0.278	0.0910	0.138	0.0207	0.212	0.0824
MIDDLE	0.132	0.0231	0.210	0.0649	0.144	0.0271	0.278	0.0808	0.138	0.0227	0.216	0.0813
Lower-B	0.188	0.0276	0.262	0.0971	0.199	0.0292	0.273	0.1173	0.194	0.0273	0.267	0.1116
Lower-A	0.192	0.0392	0.268	0.0595	0.211	0.0413	0.338	0.1238	0.202	0.0387	0.294	0.1096
LOWER	0.190	0.0339	0.268	0.0595	0.205	0.0362	0.338	0.1173	0.198	0.0337	0.294	0.1096
MTSIMON	0.149	0.0380	0.268	0.0516	0.160	0.0422	0.338	0.0714	0.154	0.0384	0.294	0.0770
ARGENTA	0.095	0.0540	0.200	-0.0403	0.172	0.0341	0.295	0.1023	0.133	0.0331	0.209	0.0702

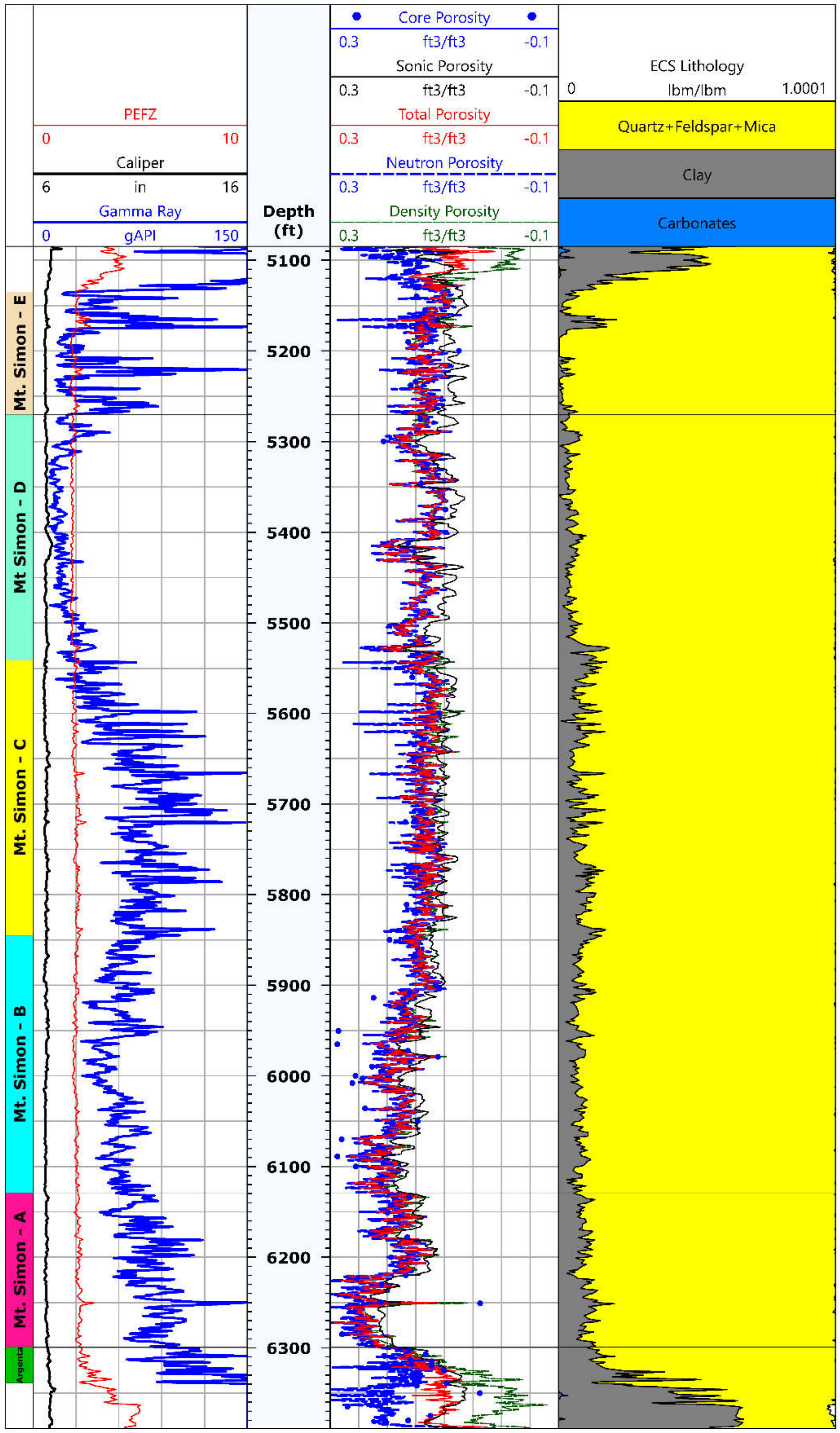

Figure 20. Porosity and lithology geophysical logs with core measurements superimposed of the Mt. Simon and Argenta.

Permeability was measured on the 64 samples from the sidewall rotary core using standard lab methods, the summary of which is presented in Table 13. Amongst the major divisions of the Mt. Simon, average permeability was highest in the Upper Mt. Simon (Unit E) at 349 mD, compared to 92.7 mD and 90.8 mD for the Middle and Lower Mt. Simon, respectively. However, these relationships are a product of sampling bias: the portion of the Lower Mt. Simon with the best reservoir quality, and also the highest reservoir properties at IBDP, was sparsely sampled during the rotary sidewall coring since that portion was sampled during the whole core sampling. The Middle Mt. Simon, which was represented by a total of 13 samples, is overly affected by a single sample that had a value of 750 mD. Although there is no indication of error in the sample, removing the sample reduces the average from 92.7 to 38.0 mD, which is more in line with expectations. The discrepancy between the average permeability of the Middle Mt. Simon and the median, 3.03 mD, likewise demonstrates that the average is biased by the sample. The Upper Mt. Simon does contain one sample that is marked as chipped, but removing that sample does not significantly change the overall average (reduction to 298 mD). There are three samples out of seven taken from the Upper Mt. Simon that have permeabilities over 500 mD, leading to the conclusion that there do exist portions of high-quality reservoir in the Upper Mt. Simon. However, the average is strongly affected by low sampling numbers as seven samples are being used to represent 135 ft (41 m). The Upper Mt. Simon is characterized as being highly heterogenous, owing to thin, interbedded layers of sandstone and shale. Still, the data suggest that portions of the Upper Mt. Simon, although probably compartmentalized and not well connected due to the reservoir architecture, have good reservoir qualities.

Table 13. Rotary sidewall core permeability statistics

	Permeability (mD)						Log_{10} (Permeability)					
Unit	**n**	**Avg**	**St. Dev**	**Median**	**Max**	**Min**	**n**	**Avg**	**St. Dev**	**Median**	**Max**	**Min**
UPPER-E	7	348	334	173	955	5.00	7	2.09	0.832	2.24	2.98	0.699
Middle-D	7	161	252	9.52	750	1.10	7	1.31	1.05	0.978	2.87	0.0410
Middle-C	6	13.3	17.2	2.33	45.5	0.604	6	0.628	0.684	0.357	1.66	-0.219
MIDDLE	13	92.7	200	3.03	750	0.604	13	0.996	0.960	0.481	2.87	-0.219
Lower-B	25	39.7	73.0	4.38	230	0.0530	25	0.723	0.961	0.642	2.36	-1.28
Lower-A	9	233	362	17.3	1121	0.256	9	1.34	1.19	1.24	3.05	-0.592
LOWER	34	90.8	214	5.83	1121	0.0530	34	0.886	1.06	0.753	3.05	-1.28
MTSIMON	54	125	246	9.25	1121	0.0530	54	1.07	1.09	0.966	3.05	-1.28
ARGENTA	9	2.81	5.86	0.535	19.3	0.0630	9	-0.173	0.683	-0.271	1.28	-1.20

Permeability was also measured from the whole core samples, a summary of which is in Table 14. The whole core presents a more complete picture of the petrophysical properties of the Lower Mt. Simon versus the rotary sidewall core. The whole core average of the Lower Mt. Simon Unit A is 2,050 mD and at a high value of 5,530 mD exhibits some of the highest permeability recorded for the Mt. Simon. Based on these results, the reservoir quality at the well in the Lower Mt. Simon is excellent and some of the highest in the basin.

Table 14. Whole core permeability statistics

	Horizontal Permeability (mD)						Log_{10}(Horizontal Permeability)					
Unit	**n**	**Avg**	**St. Dev**	**Median**	**Max**	**Min**	**n**	**Avg**	**St. Dev**	**Median**	**Max**	**Min**
LOWER MT. SIMON A	21	2050	1660	1570	5530	4.68	21	3.01	0.716	3.19	3.74	0.670
ARGENTA	3	124	156	9.40	365	5.42	3	1.51	0.780	0.973	2.56	0.734
	Vertical Permeability (mD)						**Log_{10}(Vertical Permeability)**					
Unit	**n**	**Avg**	**St. Dev**	**Median**	**Max**	**Min**	**n**	**Avg**	**St. Dev**	**Median**	**Max**	**Min**
LOWER MT. SIMON A	21	726	932	396	3490	1.25	21	2.37	0.871	2.60	3.54	0.0969
ARGENTA	3	21.7	31.4	0.714	71.3	0.361	3	0.485	0.957	-0.146	1.85	-0.442

Permeability was estimated from the geophysical logs through different methods. Permeability was estimated from the Combinable Magnetic Resonance (CMR) log, a nuclear magnetic resonance-type log, which estimates permeability by analyzing the rate of decay of polarized hydrogen nuclei. This type of tool has become standard in the industry for estimating permeability. Permeability was also estimated from porosity using the standard equations, Wylie-Rose and Timur. A final method employed was developed at the ISGS to estimate permeability from porosity using different regression models selected via the cementation exponent from Archie's Equation. Figure 21 is a depth display of the permeability estimates derived from geophysical logs with core measurements superimposed. Additional information on the results of the petrophysical analyses study can be found in Chapter 4 of Appendix C (Freiburg et al., 2022).

