Wabash CarbonSAFE

Final Report

February 1, 2019, through March 31, 2022

Illinois State Geological Survey
Prairie Research Institute
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Wabash CarbonSAFE established that commercial-scale CO_2 storage in the Potosi Dolomite – Maquoketa Group storage complex associated with the Wabash Valley Resources plant site near Terre Haute, IN is highly feasible. The CarbonSAFE project team performed this evaluation through extensive data acquisition and analysis including 2D seismic reflection data, wireline logs, well testing, and core/cuttings from the Wabash #1 stratigraphic test well (now plugged and abandoned).

This document summarizes work detailed in separate Wabash CarbonSAFE reports; the report describes the data collection efforts of the project and consolidates the geologic characterization, well testing, and storage complex modeling results for the Mt. Simon Sandstone and Potosi Dolomite, two distinct reservoirs characterized at the Wabash CarbonSAFE project site. Also presented are summaries of work to characterize the CO_2 source and infrastructure network, as well as summaries of reports analyzing stakeholder engagement options, policy, regulatory and legal considerations, and risk assessment associated with the Wabash CarbonSAFE project site. The report then presents recommendations for the next steps for site characterization, identifies data gaps for future activities, and provides an overall assessment of site potential. Data generated by this project have been uploaded to the NETL Energy Data Exchange (EDX) site.

The Mt. Simon Sandstone was the initial target for storage evaluation and was found to have generally poor reservoir qualities in the Wabash #1 well. Simulation results indicate that multiple wells are necessary for the injection of 1.67 million metric tonnes annually of CO_2 for 30 years into the Mt Simon. Due to the lower injectivity of the Mt Simon at Wabash #1 (relative to the higher injectivity typically observed in the central portion of the Illinois basin), focus was then placed on a secondary target, the Potosi Dolomite.

The storage units within the Potosi Dolomite strata are generally thin beds (ca 3-10 ft [1-3 m]) having high porosity and permeability values. In situ well tests at Wabash #1 over a 10 ft (3 m) interval within the Potosi Dolomite indicated that permeability of 2,400 md to 45,000 md or greater exists within the Potosi Dolomite at this location. The thick dense intervals of the Knox Group, including the Eminence Formation, Oneota and Shakopee Dolomites could serve as immediate confining intervals as they exhibit characteristics for effective restriction of vertical movement of fluids through negligible permeabilities. The Maquoketa Group has 312 ft (95 m) of shale and is considered a regional seal for the Potosi Dolomite reservoir interval.

There are no faults identified seismically in the study area that transect the Potosi Dolomite, overlying confining beds, or Maquoketa Group, and the Formation Micro Imager (FMI) log and Maquoketa core from the Wabash #1 well show little to no natural fractures within the Maquoketa interval. Triaxial test and mercury injection capillary pressure results indicate the Maquoketa exhibits geomechanical characteristics and membrane capillary behavior supportive of highly effective sealing capacity.

Simulation indicates the Potosi Dolomite can accept more than 50 million tonnes CO_2 injected over a period of 30 years (1.67 million metric tonnes annually); a 50-year post-injection period showed no further lateral migration of CO_2, while upward movement of CO_2 was restricted to the

lower Oneota Dolomite (1,270 ft [390 m] below the base of the Maquoketa seal). The pressure increase from injection never reaches pressures high enough to fracture the reservoir, and does not substantially propagate vertically past the Dutchtown Limestone; this results in a negligible increase in pressure in any overlying formations above the Dutchtown Limestone. However, lateral extent and connectivity of the vuggy intervals within the Potosi Dolomite is uncertain. The current model assumes that the individual vuggy intervals are in communication across the entire 22 x 22-mile (35 x 35-km) reservoir model. Additional well data in the area would allow for a more heterogenous geologic model.

Due to concerns over potential lost circulation zones in the Potosi Dolomite during Wabash #1 drilling, no core samples or FMI logs were acquired in the Potosi Dolomite. For future characterization efforts, a full suite of geophysical logs, including FMI, should be collected across the Potosi reservoir interval and its confining strata.

In subsequent wells, additional core should be collected for petrophysical and geomechanical analyses in the Potosi Dolomite reservoir interval as well as in the confining units above the Potosi injection interval. Similarly, fluid samples in the Potosi Dolomite itself, as well as above the Potosi Dolomite, would be needed to verify that total dissolved solids greater than 10,000 ppm is maintained through the confining intervals (including the St. Peter Sandstone) and to verify that the lowermost underground source of drinking water is as expected in the Silurian-Devonian strata lying above the Maquoketa Group regional seal.

Wabash Valley Resources (WVR) plans to develop a commercial CCS project in the Illinois Basin. Retrofitting the existing gasification facility reduces the technical risk and capital costs associated with the project, leading to a higher probability of implementation and more competitive product prices. The WVR facility is located above suitable geology for injection of the full amount of CO_2 expected to be captured (ca 1.82 million tonnes per year) with minimal transportation distance providing WVR the opportunity to save on transportation costs with onsite injection. The next steps for site characterization and development include the identification of the location and number of injection wells required to meet project requirements, additional data acquisition, and the generation of US EPA Underground Injection Control Class VI permits for each injection well.

INTRODUCTION

Wabash CarbonSAFE

Wabash CarbonSAFE (DE-FE0031616) was funded from February 1, 2019, through March 31, 2022. The primary objective of this project was to establish the feasibility of developing a commercial-scale geological storage complex at the Wabash Valley Resources LLC's Wabash Integrated Gasification Combined Cycle plant in Vigo County, Indiana, for storage of 50 million tonnes or more of carbon dioxide (CO_2).

Broad goals of the project were to:

- Evaluate the geological characteristics of the proposed storage site in Vigo County, Indiana;
- Drill a stratigraphic well at this location;
- Model the static and dynamic characteristics of the storage complex;
- Identify infrastructure needs and options for saline storage;
- Assess National Risk Assessment Partnership (NRAP) tools for use in commercial-scale projects;
- Evaluate business options for commercialization;
- Engage stakeholders and public on Carbon Capture and Storage (CCS); and
- Construct a detailed plan for storage complex development at this location.

The Wabash CarbonSAFE project drilled the Wabash #1 stratigraphic test well (ID# 168045; Table 1) at the Wabash Valley Resources (WVR) Integrated Gasification Combined Cycle (IGCC) facility in Vigo County, Indiana, to evaluate the feasibility of commercial-scale CO_2 storage near the site. The Wabash #1 well was drilled to a total depth of 8,739 ft (2,664 meters) between November 2019 and February 2020 as the primary data acquisition activity, and after the conclusion of well testing operations the well was plugged and abandoned on July 31, 2020. Additionally, approximately 35 miles (56 km) of local and 68 miles (110 km) of regional 2D seismic reflection data were acquired to better evaluate and interpret Illinois Basin features significant to storage at this site.

This document summarizes work detailed in separate Wabash CarbonSAFE reports (provided in Appendices A-J); this final report describes the data collection efforts of the project and consolidates the geologic characterization, well testing, and storage complex modeling results for the Mt. Simon Sandstone and Potosi Dolomite, two distinct reservoirs characterized at the Wabash CarbonSAFE project site. Also presented are summaries of work to characterize the CO_2 source and infrastructure network, as well as summaries of reports analyzing stakeholder engagement options, policy, regulatory and legal considerations, and risk assessment associated with the Wabash CarbonSAFE project site. The report then presents recommendations for the next steps for site characterization, identifies data gaps for future activities, and provides an overall assessment of site potential.

Contributors
Wabash CarbonSAFE was led by the **Illinois State Geological Survey**, of the Prairie Research Institute, at the University of Illinois.

Wabash Valley Resources, LLC was the industrial site host and CO_2 source operator for this assessment.

Geostock Sandia, LLC led well engineering, drilling, testing and data collection efforts, and contributed with geologic evaluation and model review.

Projeo Corporation provided field management support for site characterization, drilling, well installation and testing, coordinated the acquisition and processing of 2D seismic data, and led in assessing risks to address challenges associated with commercial-scale CO_2 storage at the site.

Trimeric Corporation provided process engineering support related to CO_2 capture, purification, compression, and transportation.