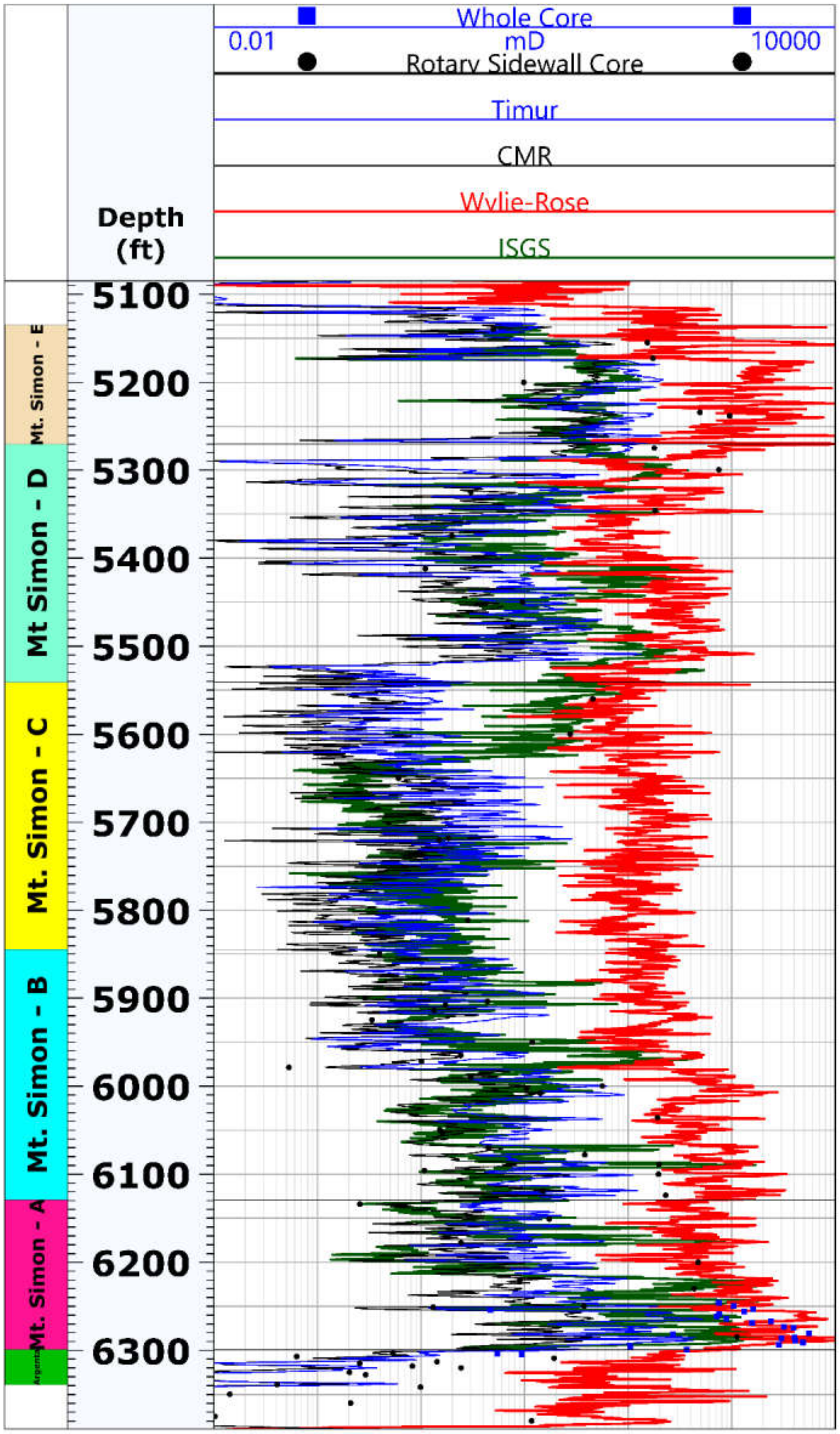

Figure 21. Permeability estimates from geophysical logs with core measurements superimposed for the Mt. Simon and Argenta

Seismic Analyses

Christian County 2D Seismic Survey

The seismic profile in northern Christian County, Illinois trends east-west and is about 29 mi (47 km) long, and the surveyed was conducted during February 2019 (Figure 22). The objective for the 2D seismic project was to image Precambrian Basement (~6,800 ft [2,070 m] MD), target reservoir (Mt. Simon ~5,200 ft [1,585 m] MD) and Seal (Eau Claire ~4,700 ft [1,430 m] MD) for potential CO_2 storage. A secondary objective was to image a fault on the Eastern edge of the 2D line to show the direction of the fault that was identified on a previous survey to the north. Maximum offsets for recording were 12,000 ft (3,658 m). The 2D line was shot just north of a well drilled east of Mount Auburn and was tied into the well with a north-south line recorded as a 10,000 ft (3048 m) offset VSP that was also part of the project.

The 2D survey was recorded with the following sweep; x2 60,000 lb. buggy vibrators utilizing 4 sweeps at 8 seconds per sweep with a 5 second listen time, sweeping from 6-100 Hertz (Hz) Linear with 500 millisecond (ms) start and end tapers. Receiver Point interval was 110 ft (34 m) and Source Point interval was 110 ft (34 m) at the halfway point between receivers (i.e. source points were shook on the half stations). The Christian County profile was shot with a split spread using 55-12,045 ft (17-3,671 m) offsets, which yielded a maximum CDP fold of cover of 45-54.

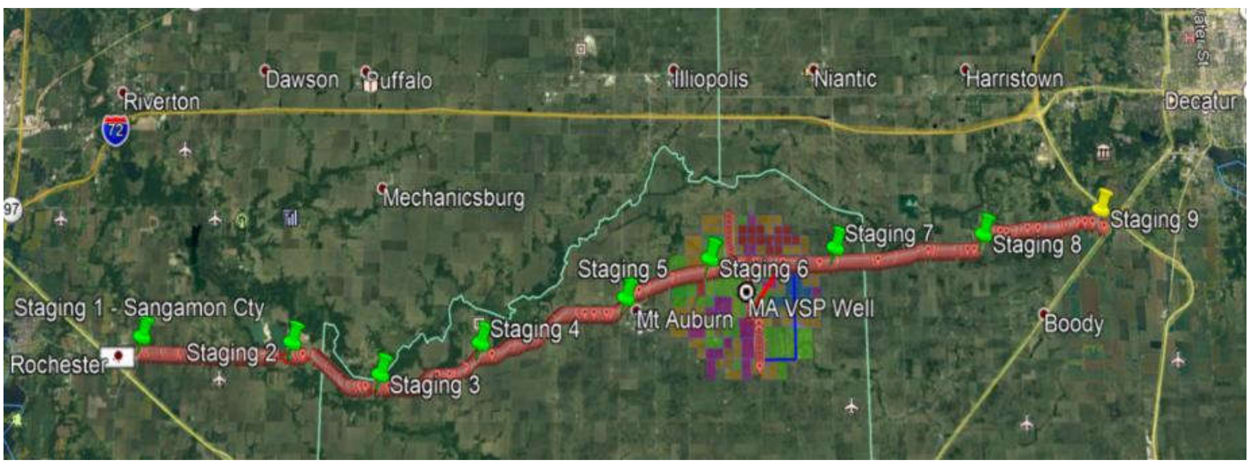

Figure 22. Location of Christian County 2D seismic line with Permitted Staging Areas

The Paleozoic strata of the Christian County section are very reflective (Figure 23). The seismic profile indicates lateral continuity of reservoir and seal strata across the extent of the survey. A basement high is observed about 4 mi (6.5 km) west of the well tie-in location with TRM2. The data was also processed for inversion and a porosity volume is shown in Figure 24. To use a multivariate statistical/Neural Network approach needs more than one well, so a crossplot Log Porosity vs Seismic AI was used to derive the porosity volume.

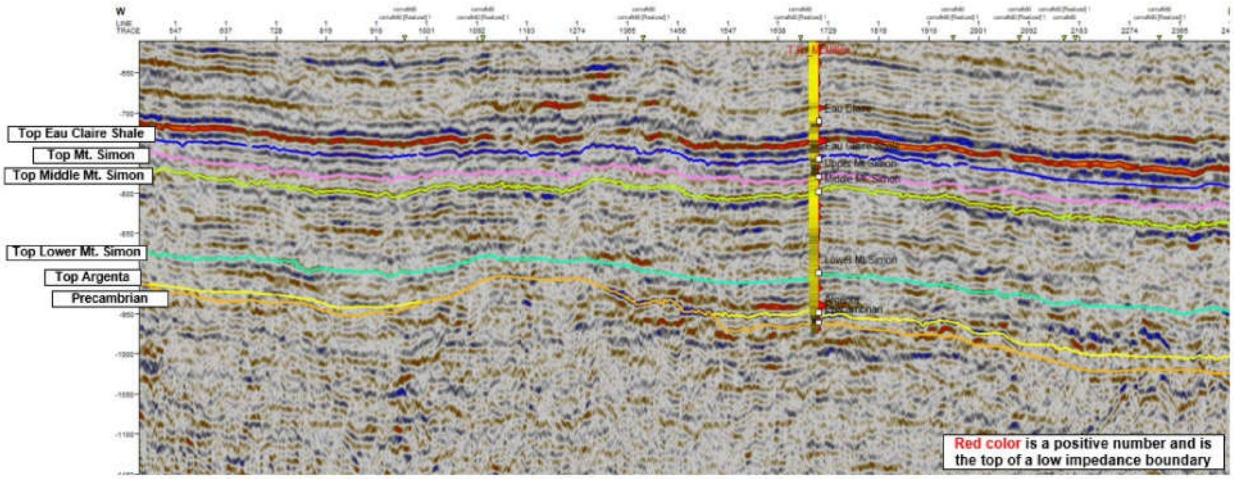

Figure 23. 2D seismic line with well tie to TRM2 showing continuity of strata of the Mt. Simon Storage Complex. A basement high is observed about 4 miles west of well location that may impact lower Mt. Simon Sandstone reservoir.

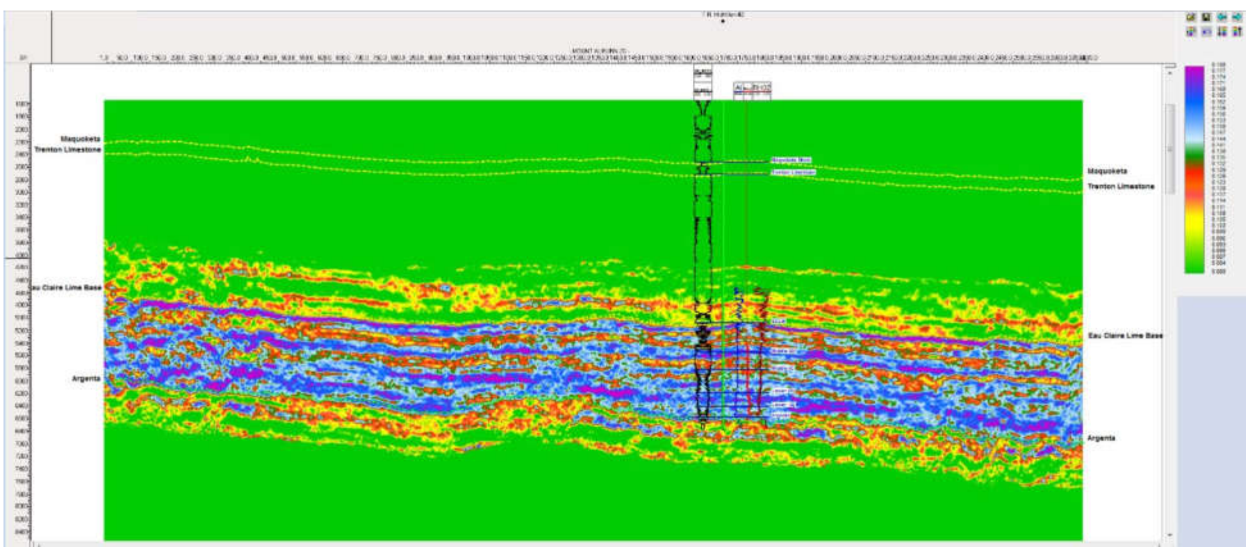

Figure 24. Porosity volume derived from seismic and log data using Log Porosity vs Seismic AI crossplot

The top of the Precambrian basement arrives at ~870-1,000 ms. Relative to Paleozoic markers, the top of the basement is less coherent, somewhat discontinuous, and mostly single cycle, implying a more complex surface. In places, the surface is gently undulating or disappears. The top of the basement is occasionally underlain by a thin, layered sequence, about 100 ms in duration. Further below the top of the basement, only a few short reflector segments and/or diffractions occur. At about 1,800 ms (below CDP 2,800), a prominent reflection arrives and extends over much of the section, before being cut off by the eastern end of the profile at 2,670 ms. The length of this reflector is over 30 km and has an apparent, unmigrated dip to the east (in the plane of the section) of 4.8°-5.2°, assuming a likely basement velocity of 6.0-6.5 km/s. The relative amplitude is strong, compared to Paleozoic markers. It shows multiple cycles (at least three) and is segmented, with edge diffractions in places. Below it are numerous, less-coherent reflector segments and diffractions, some of which are as much as 10 km in length, dipping opposite to the overlying east-dipping Precambrian reflector (Figure 25). The western portion of the section is relatively reflection-poor in the Precambrian—it is not clear if this is related to the acquisition conditions, change in attenuation levels, or an actual change in the Precambrian geology (i.e., less acoustic impedance contrasts). Additional information on the results of the CarbonSAFE Illinois – Macon County seismic reflection study can be found in Chapter 2 of Appendix C (Freiburg et al., 2022).

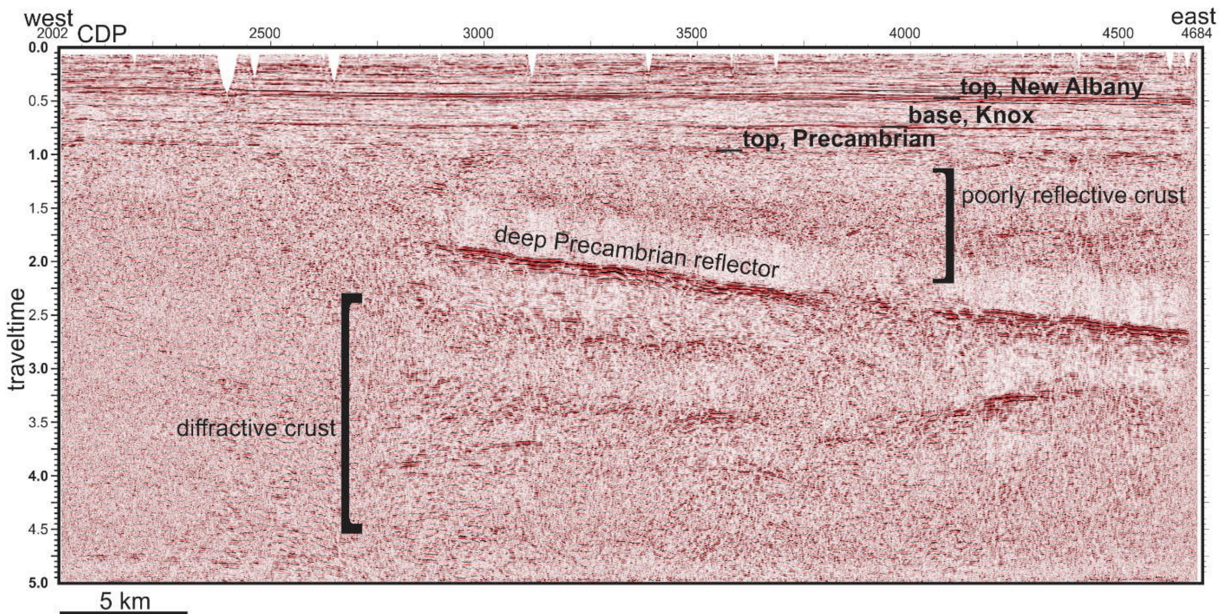

Figure 25. Christian County seismic profile. Stratigraphic markers are based on a vertical seismic profile and on regional correlations. The section is displayed with a vertical exaggeration of about 1.4:1, assuming an average velocity of 6 km/s. Note that the dimmed zone above the deep reflector is a shadowing artifact of the automatic gain control.

VSP Results

A zero offset VSP and a walkaway 2D VSP was performed using the TRM2 well (Figure 26). The zero offset VSP was acquired February 20-21, 2019 using sweep parameters: 6-140 Hz, 16 sec sweep (linear; 500/500ms tapers; 4 sec listen); and source parameters: Vibe Model: I/O 362 (63,000lbs; 70% drive), and nominal source spacing; 220 ft (67 m). The receiver geometry used an array of 60 levels and a depth range of; ZVSP 1.6 - 6,350.0 ft (0.5 - 1,935.5 m). For the 2D VSP depth range was 493.7 - 6,350.0 ft (150.5 - 1,935.5 m).

The objectives were to provide a high resolution 1D image of the zero offset VSP and travel time/depth information to the bottom of the receiver array, and to produce as a detailed 2D image from the walk away sources to provide a tie between the well location and the 2D surface seismic line approximately 3,500 ft (1,067 m) north of the well.

A P wave reflection corridor stack was produced for the ZVSP location as well as a time depth interval velocity profile sampled every 50 ft (15 m). These data can be used to support the interpretation of the surface seismic data as well as provide a high resolution "check shot" survey to allow for accurate conversion from two-way time to depth.

Because the ZVSP corridor stack is a primary-only reflection image it can discriminate between primary and multiple reflections on the surface seismic data. Several clear multiple zones were identified on the ZVSP which aided in the interpretation of the surface seismic data.

The 2D VSP image also shows improved resolution compared to the nearby surface seismic. Due to acquisition restrictions, the source line was not straight and contained two significant lateral offsets that created some discontinuities/anomalies in the final image. Additional information regarding the VSP surveys is included in Appendix F, *VSP Processing Report for CarbonSAFE Illinois – Macon County* (Sterling Seismic).

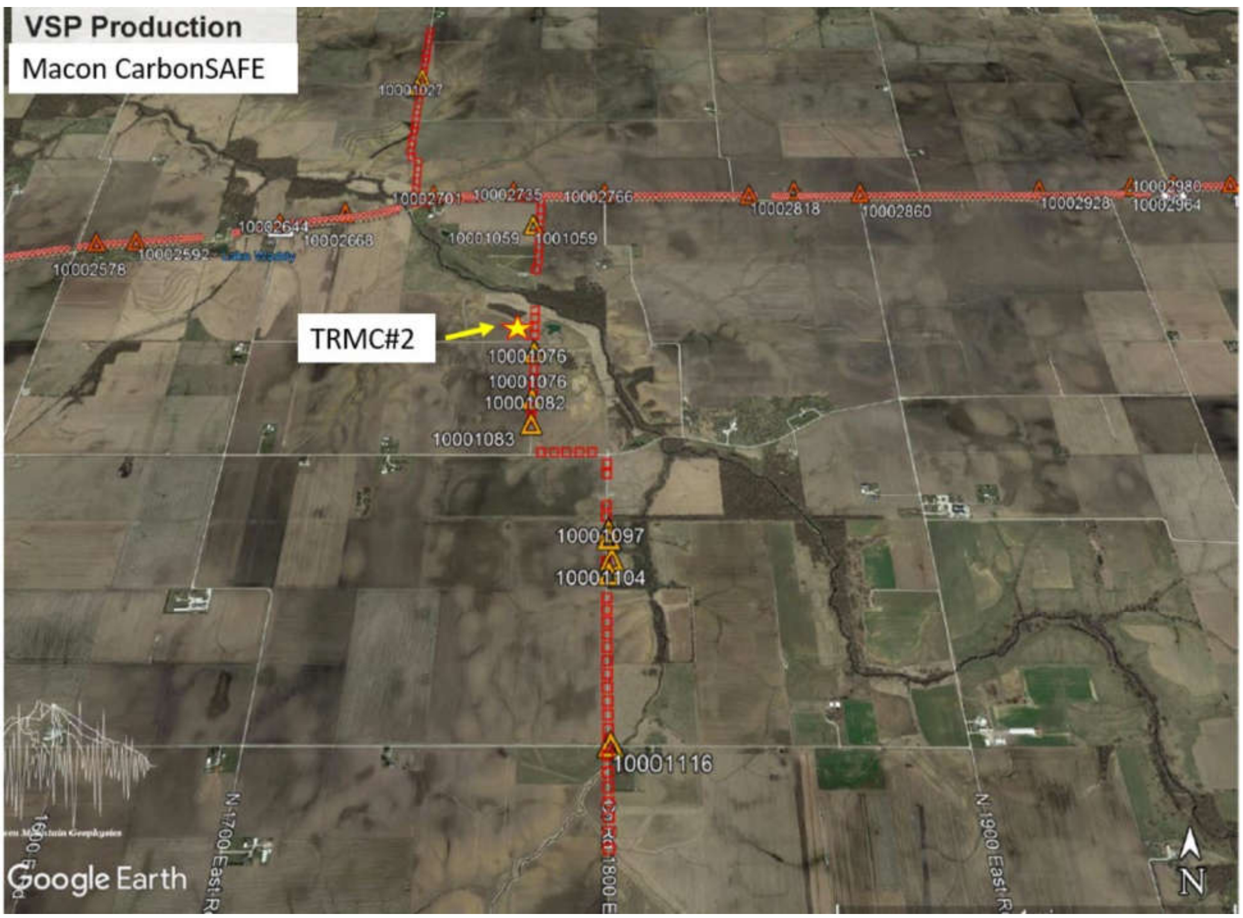

Figure 26. Location of the 2D walkaway VSP survey trending N-S and crossing the E-W 2S surface seismic survey line

Geomechanical Analyses

Geomechanical knowledge and measurements are used to understand the earth stresses and the mechanical properties of formation rocks that may be impacted by injection of CO_2. For example, at the IBDP site microseismicity has been observed to be induced by injection and which is mainly concentrated in the crystalline basement (Williams-Stroud et al., 2020). In the central Illinois Basin, the Argenta Formation is variably present (or with variable thickness) between the Mt. Simon Sandstone reservoir and Precambrian basement rock. It was observed that most microseismic events are located in the area where the Argenta is thin or missing and thus it is considered that the Argenta may impede prevent or impede downward migration of fluid/pressure and the reactivation of pre-existing faults in the basement. Therefore, geomechanical characterization of Argenta and Precambrian rhyolite was conducted to evaluate the role of these formations in induced microseismicity during CO_2 injection in the Illinois Basin.

For the CarbonSAFE Macon project, Argenta samples (77-114 mm in length and 59.4 mm in horizontal size) were taken from cores from the TRM2 well at depths between 6,296-6,299 ft (1,919-1,920 m) and used for the characterization of the geomechanical properties (Figure 27a). Cores (150 mm in length and 88 mm in diameter) of Precambrian rhyolite used for the study are from between 6,399-6,464 ft ([1,950-1,970 m] Figure 27b). Geomechanical testing includes measurements of index properties, ultrasonic velocities, strength characteristics, and poromechanical and flow properties for involved formations. The testing procedures and results are presented in detail in Chapter 6 of Appendix C (Freiburg et al., 2021).

(a) **(b)**

Figure 27. a) Cores of Argenta from depths between 6,296-6,299 ft. b) Cores of Precambrian rhyolite (basement rock) from depths between 6,399-6,464 ft.

The geomechanical characterization of Precambrian rhyolite and Argenta specimens indicates that Argenta is significantly softer and has a larger dominant pore size compared to Precambrian rhyolite. This observation supports an assumption that Argenta might be the upper part of the crystalline basement, significantly affected by the weathering process. Preliminary estimation of permeability for the Argenta is four orders of magnitude smaller than the permeability of the reservoir rock (permeability of Mt. Simon sandstone ~10^{-14} m^2). This fact supports the assumption that Argenta might act as a bottom seal that prevents the downward migration of fluid into the basement rock. Precise measurements of the flow properties for Argenta and Precambrian rhyolite are in progress. Strength measurements of Precambrian rhyolite indicate the significance of pre-existing weak planes in the basement rock. Cohesion for specimens of Precambrian rhyolite with visible weak planes is close to zero since they failed easily during the coring. The response of the Argenta seems to be more ductile than that of Precambrian rhyolite, which possibly explains the absence of microseismic events in the Argenta formation.