The **Indiana Geological and Water Survey** (IGWS) at Indiana University contributed expertise in geological characterization, petrophysical analysis of the reservoir sealing units, and deep-basin stratigraphy, along with CCS system analysis and *SimCCS Gateway* modeling efforts.

The **School of Public and Environmental Affairs** (SPEA) at Indiana University contributed to social site characterization, stakeholder analysis, and identifying regulatory and legislative requirements for commercialization of CCS.

Pacific Northwest National Laboratory (PNNL) assisted with application of the National Risk Assessment Partnership (NRAP) toolset and supported dynamic reservoir modeling efforts.

Brigham Young University (BYU) contributed to 2D seismic reflection and geologic interpretation.

DRILLING AND WELL DATA COLLECTION

Well Location and Drilling Operations

The Wabash CarbonSAFE project drilled the Wabash #1 stratigraphic test well (ID# 168045; Table 1) at the WVR IGCC facility in Vigo County, Indiana, northwest of the city of Terre Haute, to evaluate the feasibility of commercial-scale CO_2 storage near the site. The drill site is located at the southwestern periphery of the WVR plant (Figure 1). The facility is adjacent, to the north, to the site of the Wabash River Generating Station, a coal-fired station that was retired in 2016 and is being dismantled.

Figure 1. Wabash Valley Resources plant site and location of the Wabash #1 stratigraphic test well. Pre-drilling site imagery is from circa 2018.

The Wabash #1 well was drilled to a total depth of 8,739 ft (2,664 m) between November 2019 and February 2020 as the primary data acquisition activity, and after the conclusion of well testing operations the well was plugged and abandoned on July 31, 2020.

The following summary of well drilling and data collection operations is detailed in the separate report, *Drilling and Completion Report – Wabash #1* (Geostock Sandia, 2022), which is provided separately via the NETL Energy Data Exchange (EDX) site along with Wabash CarbonSAFE project data including geophysical logs and sample analyses from Wabash #1.

The Wabash #1 stratigraphic test well drilling permit was awarded by Indiana Department of Natural Resources (IN-DNR) – Division of Oil and Gas on November 14, 2019. The well construction was performed by Geostock Sandia, LLC, of Houston, Texas. Field activities began on November 20, 2019, with the preparation of the surface location for drilling activities. On November 20, 2019, prior to mobilizing the drilling rig, a 30-inch conductor hole was augered to 115 ft (35 m) and 20-inch conductor pipe set and cemented to surface.

Les Wilson began mobilization of Rig No. 25 on November 22, 2019, and conducted the drilling operations (Figure 2). The 17-1/2-inch surface hole was spudded on November 29, 2019, and drilled to a final depth of 375 ft (114 m). The 13-3/8-inch surface casing was set and cemented at 366 ft (112 m). A 12-1/4-inch intermediate hole was drilled to a final depth of 5,540 ft (1,689 m) and 9-5/8-inch intermediate casing was set and cemented at 5,524 ft (1,684 m). An 8-3/4-inch production hole was drilled, reaching the total depth (T.D.) of 8,739 ft (2,664 m) on February 7, 2020.

Wabash #1 drilling encountered delays related to rig issues and also to difficulty drilling/coring in the deeper part of the Cambro-Ordovician section (Figure 3) in this relatively unexplored region of the Illinois Basin. Due to mounting well costs, drilling was stopped after passing through the Lower Mt. Simon reservoir target (Table 1), but the well did not reach crystalline basement rocks which was the original intent.

Figure 2. Drilling operations at the Wabash #1 stratigraphic test well.

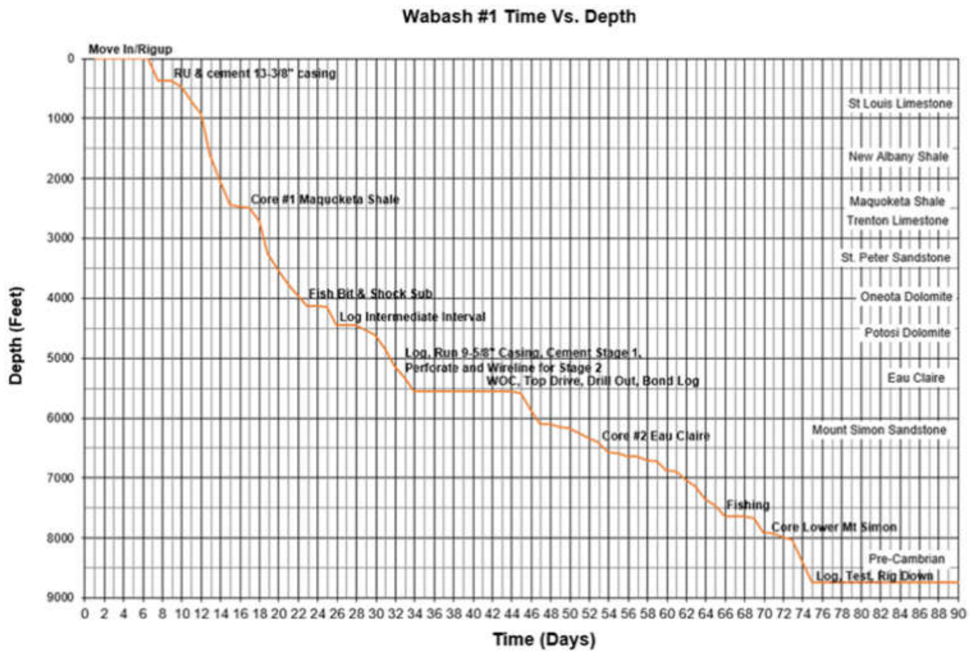

Figure 3. Drilling operations timeline at the Wabash #1 stratigraphic test well.

Table 1. Selected formation tops and measured depths (MD, ft) from the Wabash #1 well, Vigo County, Indiana.

Wabash #1 (IGWS-ID# 168045) Formation Tops	**MD (ft)**
Log reference: Kelly bushing (552 ft elev.)	0
Ground Level (537 ft surface elev.)	15
Pennsylvanian Bedrock, approximate	30
Mississippian-Pennsylvanian Unconformity	748
St Louis Limestone	748
Salem	906
Harrodsburgh	957
Muldraugh	1,032
Borden	1,126
Chouteau/Rockford Limestone	1,638
New Albany Shale	1,642
Devonian Carbonates	1,742
Silurian	1,965
Maquoketa Group	2,386
Trenton Limestone	2,700
Platteville/Black River Group	2,863
Joachim Dolomite	3,168
Dutchtown	3,257
St. Peter Sandstone	3,326
Shakopee Dolomite	3,354
Oneota Dolomite	3,970
Potosi Dolomite	4,473
Davis	5,162
Eau Claire	5,322
Mount Simon Sandstone	6,277
Basalt (Cambrian)	8,515
Mount Simon Sandstone/Argenta	8,535
T.D.	8,739

Core Samples and Geophysical Logging

During drilling, cuttings collection and mudlogging on the Wabash #1 well commenced at a depth of 600 ft (183 m) and continued to well TD at a depth of 8,739 ft (2,664 m). Well cuttings samples were collected on average every 10 ft (3 m); in certain intervals of the well they were collected every 5 ft (1.5 m).

In the Wabash #1 well, a total of approximately 245 ft (65 m) of core was collected from the Ordovician Maquoketa Group and the Cambrian aged Eau Claire Formation and Mt. Simon

Sandstone (Table 2). Additionally, a total of 79 rotary sidewall cores (approximately 1-inch diameter x up to 3-inch length) were cut from formations of the Ordovician and Cambrian strata

A full suite of geophysical logs was collected from Wabash # 1, although limited in the Deep Intermediate well interval (3,300 to 5,528.4 ft [1,006 to 1,685 m]) due to concerns over potential lost circulation zones in the Potosi Dolomite during drilling. Table 3 lists the log type, depth, interval, and acquisition company.

A detailed listing of geologic materials and data collected from the Wabash #1 well and the efforts to document and archive laboratory analyses and sample images can be found in the separate report, the *Wabash CarbonSAFE Geological Data Catalog*, which is included in this report as Appendix A.

Table 2. Whole Core Recovered from Wabash #1. Total lengths of core retrieved: Maquoketa Group (61 ft [18.6 m]); Eau Claire Formation (66.4 ft [20.2 m]); Mt. Simon Sandstone (118.9 ft [36.2 m]).