A Mechanical Earth Model (MEM) is a numerical representation of all geomechanical parameters available for the storage complex and spans the entire stratigraphic section penetrated by TRM2. A one-dimensional MEM (1D-MEM) developed for TRM2 to help select core for mechanical property testing and as a first-stage model. Well logs from TRM2 that were incorporated into the 1D-MEM were: trajectory, density, neutron porosity, photoelectric factor, caliper, array resistivity, natural gamma ray, spectral gamma ray, magnetic resonance, elemental capture spectrometry, acoustic, advanced multi-mineral log analysis, and fullbore formation microimager.

Horizontal stress direction is among the more important regional parameters for evaluating impacts of injection on reservoirs and can be determined by examining borehole images for drilling induced features such as tensile fractures or borehole breakout caused by shear failure. The TRM2 well had borehole images from FMI from 4,405 to 6,440 ft (1,343 to 1,963 m) in the TD section of the well. There were observed shear failure in this interval as well as drilling induced tensile fracturing. The observed shear failure breakout was confined to the Eau Claire formation and drilling induced tensile fractures were observed in the Eau Claire and Precambrian formations. Tensile fractures will be in the maximum stress direction, as the borehole pressure becomes greater than the minimum stress. Drilling induced formation shear failure will be orthogonal to the tensile fractures indicating the minimum stress direction. The azimuth of the drilling induced fractures interpreted from FMI logs is shown in the rose diagram in Figure 28. The drilling induced tensile fractures show the maximum stress direction to be between 70 and 100 degrees.

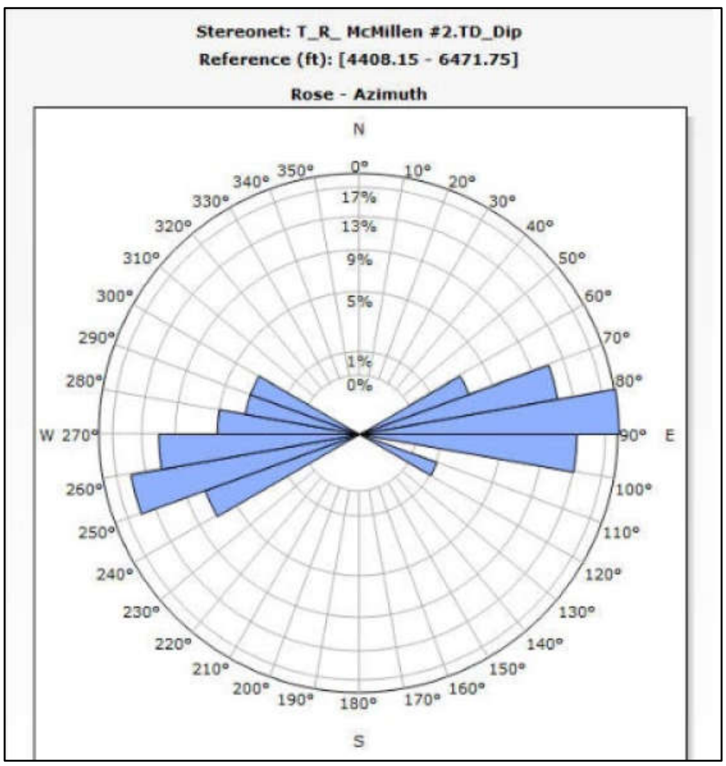

Figure 28. FMI drilling induced tensile fractures indicating the maximum stress direction in TRM2

Storage Complex Modeling

Evaluating the potential to store commercial quantities of CO_2 in the region of the TRM2 well includes the development of a geocellular static model to integrate much of the acquired data to represent the geological setting of the Mt. Simon Sandstone storage complex, and the subsequent dynamic simulation to assess injection characteristics and behavior of injected CO_2 and overall storage performance of the site.

One of the measures for commercial-scale CCS as identified by the US DOE in their CarbonSAFE program is the storage of 50 million tonnes (Mt) injected over 30 years. This target is the basis for many of the simulations performed during this project. Additional simulation scenarios considered the feasibility of storing 20 Mt of CO_2 over 12 years (1.67 million tonnes annually [Mta]) to address stakeholder interests associated with current 45Q laws. We additionally considered a project intending to store 150 Mt of CO_2 in 30 years (i.e., 5 Mta) – or 50 Mt in 10 years which is a more recent DOE target derived based on the need for acceleration of storage at larger scale for reducing greenhouse gas emissions to the atmosphere.

Modeling workflow includes developing a conceptual model to help produce a static geocellular model of the CarbonSAFE Illinois – Macon County project area. The project area static model was extracted from a regional static model, developed by the ISGS, that covers much of the Illinois Basin. Property models (e.g. porosity and permeability) were developed to include site-specific data generated from drilling of the TRM2 well, and to honor both other regional deep subsurface data as well as the localized conceptual model created by the project team. These models are discussed in *Storage Complex Modeling for CarbonSAFE Illinois – Macon County* (Okwen et al., 2022; Appendix G). The static model was subsequently used as the basis for dynamic simulations to evaluate a range of injection scenarios.

Mt. Simon Sandstone Geocellular Modeling

A geocellular model was developed, using *Petrel*®, that incorporated data obtained during and after the drilling of TRM2 in Christian County, Illinois, including core, petrophysical analyses, geophysical logs, vertical seismic profiles (VSP), and in situ well tests. Discussions around the design and inputs to the static model are presented in Okwen et al. (2022) (Appendix G). The model includes the Mt. Simon storage complex (Mt. Simon Sandstone and Eau Claire Formation), the underlying Argenta Formation and top of the Precambrian basement and incorporates both structural and property (porosity and permeability) models. The structural elements were obtained from a regional static model built by the ISGS that covers nearly the entirety of the Illinois Basin. Porosity and permeability were modeled for each stratigraphic unit within the static model.

In addition to TRM2, three other regional wells that penetrate the entire Mt. Simon Sandstone are included in the model: Hinton Brothers #7 in Champaign County, FutureGen in Morgan County, and VW#1 in Macon County drilled as part of the Illinois Basin – Decatur Project (Figure 29). The regional geocellular model developed is 107 by 70 mi (172 by 113 km) that was cropped to 40.6 by 40.1 mi (65.3 by 64.5 km) for use in dynamic simulations.

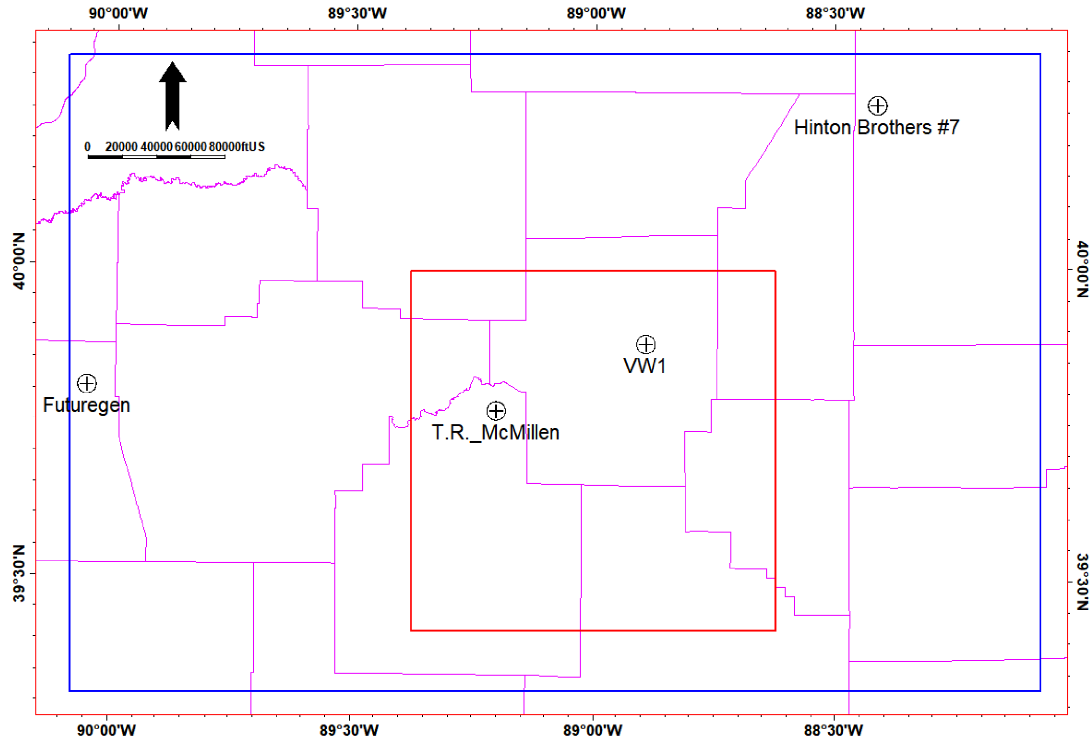

Figure 29. Map showing the location of wells used for this study and the project model area (red) and larger regional (blue) model areas.

<u>Injection Simulations</u>

Prior to drilling TRM2 dynamic simulations were performed using a layer cake model based on regional data to evaluate the feasibility of injecting 50 Mt of CO_2 into the Mt. Simon storage complex over 30 years. The simulation incorporated a 15 ft (4.6 m) perforated interval in the Lower Mt. Simon Sandstone having 150 md permeability and the results indicated that this injection target should be achieved in the Mt. Simon Storage complex at the study area.

Subsequent dynamic simulations used input from the geocellular model built using new data acquired during the project that include fluid and rock properties of the target reservoir and seal to evaluate a variety of potential injection scenarios having different injection rates, masses, and duration. Discussions around the design of the dynamic simulation and inputs to the model are presented in Okwen et al. (2022) (Appendix G**).** The metrics used to evaluate and compare the performances of simulated scenarios include:

- *CO_2 plume areal extent and height*: defined using a 1% CO_2 saturation cutoff
- *Pressure front extent*: based on 34 psi pressure change at the top of Upper Mt. Simon Sandstone. The pressure front extent is derived from the area at the top of the Upper Mt. Simon where pressure change is greater than, or equal to, a pressure buildup ($\Delta p_{i,f}$) equivalent to the hydraulic head between the Mt. Simon Sandstone and the St. Peter Sandstone, which is the deepest USDW at TRM2. The $\Delta p_{i,f}$, equivalent to the hydraulic head is 34 psi and was calculated from the initial reservoir and fluid properties of the Mt. Simon Sandstone and St. Peter Sandstone at TRM2.
- *Area-of-Review (AoR)*: the greater of CO_2 plume or pressure front extent

Included in the dynamic simulations are historical and assumed future CO_2 injection activity at the IBDP and Illinois-Industrial Carbon Capture and Sequestration (IL-ICCS) projects approximately 23 mi (37 km) northeast at the Archer Daniels facility in Decatur, IL. These were included to evaluate the impact of multiple active injection projects occurring at relatively close proximity within the basin. The simulated injection schedule is as follows:

- 2011-2014 (3 years) injection of 0.33 Mta using injection well CCS1 at the IBDP site;
- 2014-2017 (3 years) no injection occurring;
- 2017-2050 (33 years) injection of 0.6 Mta via injection well CCS2 at IL-ICCS;
- 2020-2050 (30 years) of injection of 1.67 – 5.00 Mta using TRM2 (and one or more notional wells depending on simulation), and;
- 2050-2100 (50 years) post-injection.