Well Name	Date	Core	Top Depth	Bottom Depth	Formation
Wabash 1	12/9/2019	1	2435	2496	Maquoketa
Wabash 1	1/11/2020	2	6104	6146.6	Eau Claire
Wabash 1	1/12/2020	2	6146.6	6170.4	Eau Claire
Wabash 1	2/3/2020	3	7900	7957.6	Mt. Simon
Wabash 1	2/4/2020	3	7957.6	8018.88	Mt. Simon

Table 3. Well logs collected for Wabash # 1.

Well Section	Log Type	Bottom Depth (ft)	Top Depth (ft)	Company
Surface	None	-	-	N/A
Intermediate	Dielectric Dispersion Log	4428.5	365	Schlumberger
	Triple Combo (Induction, Neutron, Density, Gamma Ray, Microlog, Spontaneous Potential, Mud Resistivity)	4428.5	365	Schlumberger
	Natural Gamma Ray Spectroscopy	4428.5	365	Schlumberger
	Elemental Spectroscopy	4428.5	365	Schlumberger
	Formation Images	4428.5	365	Schlumberger
	Magnetic Resonance	4428.5	365	Schlumberger
	Directional Survey	4426	365	Schlumberger
	1-arm and 4-arm Caliper	4426	365	Schlumberger
	Dipole Sonic	4426	365	Schlumberger
	Bond Log on Surface Casing	4428.5	365	Schlumberger
Deep Intermediate	Triple Combo (Induction, Neutron, Density, Gamma Ray, Spontaneous Potential, Mud Resistivity)	5528.4	3300	Baker Hughes
	Directional Survey	5528.4	3300	Baker Hughes
	1-arm Caliper	5528.4	3300	Baker Hughes
	Monopole Sonic	5528.4	3300	Baker Hughes
TD	Triple Combo (Induction, Neutron, Density, Gamma Ray, Spontaneous Potential, Mud Resistivity)	8734	5520	Schlumberger
	CMR/NEXT/HNGS (Magnetic Resonance, Elemental Spectroscopy, Natural Gamma Ray)	8739	5520	Schlumberger
	MSCT (Rotary Sidewall Cores)	8690	5700	Schlumberger
	FMI/Sonic (Formation Images, Dipole Sonic)	8739.5	5520	Schlumberger

Well Testing and Completion Operations

After completing the logging runs, Schlumberger rigged down their wireline truck. The hole was conditioned with 9.3 lb/gal, 46 VIS and Trilobite Testing, Inc., Hays, KS (Trilobite) prepared to run drill stem tests (DST) tool in the Mt. Simon Sandstone.

<u>Drill Stem Testing</u>

Trilobite lowered the DST tool in the open hole to 8,735 ft (2,662 m). The upper packers were set at 7,686 ft (2,343 m) and the lower packer at 8,120 ft (2,475 m), the perforated interval in the tool string was at 7,696 ft (2,346 m). On February 13, 2020, a 15-minute flow test was conducted and then shut-in for 1 hour. After attempting a 3-hour build up test, it was discovered that the tool was not closing.

The tool was retrieved to surface, re-set, and lowered back into the well. Bottom was tagged at 8,740 ft (2,664 m), and the packers were set at 6,912 ft (2,107 m) and 6,710 ft (2,045 m). On February 14, 2020, a 20-minute flow test was conducted and then shut-in for 1 hour. The tool was opened and tested for 25 minutes and then the tool was shut for a 3-hour buildup test. The packers were released, and the DST tools were retrieved to surface while collecting fluid samples. The calculated fluid top at the end of test was 1,582 ft (482 m). A copy of the data collected from the drill stem testing is included in Geostock Sandia (2022).

After open hole DSTs were conducted in the Mt. Simon Sandstone, drilling operations were concluded on February 25, 2020 and Rig No. 25 was demobilized from the site. Well logs, samples, and Mt. Simon Sandstone DST data were analyzed and interpreted before additional cased hole well testing was performed later in the year (discussed below). DST results are summarized later in the *Characterization of the Mt. Simon Sandstone* section of this report.

<u>Cased hole Injection Well Testing</u>
Well testing, completion, and abandonment operations commenced in June 2020. Complete Well Service Rig No. 16 was mobilized on June 3, 2020. Well testing consisted of injection and falloff testing across multiple zones of interest, and the well testing operations are detailed in Geostock Sandia, 2022. A packer and plug straddle assembly was used to isolate the test intervals. Memory pressure and temperature gauges (MRO) were installed on the test string below the test zone, within the test zone, and above the test zone. Surface readout (SRO) gauges were deployed via wireline within the test zone. Surface pressure and flowrates were monitored and recorded. Formation fluid samples were recovered from the Potosi Dolomite (Knox Group) and Mt. Simon Sandstone formations by swabbing.

The Potosi Dolomite (Knox Group) well testing was conducted in a single 20-ft (6 m) thick interval (at depths from 4,505-4,525 ft [1,373-1,379 m]) through the 9-5/8-inch intermediate casing. After concluding the tests, the Knox Group interval was cement squeezed and the 5-1/2-inch production casing was set and cemented to 8,724 ft. Well testing results for the Potosi are summarized later in the *Characterization of the Potosi Dolomite* section of this report.

The three test intervals in the Mt. Simon Sandstone (including sandstone below the basalt) were perforated and tested through the 5-1/2-inch production casing. Well testing results for the Mt. Simon are detailed in Technical Report DOE-FE0031626-9 (Freiburg et al., 2022), and the separate report is included as Appendix B (*The Geology of the Mt. Simon Sandstone Storage Complex at the Wabash #1 Well, Vigo Co., Indiana.*)

After the well testing was complete, the well was plugged and abandoned on July 31, 2020. The workover rig was demobilized, and the was site remediated and returned to Wabash Valley Resources.

SUBSURFACE CHARACTERIZATION AND STORAGE COMPLEX MODELING

Material in this section is taken primarily from the *Wabash CarbonSAFE Detailed Site Characterization Plan* (Technical Report DOE-FE0031626-11; Korose and Whittaker, 2022); the site characterization report summarizes and integrates work described in separate technical reports for characterization of the Mt. Simon Sandstone (DOE-FE0031626-9; Freiburg et al., 2022) and Potosi Dolomite (DOE-FE0031626-10; Khosravi et al., 2022) storage complexes, as well as static and dynamic modeling (DOE-FE0031626-8; Dessenberger et al., 2022) of these storage intervals. A later regional 2D seismic survey is summarized after discussions of the Mt. Simon Sandstone and Potosi Dolomite storage complex characterization.

Characterization of the Mt. Simon Sandstone

Geologic Data

The Cambrian Mt. Simon Sandstone and its overlying seal, the Eau Claire Formation, were the initial target for storage complex evaluation and were characterized using data collected from the Wabash #1 well, such as lithologic data collected from cuttings and core, geophysical logging, geomechanical analysis of core samples, and well testing and fluid sampling within the Mt. Simon Sandstone. The geological characterization of the Mt. Simon storage complex at the Wabash #1 Well is discussed in detail in Technical Report DOE-FE0031626-9 (Freiburg et al., 2022; included as Appendix B) and a summary is presented here.

Core and Wireline Log Analyses

The primary seal for the Mt. Simon Sandstone, the Eau Claire Formation, can be lithologically separated into two sections: an upper, carbonate-rich section and a lower, silty-shale section often referred to as the Eau Claire shale. The Eau Claire in the Wabash #1 well is around 900 ft (274 m) thick (Figure 4).

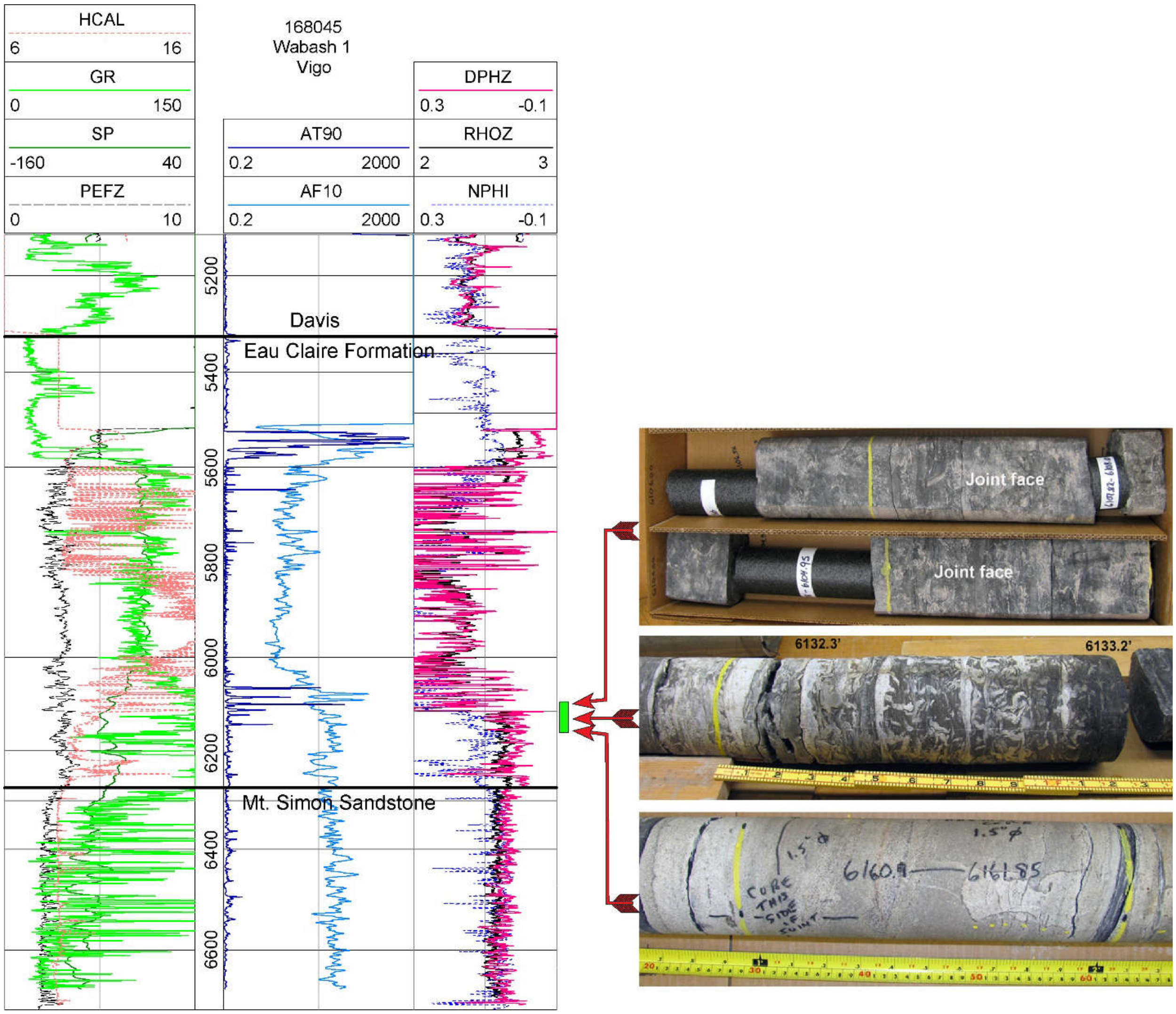

Figure 4. Geophysical log signatures and photographs of the Eau Claire Formation core from the Wabash #1 Well, Vigo County, Indiana. Note the interbedded sandstone, shale, and heavily bioturbated shale/siltstone in the lower part of the formation.

The Mt. Simon in the Wabash #1 well is characterized by dominantly fluvial sandstone strata that contain thinner floodplain muds and aeolian sandstone (Figure 5 and Figure 6). For this study and to correlate this well to other wells, the Mt. Simon Sandstone is divided into three major subunits (Upper, Middle, and Lower; Table 4) that are observable amongst most Mt. Simon wells throughout the Illinois Basin. An additional portion of the Mt. Simon, called the Arkose, is located below the Lower Mt. Simon, generally has favorable reservoir qualities, and is also identifiable in other wells. A porous interval below the Arkose is defined here as the Argenta sandstone, but more work is required on the Wabash #1 dataset to determine if this unit is truly the Argenta or a sub-Arkose member of the Mt Simon at this location. In the Wabash #1 well, a 20-ft (6 m) thick Cambrian age-dated basalt (interpreted to be a flood basalt) is found at the base of the Argenta; below the basalt an unidentified sandstone is present to the total depth (T.D.) of the well (tentatively correlated for regional mapping as Mt. Simon/Argenta sandstone).

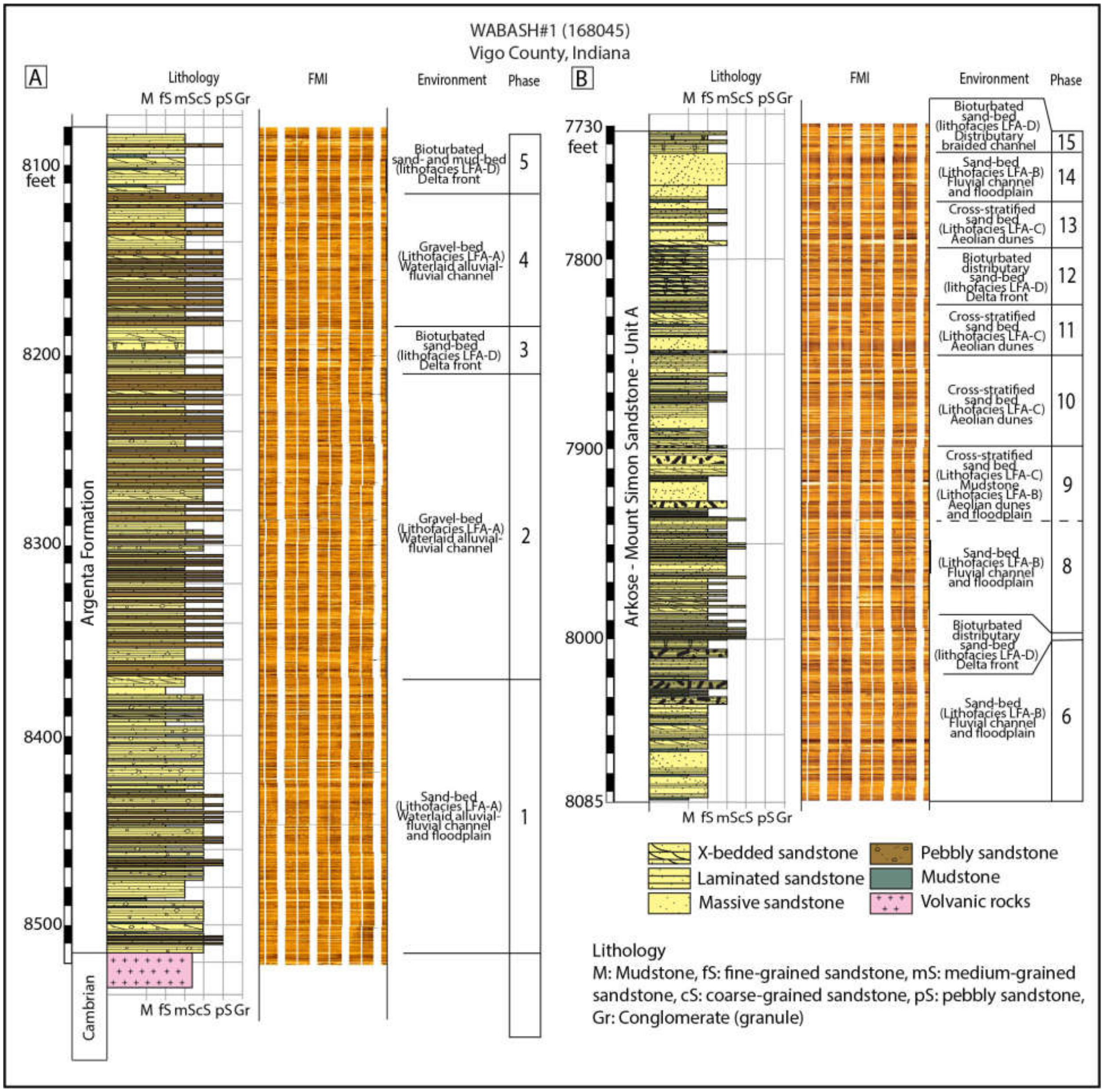

Figure 5. Lithostratigraphic column, FMI log, and composition of the Argenta sandstone and arkose of the Lower Mt. Simon Sandstone showing lithofacies associations and paleoenvironmental interpretation.