Injection Scenarios

A common question is how much CO_2 can be injected annually using a single CO_2 injection well. Simulations were performed to address this question and used wellbore specifications similar to CCS2, which is the largest commercial-scale injector in the region, and targeted injection into a high-permeability interval (~2500 md) observed at TRM2 and informally referred to as the Arkosic Zone. Constraints considered in the simulation include regulated maximum injection pressure (90% formation fracture pressure), regulated tubing head pressure of CCS2 (2,284 psi), and CO_2 threshold vibration velocity. Threshold vibration velocity is the fluid velocity below which excessive noise within a wellbore is mitigated. Simulation results show that the threshold vibration velocity (equivalent to 1,750 psi tubing head pressure) is the most stringent constraint. Using this constraint, it is technically feasible to achieve an injection rate of 2.3 Mta using a single well that would result in storage of 69 Mt in 30 years (i.e., reservoir capacity is not a limitation in this scenario). There are, however, other constraints to consider for any site such as, for example, reservoir pressure changes and distribution that could lead to induced seismicity. It is not suggested that such a high sustained injection rate would be feasible for ongoing storage operations.

For the simulation scenarios at TRM2 the primary constraint applied is to limit pressure change to a maximum of 450 psi at the injection interval. This is based on an empirical observation from injections well at the ADM site in Decatur that reservoir pressure changes of up to 450 psi are associated with minimal injection-induced seismicity. Although a single well can potentially inject the target of 50Mt over 30 years using the Arkosic Zone, because this zone is highly permeable the CO_2 moves laterally, and plume size is relatively large at ~50 mi^2 (130 km^2). As a result, single and multiple injection well scenarios were simulated to determine strategies to minimize CO_2 plume size. Local grid refinement centered around injection well(s) was used to increase grid resolution and capture the dominant fluid flow mechanisms during injection and post-injection. We considered three tiers of injection scenarios: (1) 50 Mt of CO_2 in 30 years, (2) 20 Mt of CO_2 in 12 years, and (3) 150 Mt of CO_2 in 30 years.

Tier 1 - inject 50 Mt of CO_2 in 30 years: Eight scenarios, including vertical wells and horizontal wells of variable length were simulated to determine strategies to inject 50 Mt of CO_2 in 30 years (1.67 Mta) at TRM2.

1. Perforate entire Arkosic Zone (80 ft [24 m])
2. Perforate Lower Mt. Simon Sandstone (752 ft [229 m])
3. Perforate Upper Mt. Simon Sandstone (140 ft [43 m])
4. Perforate Upper and Lower Mt. Simon Sandstone (270 ft [82 m])
5. Perforate 4,000 ft (1,220 m) horizontal well in Lower Mt. Simon Sandstone
6. Perforate 2,500 ft (762 m) horizontal well in Middle Mt. Simon Sandstone
7. Perforate Upper (140 ft [43 m]), Middle and Lower (931 ft [284 m]) Mt. Simon Sandstone, and Arkosic Zone (80 ft [24 m]) sequentially
8. Perforate Middle and Lower (913 ft [279 m]) Sandstone and Arkosic Zone (80 ft 24 m]) sequentially

Tier 2 - inject 20 Mt of CO_2 in 12 years: Two injection strategies were simulated to evaluate the feasibility of injecting 20 Mt of CO_2 in 12 years (ca 1.7 Mta).

9. Perforate the Arkosic Zone (similar to scenario 1 above); and
10. Perforate a 4,000 ft (1,220 m) horizontal well in the Lower Mt. Simon Sandstone (similar to scenario 5 above).

Tier 3 - inject 150 Mt of CO_2 in 30 years: Two injection scenarios based on three or four injection wells were simulated to evaluate the feasibility of storing 150 Mt of CO_2 in 30 years (5 Mta). Each scenario also includes multiple cases varying well types, location, or injection interval.

Multiple injection wells are required to achieve the injection of 150 Mt CO_2 over 30 years using the parameters of the Mt. Simon Storage Complex near the TRM2 well. We simulated scenarios using three and four injection wells including variable perforations and well spacing. Simulation results show that either three or four injection wells spaced one mi (1.6 km) apart can inject 150 Mt of CO_2 in 30 years.

11. Three wells:
    - 2,500-ft (762-m) horizontal well at TRM2 perforated in the Middle Mt. Simon
    - Vertical well east of TRM2 perforated in the Arkosic Zone
    - Vertical well southeast of TRM2 perforated in the Arkosic zone

12. Four wells:
    - 2,500-ft (762-m) horizontal well at TRM2 perforated in the Middle Mt. Simon
    - Vertical well east of TRM2 perforated in the Arkosic Zone
    - 4,000-ft (1,220-m) long horizontal well south of TRM2 perforated in the Lower Mt. Simon
    - Vertical well southeast of TRM2 perforated in the Arkosic Zone

The three scenarios above that perform best in terms of reducing CO_2 plume extent, pressure front and AoR are scenarios 1, 5 and 6. The CO_2 plume migrates up-dip and vertically in the simulated scenarios due to buoyancy. However, low-permeability intervals, especially in the bottom of the Middle Mt. Simon Sandstone, retard vertical migration of the plume. In all scenarios the maximum pressure front extent (852 – 931 mi^2 [2,207 – 2,411 km^2]) is larger than the CO_2 plume area (38 –

60 mi^2 [98 – 155 km^2]) indicating the maximum pressure front extent defines the AoR. At the end of injection (30 years in the above scenarios) pressure directly at the injection well(s) dissipates significantly within the first two years and the pressure front within the reservoir progressively diminishes throughout the 50 years of the Class VI-defined Post Injection Site Care (PISC) period. The pressure front in these scenarios was determined at the top of the Mt. Simon Sandstone (i.e. base of top seal), and because buoyancy is the main force impacting CO_2 movement during post injection, those scenarios that inject nearest to the upper zones of the reservoir (e.g. 3, 6, and 7) have the slowest reduction in pressure front.

Each scenario can achieve the target injection rate with capacity for the required mass of CO_2. The CO_2 plume area of scenario 9 (37 mi^2 [95 km^2]) is larger than that of scenario 10 (22 mi^2 [57 km^2]) because the relatively higher permeability of the Arkosic Zone results in broader lateral spread of injected CO_2. The pressure front areas for both scenarios diminish within ten years of post-injection. Each scenario can achieve the target injection rate of 5 Mt CO_2 annually with capacity for the required mass of 150 Mt CO_2. In the Tier 3 scenarios about 60% of the total volume of CO_2 is injected via the wells perforated in the higher permeability Arkosic Zone. In general, four injection wells (scenario 12) result in smaller CO_2 plume area (156 mi^2 [404 km^2]) and AoR (1,364 mi^2 [3,533 km^2]) than the three wells of scenario 11 (200 mi^2 and 1,415 mi^2 [518 km^2 and 3,665 km^2]) respectively) because less CO_2 is injected per well.
Simulation results from this study indicate:

- A single well can inject 1.67 Mta into the Mt. Simon Sandstone having parameters similar to those observed at TRM2 in Christian County, IL. This can achieve the objectives of injecting 30 Mt of CO_2 in 30 years, or 20 Mt of CO_2 in 12 years. Whereas this injection rate is theoretically possible, it must be noted there is no operational experience for sustained injection at these rates. Most existing CO_2 injection in projects globally is ca 1 Mta or lower.
- For single injection well scenarios, AoRs generally become larger the nearer perforations are to the top of Mt. Simon Sandstone.
- The maximum CO_2 plume and pressure front areas of the single well Tier 1 and 2 scenarios 38 – 60 mi^2 (98 – 155 km^2) and 852 – 931 mi^2 (2,207 – 2,411 km^2) , respectively.
- Up to 150 Mt of CO_2 (5 Mta) can be injected into the Mt. Simon Storage complex over a period of 30 years using 3 to 4 injection wells spaced at one mi (1.6 km) or more.
- The maximum CO_2 plume and pressure front areas of the multiple well Tier 3 scenarios are 156 – 200 mi^2 (404 – 518 km^2) and 1,364 – 1,415 mi^2 (3,533 – 3,665 km^2) , respectively.
- Reservoir heterogeneity within the storage complex influences movement of CO_2. The CO_2 plume migrates vertically and laterally up-dip within relatively higher permeability facies due to buoyancy. Low-permeability layers, such as observed in lower strata of the Middle Mt. Simon Sandstone retard vertical migration of the CO_2 plume. Using these reservoir variations as part of an injection strategy can potentially help minimize CO_2 plume and AoR size.

Risk Analyses

Qualitative assessment

A qualitative risk evaluation was performed for the overall project and to identification technical project risks and is attached as Appendix H, *Project Risk Assessment and Monitoring for*

CarbonSAFE Illinois – Macon County (Khan et al., 2021). This was performed through a combination of risk assessment meetings, workshops, expert solicitation, and implementing risk mitigation or prevention activities. Information from previous carbon storage projects and from the execution of the project (including drilling a test well and conducting 2D seismic survey) were assessed to identify future risks towards the development of a storage complex.

An initial risk workshop in September 2017 focused on defining the core values of the project as they related to the CarbonSAFE Macon project objectives to aid in how risk was perceived at a project level. Workshop participants determined loss criteria to help quantify severity and likelihood for each risk. The team reviewed high-level project risks and developed risk mitigation strategies. A second risk workshop in March 2018 included a discussion of risk mitigation plans for each of the previously identified risks, as well as a subset of risks that were identified during the meeting. The group ranked the residual severity and likelihood based on the mitigation or management plans for each risk. A third risk workshop in June 2019 was held to further discuss the specific risk mitigation strategies regarding the modeling and simulation phases of the project, as well as methods to integrate the model inputs into the National Risk Assessment Partnership (NRAP) methodology. Risks associated with modeling and simulation were identified, and risk management strategies were developed.

Application of NRAP Tools

Tools developed by NRAP, a U. S. DOE program that is quantifying the risks associated with geologic carbon storage (GCS) operations, were used to assess the probabilistic risk associated with a hypothetical leakage of CO_2 and brine along an injection well and one monitoring well, and the potential level of impact to two overlying aquifers. This work is available in Appendix I, *NRAP Toolkit Screening for CarbonSAFE Illinois – Macon County* (Huerta et al., 2020).

The results indicate that, for all realizations and both hypothetical wells, the modeled leak rate into the aquifers is low, and the total amount is far below the 1% leakage value commonly cited as the acceptable criteria in GCS. Changes in TDS, ΔP, and pH were observed, but had either an undetectable impact greater than 0.5 m from the hypothetical leaky well (TDS and ΔP) or undetectable impact after 5 years into the simulation. The negligible modeled impacts of a leaky open borehole indicated to the project team that general observations on monitoring technology choices could be made based on the aquifer impact simulations alone, and that further analysis using the NRAP Designs for Risk Evaluation and Management (DREAM) tool would be unwarranted.

CO_2 SOURCE AND INFRASTRUCTURE DEVELOPMENT

Sources

The Illinois Basin is situated within a region of the US Midwest in which there are a variety of industries producing many 10s of million tonnes of CO_2 annually. Lu et al. (2020) In *Modeling Assessment of Retrofitting Power Plants and Industrial Facilities for Carbon Capture and Storage in the Illinois Basin,* Lu et al. (2020) described that in the region including Illinois, southwestern Indiana, and western Kentucky, emissions from energy production using fossil fuels in 2018 alone were estimated to be 220 million tonnes from 234 power plants: 54 coal, 134 natural gas, 41 oil, and 5 other fossil-derived (Appendix J). Coal power plants in 2018 had a total generating capacity similar to natural gas plants but they generated 80% of the total fossil fuel electricity and were the predominant source of CO_2 emissions in the Illinois Basin, although this percentage has lowered during the course of this study. In 2018 fossil fuel combustion contributed to 41%, 92%, and 91% of electricity generation in Illinois, Indiana, and Kentucky, respectively.