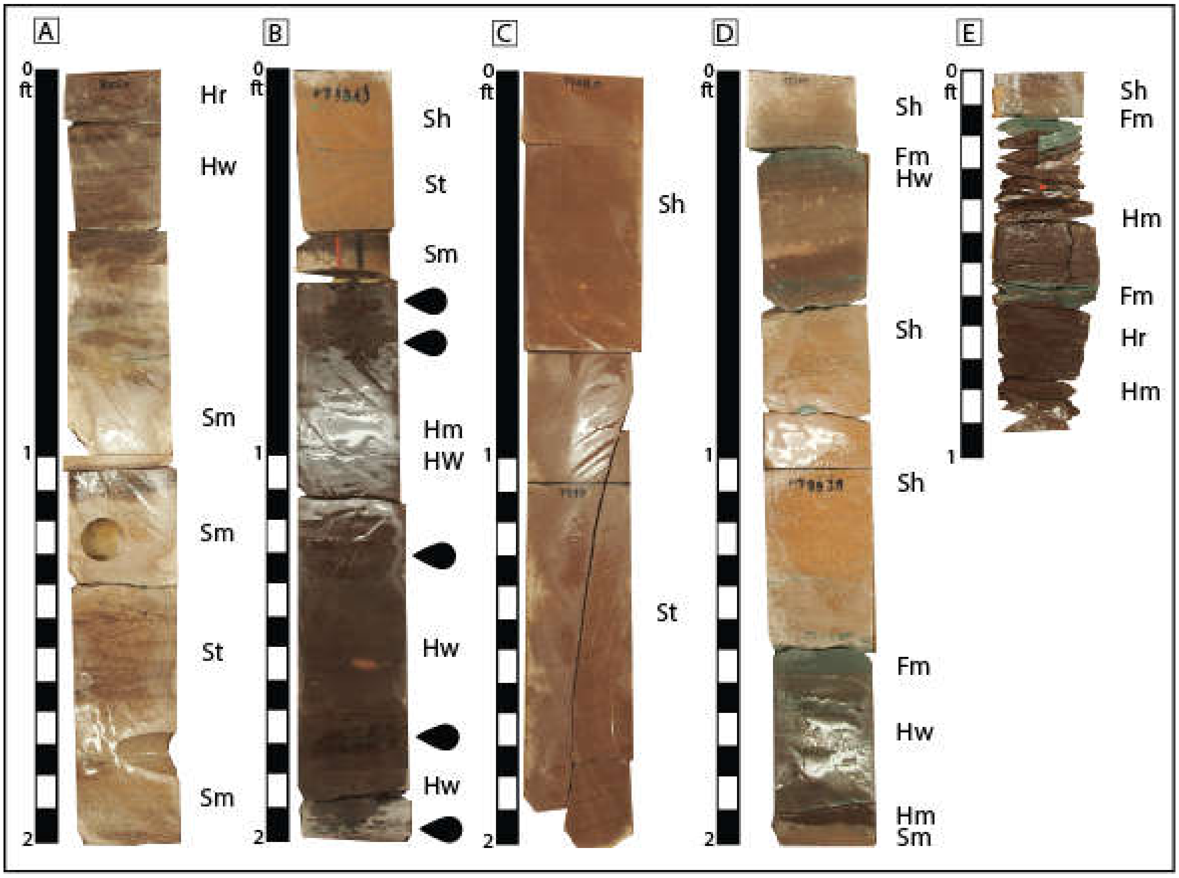

Figure 6. (A) Distributary channel bars that composed massive (Sm) and trough cross-stratified (St) sandstone capped by mouth bar-type facies (Hw, Hr). Arkose (unit A), Lower Mt. Simon Sandstone, depth: 8,002-8,004 ft. (B) Bioturbated heterolithic mudstone (Hw, Hm) and sandstone forming a mouth bar facies. Arkose (unit A), Lower Mt. Simon Sandstone, depth: 7,994-7,996 ft. (C) Fluvial sand dunes that are composed of planar parallel (Sh) and trough cross-stratified (St) sandstone. Arkose (unit A), Lower Mt. Simon Sandstone, depth: 7,948-7,950 ft. (D) Floodplain mudstone at the base, followed by fluvial sandstone. Notice the presence of mud intraclasts in the planar parallel laminated sandstone (Sh). Arkose (unit A), Lower Mt. Simon Sandstone, depth: 7,951-7,953 ft. (E) Floodplain facies composed of heterolith mudstone (Hr, Hm) and fine-grained mudstone (Fm). Arkose (unit A), Lower Mt. Simon Sandstone, depth: 7,914.8-7,915 ft.

The Mt. Simon extends from a depth of 6,277 ft (1,913 m) to 8,085 ft (2,464 m), for a thickness of 1,808 ft (551 m). The Argenta is 430 ft. (131 m) thick, and the unidentified sandstone below the basalt was not fully penetrated but is at least 204 ft (62 m) thick; cumulatively, the "pre-Mt. Simon" sandstones and Mt. Simon Sandstone are at least 2,462 ft (750 m) thick at the Wabash #1 well location.

Table 4. Stratigraphic subdivisions in the Wabash #1 well used in peterophysical analyses.

Formation	Top (measured depth [ft])
Upper Eau Claire	5,322
Eau Claire shale	5,578
Upper Mt Simon	6,277
Middle Mt Simon	6,751
Lower Mt Simon	7,418
Arkose	7,733
Argenta	8,085
Basalt	8,515
Unidentified sandstone	8,535
T. D.	8,739

Petrophysical analysis of well logs is one of the primary methods to characterize the reservoir properties of the formations evaluated for CO_2 injection and their associated confining zones. A full suite of modern well logs, including a standard triple combo (Gamma ray [GR], resistivity, neutron-density porosity), Spectral Gamma ray (SGR), photoelectric (Pe), Nuclear Magnetic Resonance (NMR) and interpreted Combinable Magnetic Resonance (CMR), and Elemental Capture Spectroscopy (ECS) logs were acquired at the Wabash #1 well used for interpretation of the Mt Simon Sandstone storage complex. Rotary sidewall cores (RSWC) taken for all the intervals evaluated and whole core taken from the Arkose interval (the suspected target interval) were also used to calibrate the log data (Figure 7) and better understand the petrophysical properties.

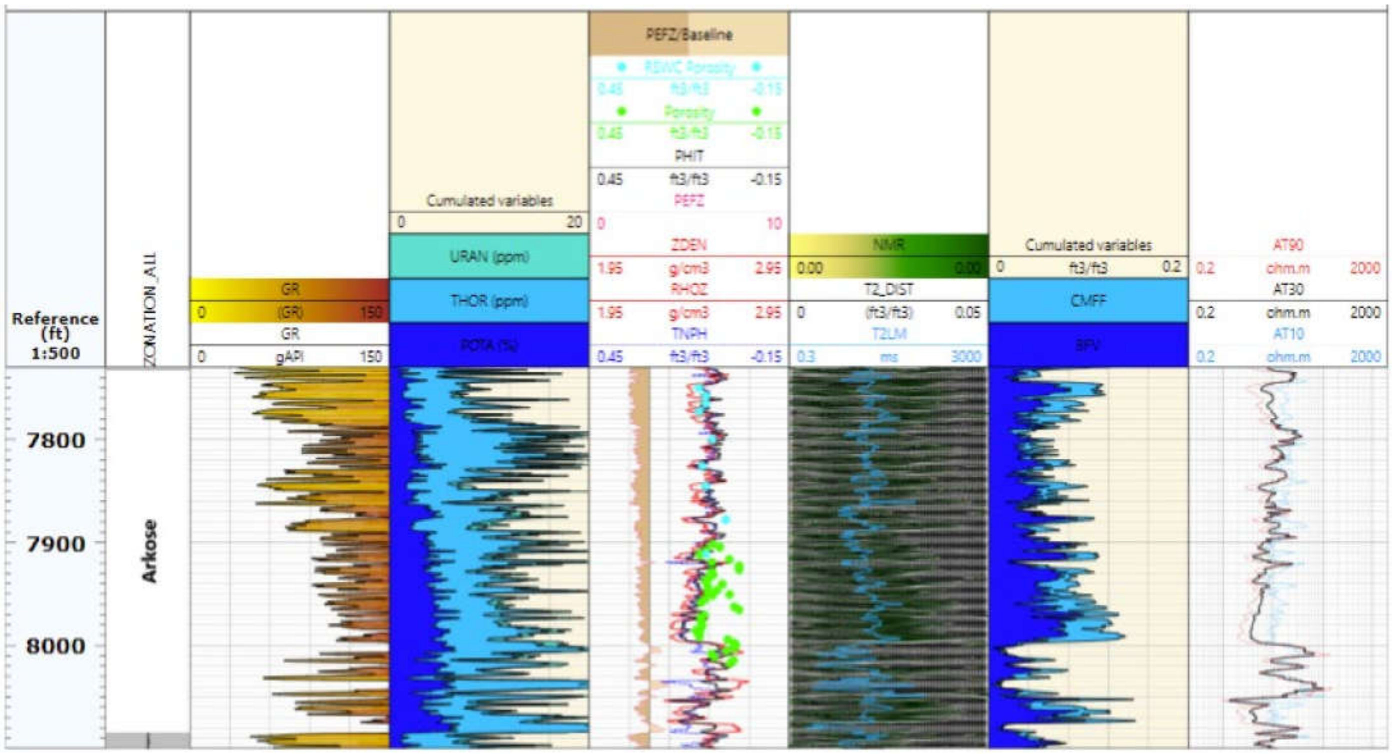

Figure 7. Geophysical logs vs depth for the Arkose interval.

Statistics of the logs for each of the intervals were compiled and analyzed. The average log responses for each of the Mt Simon intervals are similar (Table 5), but the Upper Mt Simon has the highest clay content and lowest reservoir quality, as illustrated by the GR, Pe, and Neutron (TNPH)/Density (DPHZ) separation (which are all higher than in the Middle and Lower intervals).

The Arkose was expected to be the best candidate for CO_2 storage, but whereas it does have some permeable feldspar rich units (as determined by the correlation between elevated Pe/GR and effective porosities from the NMR and SPHI logs), these units are thinner than anticipated. The permeability observed in core, both RSWC and whole core, was also lower than anticipated.

The SGR suggests that the Argenta has four intervals with different clay constituents, so the raw statistics for the whole interval can be misleading, but the NMR log suggests that none of it has very good reservoir quality.

The unidentified sandstone has the highest average estimate of total porosity (PHIT) of all the sandstone units evaluated, but high GR, Pe, pronounced TNPH/DPHZ separation, and NMR derived bound water show that the upper half of the interval has a high proportion of clay and ineffective porosity.

Table 5. Average log values for each of the intervals evaluated.

Formation	PHIT	DPHZ	TNPH	SPHI	GR	Pe
Upper Eau Claire	-20.82%	-53.51%	11.86%	2.16%	28.86	4.92
Eau Claire shale	23.02%	17.91%	28.14%	16.10%	123.05	2.95
Upper Mt Simon	6.11%	4.90%	7.32%	7.45%	66.62	2.12
Middle Mt Simon	6.10%	5.71%	6.49%	7.54%	43.66	1.97
Lower Mt Simon	5.24%	5.03%	5.45%	7.08%	35.07	1.93
Arkose	9.70%	8.24%	11.15%	10.53%	114.15	2.53
Argenta	9.08%	5.38%	12.78%	11.11%	80.65	2.62
Basalt	-1.71%	-14.21%	10.80%	1.98%	45.95	5.18
Unidentified sandstone	11.27%	3.59%	19.14%	14.75%	191.26	3.37

A total of 37 RSWC samples were taken and subjected to routine testing (Table 6). The average porosity and permeability of all the Mt. Simon samples is 9.85% and 3.09 md, respectively, while the Arkose zone, which was expected to have the best reservoir properties, has an average porosity and permeability of 9.67% and 6.57 md. The unidentified sandstone had the best petrophysical properties of all the intervals sampled with 17.25% average porosity and 27.95 md average permeability.

Table 6. Rotary sidewall core porosity statistics for the reservoir.

Unit	Porosity (%)				Permeability (md)		
	Count	Average	Minimum	Maximum	Average	Minimum	Maximum
Eau Claire sh.	1	6.00	6.00	6.00	**0.09**	**0.09**	**0.09**
Upper	2	12.50	12.00	13.00	5.35	0.09	10.61
Middle	5	11.20	7.00	13.00	1.22	0.04	3.54
Lower	11	8.91	5.00	11.00	0.68	0.02	2.91
Arkose	9	9.67	4.00	12.00	6.57	0.02	27.93
Whole Mt. Simon	**27**	**9.85**	**4.00**	**13.00**	**3.09**	**0.02**	**27.93**
Argenta	10	14.20	11.00	20.00	1.34	0.10	7.02
Unidentified	4	17.25	8.00	30.00	27.95	0.09	109.08
All Data	**42**	**11.50**	**4.00**	**30.00**	**5.09**	**0.02**	**109.08**

In addition to sidewall core, 120 ft (37 m) of whole core was taken from the Arkose zone between the depths of 7,900 ft (2,408 m) and 8,020 ft (2,444 m). The core was sampled at regular intervals, resulting in 40 total measurements which were subjected to routine testing (Table 7; note: three samples were fractured and not included in the statistics). These data were consistent with the data from the rotary sidewall cores and confirm that the Arkose interval has lower porosity and permeability than expected.

Table 7. Whole core porosity and permeability statistics.

	Count	Average	St. Dev	Median	Minimum	Maximum
Porosity (%)	37	7.61	3.77	8.19	0.97	12.95
Permeability (md)		2.19	2.76	1.00	0.09	10.90

Drill Stem Tests

During the well drilling process, two drill stem tests, DST1 and DST2, were completed across two unique subintervals, 7,696-8,120 ft (424 ft; parts of Lower Mt Simon/Arkose/Argenta) and 6,710-6,912 ft (202 ft; parts of Upper and Middle Mt Simon), respectively. During each DST, two flow and two shut-in (SI) periods were planned, but DST1 had an atypical response and the 2nd flow and SI period failed. DST1's first flow period was 14 mins, and the SI period was 62 mins. DST2's flow periods were 21 and 23 mins, and the SI periods were 59 and 190 mins. Table 8 shows flow and SI durations, fluid produced, and initial and final flow and SI pressures. The SI period of each test was analyzed for permeability-thickness product. (To estimate permeability, it is necessary to estimate net thickness or assume the subinterval between the DST's packers is the net thickness.) Derivative and semilog (i.e., Horner or superposition) analyses were used to estimate permeability-thickness, and are discussed further in Freiburg et al., 2022.

Because the production period of DSTs are short, initial pressure is often measured directly and confirmed with semilog analyses. The initial pressure for DST1 and DST2 is 3,828 and 3,227 psia at datum depths of 8,109 ft (2,472 m) and 6,901 ft (2,103 m; KB), respectively.

Table 8. Results of the two DSTs conducted in different Mt Simon Sandstone (MtS) subintervals.

Attribute	DST 1	DST 2	Comment
Name	Deeper MtS DST	Shallower MtS DST	
Subinterval, ft (KB)	7,696-8,120	6,710-6,912	
1st flow duration, mins	14	21	
1st SI duration, mins	62	23	
2nd flow duration, mins	-	59	DST1: 2nd SI failed
2nd SI duration, mins	-	190	DST1: 2nd SI failed
Fluid produced, bbl	101.04	71.03	
Test thickness, ft	424	202	
Perm-thickness, md-ft	1,260	980, 460	DST2 Two apparent radial flow periods (more confident in 980)
Initial pressure*, psia	3,828	3,227	
Initial pressure datum, ft (KB)	8,109	6,901	

* Pressure gauge was calibrated for psig; 14.79 psia was average atmospheric pressure in this area during this month.

Porosity to Permeability Transform

Geocellular modeling requires porosity and permeability vs. depth for individual wells. Generally, porosity logs (e.g., neutron and/or density) provide porosity vs. depth directly every 0.5 ft (0.15 m), but permeability vs. depth must be estimated from correlations with well log properties.