Facilities with the potential to capture large quantities of CO_2, within proximity of the proposed storage site, include: 1) coal-fired electric utility plants, 2) natural gas utility plants, and 3) ethanol production facilities. Although other facility types may have the potential to capture CO_2, the project focused specifically on these three facility classes as most capable of generating sufficient quantities of CO_2 to facilitate a cost-neutral business case. Below is summary-level information on the location and characteristics of each facility type.

Note that whereas the following analyses reference real-world facilities, e.g., the Dalman Station power plant in Springfield, IL, these references are made to contextualize potential CCS projects leveraging the Macon CarbonSAFE storage site in a real-world context, but use screening-level, industry-average cost and scaling parameters as described in Koenig et al. (2020), *CCS Business Development Case Study for CarbonSAFE Illinois – Macon County* (Appendix K), and are made for research purposes only. In actuality, each potential capture partner facility has its own unique array of factors and cost considerations that will inform its involvement, and the costs and revenues associated with such involvement, in a potential CCS project.

Electrical Utility Plants

Data collected by the U.S. Environmental Protection Agency (U. S. EPA) indicate that nineteen coal-fired electric utility plants and one natural gas plant are located within 125 mi (200 km) of the Macon CarbonSAFE storage site and emitted over 1,000,000 metric tons of CO_2 in 2018. Ten of these facilities emitted over five million tons of CO_2 in 2018, with the top three facilities (Gibson, Labadie, and Prairie State) emitting 18.0, 16.6, and 12.1 million tons of CO_2, respectively. Of the three facilities that emitted over ten million tons of CO_2 in 2018, Prairie State is the closest to the Macon County storage site, which is located approximately 106 mi (170 km) away. Of note, since the analyses was performed for the project, 8 of the facilities have announced closure.

In Illinois alone, there are thirteen power plants, consisting of thirty-four electric generating units in the Illinois Basin that were constructed after 1990, each with an installed capacity greater than 150 MWe. Among these relatively young plants, ten are fueled by natural gas and three by coal. However, existing power plants often have lower energy efficiency and higher marginal operating costs than new power plants, so the CarbonSAFE Illinois – Macon County project CO_2 source study focused on assessing the technical and economic opportunities for CO_2 capture retrofit to existing fossil fuel power plants in order to identify those plants with the greatest potential for CCS deployment. The attributes and CO_2 emissions of fossil fuel power plants in Illinois, Indiana, and Kentucky were assessed, and a representative natural gas and coal-fired power plant were selected for case studies of carbon capture retrofit. These results are presented in Appendix J (Lu et al., 2020).

Cost correlations with respect to unit size and remaining lifetime were developed and compared for natural gas vs. coal power plants. The capital cost per unit of net generation capacity for retrofitting coal power plants was found to be almost double that of the natural gas plants. However, because of the larger amounts of CO_2 captured in the coal plant retrofits, the resulting CO_2 capture costs (%50 - %60/ton) were much lower than those of natural gas plants retrofits ($80 - 100/ton), revealing a tradeoff between capital investment need and cost of CO_2 capture. Additional details on CO_2 sources in the region and locale are available in Appendix L, *Screening-Level Cost Estimates for CO_2 Capture and Transportation: CarbonSAFE Illinois – Macon County* (McKaskle, 2021), and Appendix J (Lu et al., 2020).

Ethanol Production Facilities

Of the ethanol production facilities recorded in a database maintained by the Renewable Fuels Association, eleven are located within 125 mi (200 km) of the Macon County storage site. The ethanol production facilities proximal to the Macon CarbonSAFE site produce significantly lower CO_2 emissions than the electric utility plants. Of the eleven ethanol plants, by far the largest emitter (Archer Daniels Midland's facility in Decatur) is already permitted and operating a Class VI injection well. One Earth Energy's Gibson City facility is located within 65 mi (105 km) of the storage facility.

Other Potential CO_2 Capture Partners

It is possible to expand the range of potential capture partners to identify those beyond the 125-mi (200-km) radius used in this study. For example, increasing the radius from 125 mi (200 km) to 250 mi (400 km) yields a total of 100 coal-fired electric utility plants, natural gas plants, and ethanol production facilities proximate to the Macon CarbonSAFE storage site.

Capture, Compression and Transportation

Five sources were identified more specifically as potential suppliers of CO_2 to the study area: ADM Corn Processing in Decatur, IL; the CWLP Dallman Unit #4 in Springfield, IL; (3) the Wabash Valley Resources (WVR) facility in Terre Haute, IN; (4) the Abbott Power Plant in Champaign, IL; and (5) the Prairie State Generating Company (PSGC) power plant in Marissa, IL. For the project screening-level estimates were prepared for the cost of transporting CO_2 from the five sources to a potential injection well located in northern Christian County. The results of this study are summarized in Table 15, and further details are available in Appendix L (McKaskle, 2021).

Table 15. Annualized Costs of CO_2 Capture, Compression, and Transportation for the Five Selected Facilities

Source	Minimum Capital and Operating Costs ($/tonne)	Average Capital and Operating Costs ($/tonne)	Maximum Capital and Operating Costs ($/tonne)
ADM Decatur	18	21	24
WVR Syngas	26	29	33
Prairie State Unit #1	51	53	55
CWLP Dalman #4	66	67	68
Abbott Power Plant	149	154	161

Costs above include estimates for capital and operating costs for capture (when applicable), compression, dehydration, and transportation (pipelines), storage and monitoring (TS&M). We did not include operating and maintenance costs for the pipelines themselves. These could be added as these estimates are refined. In each case, estimated pipeline diameters trend towards the larger end of a typical range coupled with assumption that no booster pump stations would be required to deliver CO_2 at the required surface injection pressure of 1,345 psig. This initial surface injection pressure estimate was used for all cases. The addition of booster stations could allow use of lower cost, smaller diameter pipelines with the tradeoff of capital and operating costs at the booster stations. The assumptions regarding required surface injection pressure and pipeline diameter may be adjusted as the projects become more defined.

As shown in the summary table, the average cost of capture, compression and TS&M varies between $21 to $91 per tonne of CO_2 for these five locations. The two most cost effective options are the locations where there are no added costs for CO_2 capture (ADM Decatur and WVR); ADM Decatur has a lower estimated cost because the CO_2 source is closer to the Mt. Auburn injection when compared to WVR. The next two lowest cost sources are Prairie State and CWLP, which capture CO_2 from coal-fired flue gas. Prairie State's estimated costs are approximately 15% lower than CWLP due to economies of scale associated with building a larger facility. The highest cost source is the Abbott Power Plant; this can be attributed to the low concentration of CO_2 in the exhaust gas, and the relatively low amount of CO_2 available compared to the other sites.

STORAGE COMPLEX DEVELOPMENT

Business Environment

Commercial deployment of CCS has already been demonstrated as feasible in the Macon County region by Archer Daniels Midland's IL-ICCS project in Decatur, IL. The business climate in the Central Illinois area is one that is familiar with industrial activities and has already hosted other CCS projects. The central and south-central regions of Illinois are home to multiple coal-fired power plants and ethanol plants, as well as other industrial production and manufacturing facilities that produce CO_2. The geological setting in this region is also favorable for secure, long-term storage of CO_2. Financial backing for CCS projects in this region can come from a variety of sources including owner/operator financing, equity financing, or debt financing. For qualifying CCS projects, low interest loans and loan guarantees can be obtained through the U. S. DOE Loan Program Office and rural electricity generation CCS projects may also obtain low-interest loans through the USDA Rural Utilities Service. Any project undertaken with partners must have contracts outlining roles, responsibilities, and financials. Other contracts may be required with surrounding landowners for land rights-of-way and pore space rights for injection. The State of Illinois has demonstrated continued support for CCS development in the state through its tax incentives and CCS-based goals set in the Clean Coal Portfolio Standard as well as the declaration that CCS is in the best public interest of Illinoisans, allowing for CO_2 pipeline eminent domain. Perhaps most significantly, 45Q tax credits, private tax-equity investments, or storage agreements with multiple CO_2 sources in the region provide revenue paths for CCS projects in the area. Commercialization of CCS in the Illinois Basin region has a viable forward path.

Additional key considerations are associated with CCS projects in the current economic and regulatory climate:

- The presence of existing pipeline rights-of-way owned by electric utilities or other entities in Illinois, and the reasonableness of using such rights-of-way to develop additional pipelines to convey CO_2
- The costs, difficulty, and potential pitfalls associated with new pipeline construction in Illinois, including considerations regarding procurement of engineering services, permitting, and ongoing pipeline monitoring and maintenance
- The potential for premature shutdown of a capture partner facility. As recently as July 2019, the U.S. Energy Information Administration noted that coal-fired electricity generation lacks a healthy prognosis

An analysis presented in Koenig et al. (2021) (Appendix K) regarding commercialization potential focused on the costs of new pipeline construction to deliver CO_2 to the prospective storage site. This analysis could be further expanded with some or all the following analytic steps to examine the financial feasibility of a CCS project involving CO_2 storage at the Macon CarbonSAFE site. The aim of these analytic steps would be to develop a potential breakeven estimate assessing 45Q (and potentially 48A/48B) tax credit potential against total project costs:

- Development of a present value "revenue" stream, based on anticipated tax credits associated with per-ton 45Q credits (at a minimum) and/or project-level 48A/48B credits

- Assessment of capital retrofit costs to develop carbon capture units at capture partner facilities
- Assessment of other capital costs, including compressors and co-generation (combined heat and power) units as they may be relevant to specific capture partner facilities as part of carbon-capture retrofits
- Assessment of annual operating costs and annual storage costs. Based on the five facilities examined, annual operating costs could range between $4.5 million and $75 million, whereas annual storage costs could range between $2.5 million and $39 million

As part of the evaluation of commercialization potential of CCS in the project's study area in central Illinois information was compiled to leverage the project's stakeholder analysis to provide recommendations for an engagement plan, explore the business surrounding of a CCS project that would allow a private firm to profit, analyzed the legal, regulatory, and policy influences over CCS projects, and studied the existing infrastructure that can be best adapted for commercial-scale CCS projects. This compilation is presented in *Integrated and Regional Overview for Commercialization CarbonSAFE Illinois – Macon County* (Koenig, 2021; Appendix M).

Policy, Regulatory and Legal Considerations

Illinois does not have state laws or regulations that directly address the capture and storage of CO_2. Instead, Illinois follows the federal UIC Class VI Well permitting and monitoring regulations authorized under the federal Safe Drinking Water Act's (SDWA) Underground Injection Control (UIC) Program. The UIC Program along with the federal Greenhouse Gas Reporting Program (GHGRP), directly regulate the geological storage of CO_2.

Long-term CO_2 storage requires significant amounts of deep pore space for geologic storage which raises the question of who owns the potential storage volume of subsurface reservoirs or "pore space" in Illinois. The Federal Class VI Regulations do not directly address property rights associated with CO_2 storage. Likewise, neither Illinois caselaw nor legislation squarely address property rights associated with obtaining title to and control over pore space suitable for CO_2 storage.

Generally, in Illinois, an owner of land is entitled to the surface and all that is below it unless it is a mineral estate, which may be legally severed from the surface estate by granting the minerals and reserving the surface, or by granting the surface and reserving the minerals. Notably, the Illinois Supreme Court has long held that "oil and gas are classed as minerals, that term not being confined to metallic substances.

Illinois caselaw also supports the premise that corporations or government departments can exercise the power of eminent domain when it has been specifically conferred by legislative enactment, but the authorizing law must itself always be strictly construed to protect property owners.