Porosity-permeability transforms developed for the Illinois Basin – Decatur Project were adapted for the Wabash #1 well using reevaluated cementation exponent (m) ranges for each Wabash #1 transform. The range of m for Wabash #1 was iteratively changed to get the best match of permeability from the transforms to the core, DST and/or well test permeability on a semilog plot with porosity (Figure 8) and Cartesian plot with depth (Figure 9). There was disagreement between well test (DST) and core-derived permeability, so two permeability curves were developed and used for geocellular models: one matched to the core data and another matched to the DST data; Figure 9 (blue and grey curves) shows the estimated permeability used as the basis for the Wabash #1 Mt. Simon geocellular model.

Modeling of the Mt. Simon storage complex was performed after DST testing but before additional cased-hole injection testing was conducted in the Wabash #1 well. While the modeling helped inform the selection of zones to be injection tested, the injection test results (discussed in Freiburg et al., 2022) further indicated that reservoir quality in the Mt. Simon was less than initially expected. The results of static and dynamic modeling of the Mt. Simon storage complex are summarized below.

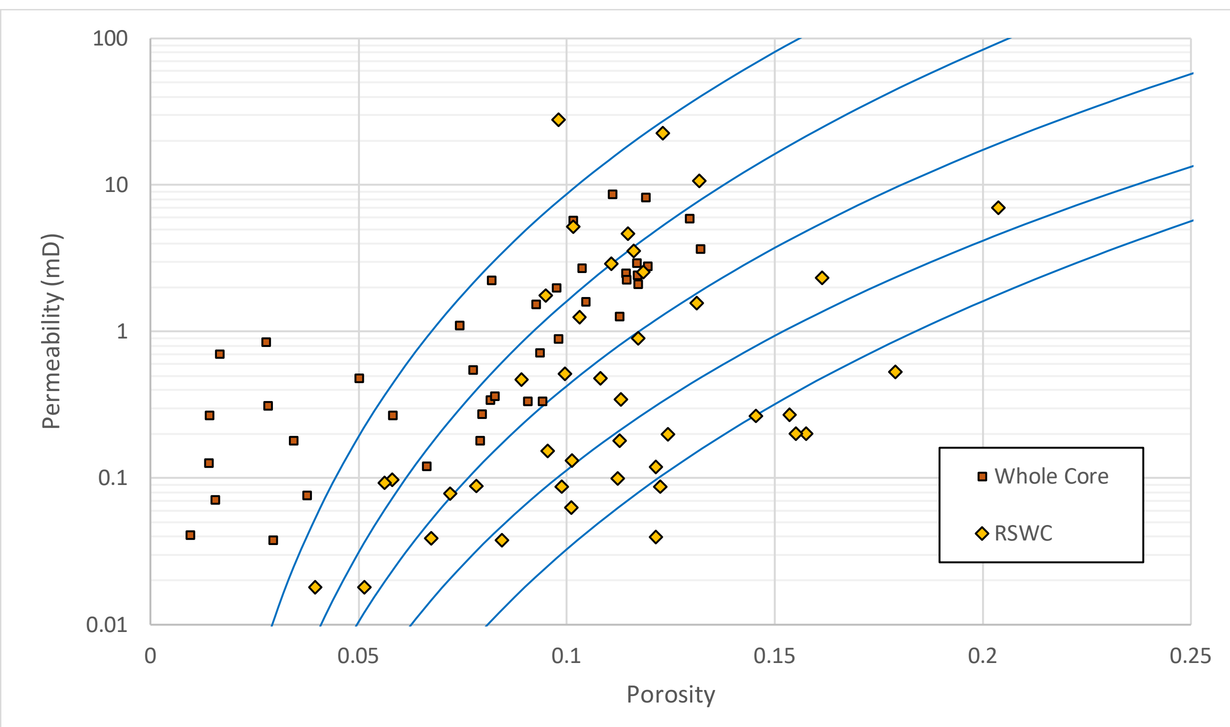

Figure 8. Semilog plot of porosity vs permeability. Whole core data shown with brown squares, RSWC data shown with yellow diamonds, and porosity to permeability transforms shown with blue lines.

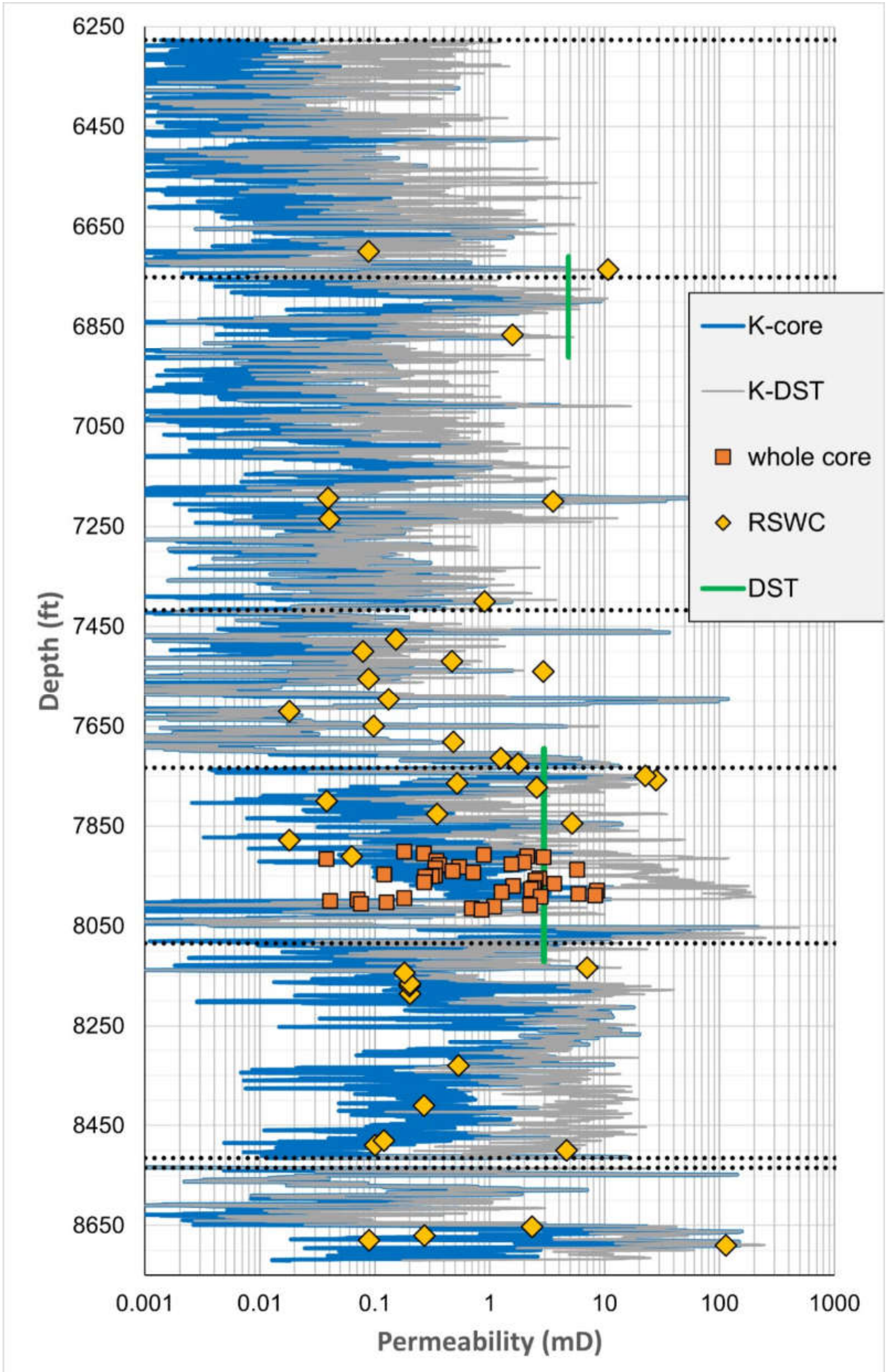

Figure 9. Permeability vs depth. The boundaries of the intervals evaluated are shown with dashed black lines. Data from whole cores shown with orange squares, data from RSWC shown with yellow diamonds. Average permeability determined by DSTs shown with green lines. Permeability derived from the transform matched to the core data shown in blue line and permeability derived from the transform matched to the DST is shown in grey line.