The Illinois Power Agency Act (20 ILCS 3855) authorizes the State Power Agency to take real or personal property needed for construction of power plants Notably, the Act says that the "State should encourage the use of advanced clean coal technologies that capture and sequester CO_2

emissions to advance environmental protection goals and to demonstrate the viability of coal and coal-derived fuels in a carbon-constrained economy" and defines "storage" as "permanent storage of CO_2 by injecting it into a saline aquifer, a depleted gas reservoir, or an oil reservoir, directly or through an enhanced oil recovery process that may involve intermediate storage". The Illinois Power Agency Act does not directly address property rights related to CCS but could support legislation that extends limited rights of eminent domain to subsurface pore space used for CCS.

The "*ad coelum* doctrine" forms the basis of U.S. common law property law. The doctrine defines the boundaries of property ownership in the state as follows: from the surface to the heavens and below the surface to the depths, without limitation. Examples of the *ad coelum* doctrine in practice include Illinois' purchase of subsurface property for the construction of the Superconducting Super Collider, and the legal premise that title or real property rights in Illinois can be surveyed for "any portion of the volume of the earth's surface, subsurface, or airspace involving the lengths and direction of boundary lines, areas, parts of platted parcels or the contours of the earth's surface, subsurface, or airspace." Both examples suggest that Illinois recognizes title and/or real property rights in the subsurface, which could include pore space for carbon storage. The scope of the potential property right, however, continues to remain unclear as is evidenced by the lack of Illinois caselaw on the subject.

Additional regulatory uncertainties include:

- Potential for greater CCS project incentives, e.g., expanding the criteria for awarding 48A tax credits
- Regulatory rollbacks, e.g., the replacement of the Obama-era Clean Power Plan with U. S. EPA's recently-announced Affordable Clean Energy rulemaking
- The continued presence and application of existing environmental regulations, such as the U. S. EPA's 2015 coal combustion residuals (CCR) rulemaking (regulations codified at 40 CFR Part 257), which adds management costs to coal-fired electric utility plants and can lead to premature shutdown or fuel-switching for affected facilities.

UIC Class VI Permit Planning

Pre-Permitting Activities
This UIC permitting plan provides a general outline of tasks, timelines, and information needed to prepare U. S. EPA Class VI permit applications for a storage site in the CarbonSAFE Macon region. Meetings with regulators should be held as needed to review requirements for a Class VI permit as set forth in 40 CFR 146.82(a) and to review and concur on submittal requirements (e.g. electronic submittal formats). These meetings should provide information to the regulatory agency on site characterization, methods to establish AoR, modeling, well construction, financial requirements, risks, communication and outreach, and permit schedule.

UIC Class VI Permit Application
The permit applications must be prepared in accordance with Class VI guidance. Adhering to the regulatory guidance assures that required technical and administrative aspects of the project are addressed, and that documentation is complete. Key sections of the permits include: Site

Characterization, AoR and Corrective Action, Financial Responsibility, Injection Well Construction, Pre-Operational Testing, Proposed Operating Conditions, Testing and Monitoring Plans, Injection Well Plugging, Post-Injection Site Care (PISC) and Site Closure, Emergency and Remedial Response, Demonstration of Containment, Public Participation, CO_2 source and chemical makeup of CO_2 Stream.

Permit Application Revisions

The project proponent must also be prepared to respond to technical questions and comments from U. S. EPA. The permit applicant will also respond to questions and comments from the public received during the public review period. The permit application will be revised as needed and resubmitted to U. S. EPA. Upon approval, the permit applicants will receive a "*Permit to Construct Class VI Underground Injection Well*".

General Timeline

There are several critical path elements that must be completed to develop the UIC permit application submittals. These include timely drilling and completion of a stratigraphic test well along with other testing and analysis to support site characterization, a site characterization report, and development of geologic and hydrogeologic models. Interim modeling results will be used to develop permit application components (preliminary AoR, monitoring planning, injection scenarios and conditions, injection well design, etc.).

Stakeholder Analyses

The CarbonSAFE Macon County project conducted a stakeholder analysis to identify potential stakeholders and their concerns, map the project area using demographic and environmental indicators, and consider project activities in the context of environmental justice (Greenberg and Jung, 2021; Appendix N, *Stakeholder Analysis Report for CarbonSAFE Illinois – Macon County*). Although the characterization well is in Christian County, it is just outside of Macon County which has the major population center in the region and so the stakeholder evaluation was centered there. Macon County is in central Illinois and has a population of approximately 104,000 people, and an area of 374,920 acres (581 mi^2 [1,505 km^2]). Decatur is the county seat and has major industrial facilities for Caterpillar, Archer Daniels Midland, Mueller Co., and Tate and Lyle. Natural resources in Macon County include oil, gas, sand, gravel, soil, and surface water.

Various stakeholders in Macon County were identified, including but not limited to government bodies, educational organizations, conservation and environmental groups, agricultural communities, landowners, community groups, and religious organizations. To identify which environmental issues are currently and historically important to stakeholders in the county, recent news media, Facebook, and Twitter were searched for certain keywords (e.g. "environmental issues" and "energy"). The three major categories of local environmental concern were defined as:

1) recycling promotions and accessibility,
2) preventing ecosystem degradation, and
3) clean energy generation.

Social media discussions focused on the development and/or refinement of local recycling initiatives, while news media was focused on establishing regulations to protect regional ecosystems, and potential impacts of the Clean Energy Bill, especially as related to coal-fired power plants in central and southern Illinois, and the potential to further develop wind energy generation.

Environmental Justice (EJ), as defined by the U. S. EPA, is "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies" (U. S. EPA, 2019). Environmental Justice must be considered whenever federal funding is used, specifically in applications for Class VI Underground Injection Control (UIC) permits, and pending success of the application, any further development of geologic CCS sites.

The CarbonSAFE Macon County stakeholder analysis accessed environmental justice areas of concern using the U. S. EPA's EJ tool, "EJ Screen," to better understand the potential for EJ in Macon County. The EJ Screen tool enables the user to map environmental and demographic indicators individually and provides an "EJ Index" mapping function that combines demographic factors with a single environmental factor. The tool also allows the user to directly compare multiple maps, e.g., the EJ Index for Hazardous Waste Proximity with Low-Income Population blocks at a sub-municipality granularity.

Key findings from the EJ analyses include:

- Overall Particular Matter National Percentiles ($PM_{2.5}$) in Macon County is 75% and does not show any significant difference between cities and towns
- U. S. EPA's National Air Toxics Assessment (NATA) Respiratory HI National Percentiles are very similar across the county and show less than 50% difference
- Hazardous Waste Proximity National Percentiles are high near the center of Decatur, exceeding 80-90%. The northeast side is particularly high between 90 to 95%. This area includes some high National Percentiles of 'People of Color Population' and 'Low Income Population'
- Areas with a high National Percentiles of Hazardous Waste Proximity have relatively lower National Percentiles of Population over Age 64
- The Wastewater Discharge Indicator National Percentile in Macon County is relatively high on the east side of Decatur and these areas include some areas of high National Percentiles of People of Color Population and Low-income Population
- Hazardous Waste Proximity areas with high Wastewater Discharge Indicator National Percentiles have relatively lower National Percentiles of Population over Age 64

Additional details on the stakeholder analysis are available in Appendix N (Greenberg and Sung, 2021).

CO_2 Network Expansion Modeling

Resource estimates for the Lower Mt. Simon Sandstone were developed using the Sequestration of CO_2 Tool (*SCO_2T*) and data provided by the ISGS, and regional roadmaps for CCS deployment were developed in *SimCCS Gateway*, a decision-support tool for designing CCS infrastructure. The results are detailed in *Development of a Regional Roadmap for Source Network and Storage Deployment for CarbonSAFE Illinois – Macon County* (Kammer and Carman, 2021; Appendix O), and show considerable CO_2 storage potential within the Lower Mt. Simon Sandstone (Figure

30), totaling 52.1 $GtCO_2$, at an average total unit cost of $23.45 per tCO_2, and a minimum and maximum total unit cost of $2.53 per tCO_2 and $189.60 per tCO_2, respectively. A subset of these results was then used to develop the storage facility inputs for *SimCCS Gateway.*

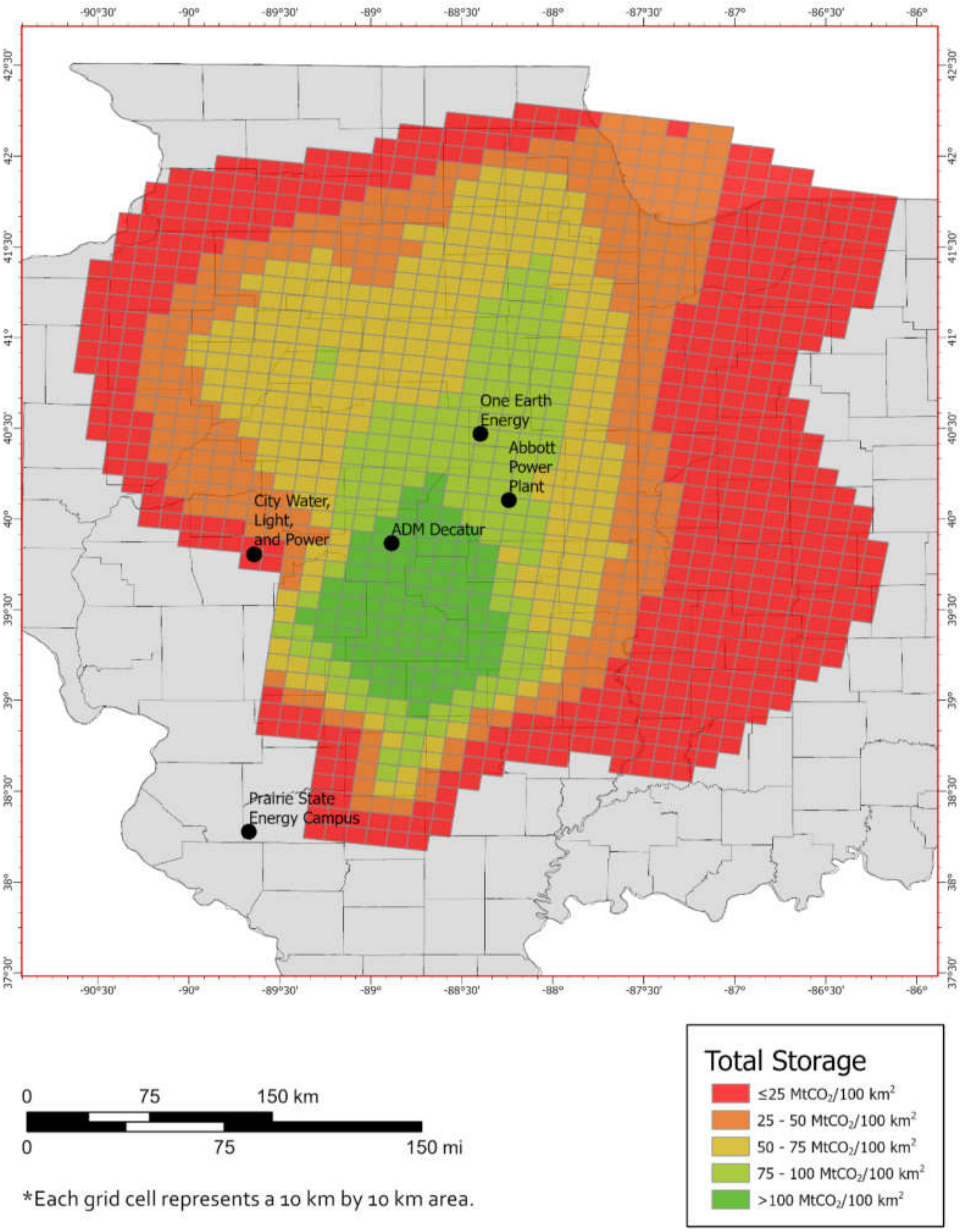

Figure 30. Total storage estimates from SCO_2T for the Lower Mt. Simon Sandstone

In addition to basin-scale resource estimates, four scenarios were used to develop regional roadmaps for CCS deployment, with storage facility locations as the primary variable between each scenario. Total annual capture amounts and associated costs for five capture facilities were used with the storage facility locations to develop candidate pipeline networks for transporting CO_2 between capture and storage facilities (Table 16).

Table 16. Overview of capture facility input data used for SimCCS Gateway simulations

Facility	Annual Capturable CO_2 ($MtCO_2$/yr)	Total Unit Cost ($/$tCO_2$)
ADM Decatur	1.000	18.4
Abbott Power Plant	0.292	81.21
City Water, Light, and Power	1.434	48.72
One Earth Energy	0.450	26.07
Prairie State Energy Campus	6.000	26.45

A total of 76 simulations were conducted within *SimCCS Gateway*, nineteen for each of the four scenarios. An aggregate example of all simulations for Scenario 1 is presented in Figure 31. The pattern of deployment of the five sources is nearly identical in all four scenarios. The five sources are typically deployed based on the total capture cost of each source, with the lowest cost capture facilities deployed first. Interestingly, the pattern is broken in all four scenarios when the annual project capture target is 1.5 $MtCO_2$/yr, before returning to the pattern of capturing from the lowest cost sources available at 2.0 $MtCO_2$/yr and continuing for the remainder of the annual capture target amounts. This is likely due to the limited reservoir-quality Lower Mt. Simon Sandstone near the PSEC, which requires routing CO_2 to higher quality reservoirs closer to the other sources to be cost competitive. At 1.5 $MtCO_2$/yr, the savings in capture cost from PSEC over CWLP are outweighed by the cost of pipeline routing, but this is reversed beginning at 2.0 $MtCO_2$/yr.

The project total unit cost ranges from $21.04 per tCO_2 to $35.59 per tCO_2. The project total unit cost increases as the annual project capture target increases since higher cost capture and storage facilities are not utilized until they are required. The difference in total unit cost between the four scenarios ranges from $0.25 per tCO_2 to $1.04 per tCO_2. The project capture unit cost ranges from $18.40 to $30.73 per tCO_2. Though capture facilities provide most of the total unit cost for a CCS project, the cost difference between scenarios attributed to cost of capture is zero in all scenarios and annual capture targets, with the exception of an annual capture target of 4.5 $MtCO_2$/yr. At the 4.5 $MtCO_2$/yr capture target, Scenario 3 has a total unit cost for capture $0.16 greater than the other three scenarios because it has a fourth capture facility in use while the other three scenarios only have three. The project storage unit cost ranges from $2.57 to $3.02. The difference in total unit cost for storage ranges from $0.00 per tCO_2 to $0.28 per tCO_2, the difference increasing as the annual project capture target increases. The project transport unit cost ranges from $0 to $2.23 per tCO_2. The difference in total unit cost for transport between scenarios is nearly zero at capture targets up to 1.5 $MtCO_2$/yr, but significant at capture targets greater than 1.5 $MtCO_2$/yr, which is largely attributed to the lack of any pipeline needed at low capture amounts for Scenarios 3 and 4. The difference in total unit cost ranges from $0.25 per tCO_2 to $0.86 per tCO_2.

An analysis of the repeated occurrence of specific sources, sinks, or pipeline networks across various scenarios can probabilistically inform the decision-making process to deploy large-scale CCS project. Using the lowest-cost capture options, even when they are not near a suitable storage complex, often results in the lowest total project unit cost for a given annual capture target. This is shown with PSEC being used before CWLP and Abbott Power Plant in almost all project capture amounts, even though the captured CO_2 is transported hundreds of kilometers. Details of this study, including maps, can found be in Appendix O (Kammer and Carman, 2021).

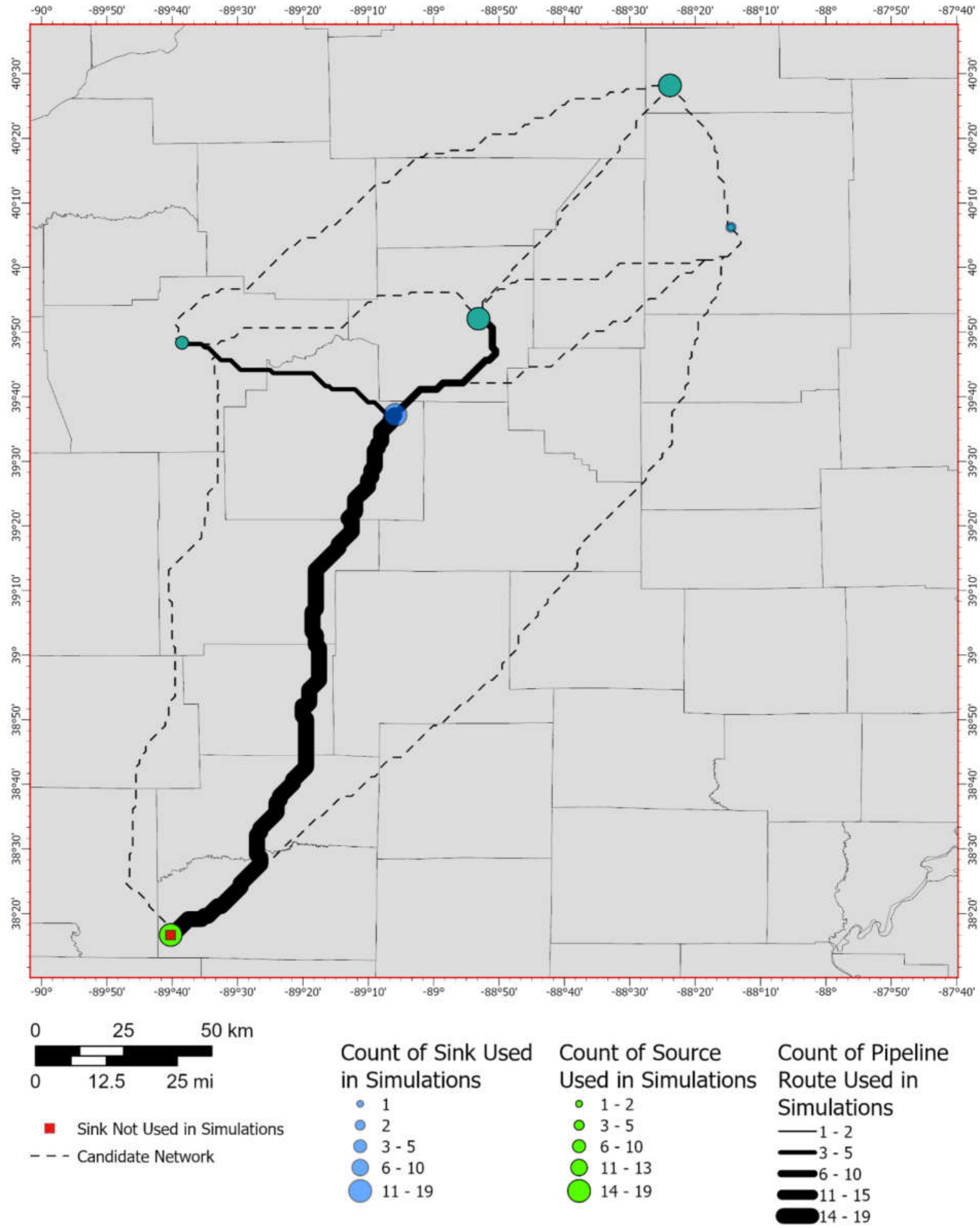

Figure 31. Aggregate of all SimCCS Gateway simulations for Scenario 1. Heavier lines indicate a pipeline route was used in a larger number of simulations. Larger green and blue circles indicate a greater number of simulations used a source or sink, respectively. Circles that appear blue-green include both capture and storage facilities.

SUMMARY

CarbonSAFE Illinois – Macon County established that commercial-scale geologic storage of CO_2 is highly feasible in the central portion of the Illinois Basin. The objectives of the project are to evaluate the feasibility of geologic storage of 50 million tonnes of CO_2 over a 30-year time-frame, and to generate data and establish workflows to assist the development of commercial CCS.

The workflow for the technical evaluation of the storage resource included data acquisition by drilling a stratigraphic well (TRM2) in Christian County, IL, collecting core and cuttings, wireline geophysical logs, performing injection well tests, and conducting vertical seismic profile surveys. In addition, a 30 mi- (48 km-) long 2D seismic profile was surveyed to evaluate the regional structures and lateral continuity of reservoir and containment strata. The data were analyzed, interpreted and incorporated into geostatic models as a basis for dynamic simulation of injection performance.

The project was undertaken as a series of tasks that addressed risk, stakeholder engagement, business and economic issues, permitting, drilling and well testing, geologic characterization, seismic surveys, modeling, CO_2 source suitability and infrastructure development. Detailed reports associated with these tasks are included as appendices to this report. Data generated by this project have also been uploaded to the NETL EDX data exchange site.

The Mt. Simon Storage Complex was the primary target and is comprised of the Mt. Simon Sandstone as the storage unit, and the Eau Claire Formation as the seal, or confining strata. TRM2 reached a total depth of 6,478 ft (1,975 m) and encountering over 1,600 ft (488 m) of Mt. Simon Sandstone. Excellent quality reservoir rock was observed within the Mt. Simon Sandstone strata, particularly in the Lower Mt. Simon Sandstone, but also in other intervals within the formation. The Eau Claire Formation is regionally extensive and includes a thick shale sequence near its base in TRM2 and is an excellent seal to the reservoir.

Geophysical log interpretations and core descriptions were used to characterize the reservoir quality and identify depositional environments to formulate a conceptual model for the Mt. Simon Sandstone in this part of the Illinois Basin. The 2D seismic data indicates little structure in the region with some faults in the upper Precambrian potentially being present regionally. A basement high is observed west of TRM2 that may reduce the thickness of some of the Lower Mt. Simon strata. Extensive well testing confirmed the high quality of reservoir in the Lower Mt. Simon Sandstone at this location.

Dynamic modeling of a series of injection scenarios indicates that commercial-scale storage is highly feasible in this region. The modeled scenarios included single and multiple well injection schemes including to address reaching 50 million tonnes (Mt) stored over 30 years, 20 Mt over 12 years, and 150 Mt over 30 years using 3 to 4 injection wells. The simulations determined CO_2 plume extent, pressure distribution and potential Area of Reviews. Reservoir heterogeneity within the storage complex influences movement of CO_2. The CO_2 plume migrates vertically and laterally up-dip within relatively higher permeability facies due to buoyancy. Low-permeability layers, such as observed in lower strata of the Middle Mt. Simon Sandstone retard vertical migration of the CO_2 plume. Using these reservoir variations as part of an injection strategy can potentially help minimize CO_2 plume and AoR size.

Multiple options for CO_2 sources in the region are present, and were evaluated with cost estimates for compression, transportation, and storage. The business environment in the region indicates that CCS projects would be viewed favorably as there is experience with CCS in the area. A stakeholder analyses highlighted concerns and views in the region that did reflect negatively on CCS. The stakeholder engagement also addressed high level environmental justice issues for Macon County. SimCCS modeled a range of options for expansion of infrastructure networks for the region.

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