Storage Complex Modeling Results

The objective of the Wabash CarbonSAFE project's storage complex modeling was to assess the feasibility of storing 50 million tonnes (1.67 million metric tonnes annually; MMTA) of industrially sourced carbon dioxide (CO_2) in a commercial-scale geological storage complex at the WVR gasification facility near Terre Haute, Indiana over a period of 30 years. Results from the geological characterization of the Mt. Simon in the Wabash #1 well, now plugged and abandoned, served as a basis for the development of static and dynamic models to evaluate the commercial potential of storage using the Mt. Simon Sandstone – Eau Claire Formation as a storage complex. Mt. Simon modeling is discussed in detail in Technical Report DOE-FE0031626-8 (Dessenberger et al., 2022); the separate report, *Wabash CarbonSAFE Static and Dynamic Modeling*, is included as Appendix C, and a summary is presented here.

Mt. Simon Geocellular Model

For constructing the Mt. Simon geocellular model, in addition to Wabash #1 well data, the petrophysical log data of over 20 wells in the Illinois Basin that penetrated the Lower Mt. Simon were imported into the Petrel^{TM} software. The data were used to correlate the formation tops, build the surfaces, thickness maps, and estimate the spatial distribution of porosity and permeability data. In addition to the porosity and permeability data of the Wabash #1 well, the porosity data of 28 wells and permeability data of 6 wells were imported into a larger-area, regional, static model (example shown in Figure 10) for: 1) data analysis and defining the vertical and horizontal variograms through the Illinois Basin, and 2) using the parameters for distributing porosity and permeability into the smaller-area Wabash CarbonSAFE Mt. Simon model.

There are differences between permeability values determined by laboratory core measurements and well-test (DST) derived values from the Wabash #1 well. Thus, two permeability models were developed and used in the dynamic simulations: Core-correlated and DST-correlated models which are low-permeability and high-permeability realizations, respectively. The Core-correlated permeability model matches the permeability measured on the Wabash #1 cores. The DST-correlated permeability model matches the permeability from Wabash #1 well drill stem tests.

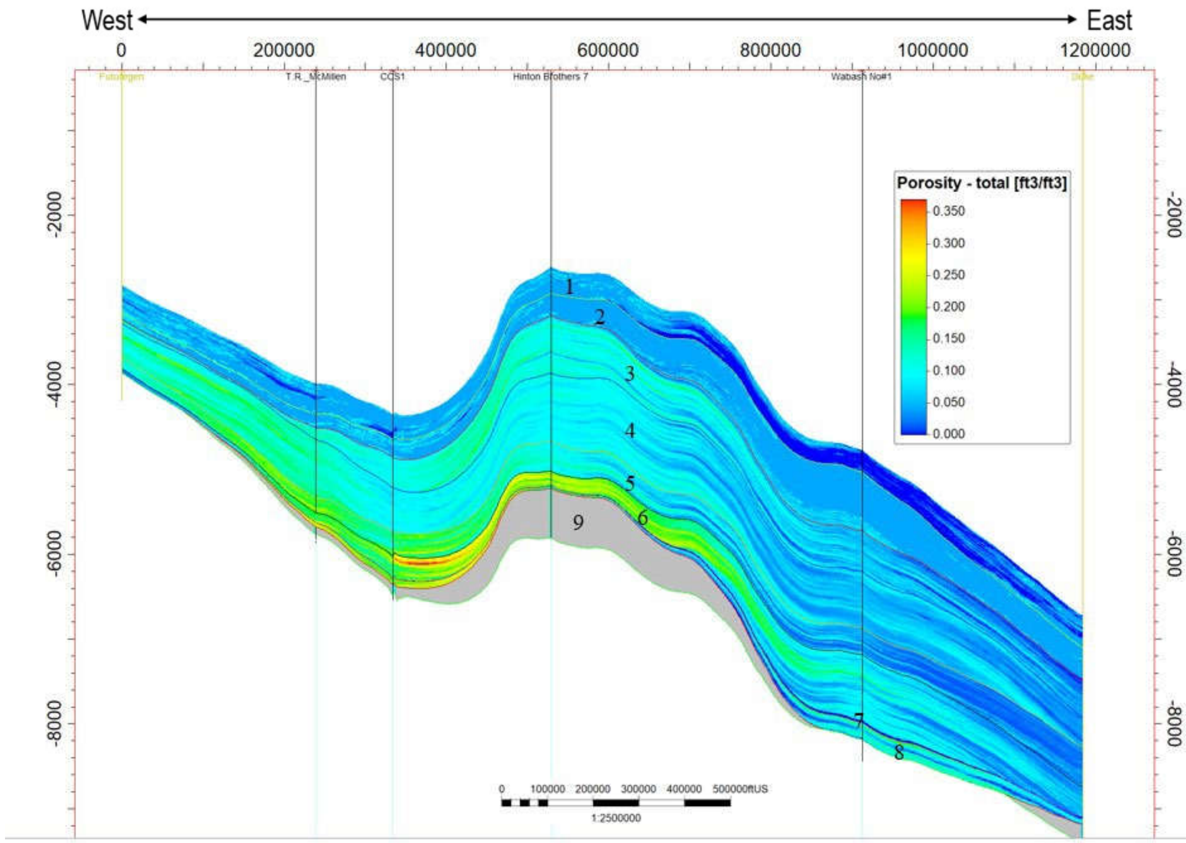

Figure 10. West-East cross section of porosity model showing the distribution and trend of the porosity. The vertical exaggeration (Z scale) of the model is 100 scale to better show the depth of the model and the trend of porosity. Formation codes: 1: Eau Claire Fm.; 2: Eau Claire shale; 3: Upper Mt. Simon; 4: Middle Mt. Simon; 5: Lower Mt. Simon; 6: Arkose zone; 7: Basalt; 8: interval below basalt; 9: Precambrian.

Injection Simulations

A *Nexus*® dynamic simulation model for the Mt Simon Sandstone was constructed using the geologic model exported from Petrel™. Porosity and permeability were populated within the Petrel™ model and exported to *Nexus*®. The simulation model is 22 x 22 miles (35 x 35 km) and includes the Mt Simon Sandstone and the overlying Eau Claire Formation that is the upper confining unit. The model is centered over Wabash #1. The model is heterogenous in both the lateral and vertical directions.

The Mt Simon permeability is lower than pre-drilling expectations and as such it will be a challenge to inject 1.67 MMTA for 30 years. As a result, multiple CO_2 injection scenarios were run on the Mt Simon model to assess single well injectivity for different completion intervals using both the DST-correlated and Core-correlated permeability models (Table 9). All simulations were run by constraining the well maximum BHP to 90% of the fracture pressure.

Table 9. Mt Simon single well simulation cases.

Case	Interval	Perforation Length
		ft
1	Vertical well, All of Mt Simon (5,721' - 7,958')	2,237
2	Vertical well, All of Mt Simon + sandstone below Basalt (5,721' - 8,155')	2,434
3	Vertical well, Lower Mt Simon + sandstone below Basalt (7,280' - 8,155')	877
4	1,000 m Horizontal well, within DST1 interval (7,415')	3,281
5	1,000 m Horizontal well, in sandstone below basalt (8,127')	3,281

Case 3, in particular, was set-up to optimize the productivity of the well relative to the fracture pressure. In all the cases considered, the well BHP is constrained by fracture pressure, and the fracture pressure increases with depth. Therefore, targeting deeper injection intervals will yield larger injection rates. The perforated interval for Case 3 of 7,280 – 8,155 ft (2,219-2,486 m) ss captures 88% of the cumulative permeability thickness (KH) of the Mt Simon.

Figure 11 shows a partial cross section (5,300 ft [1,615 m] in length) through the model at Wabash #1 from both the Core-correlated (low perm realization) and DST-correlated (high perm realization) permeability models. The warmer colors are high permeability, and the cooler colors are low permeability; these two images illustrate that the DST-correlated permeability is significantly higher than the Core-correlated permeability. In the images, the overlying Eau Claire has been removed from the model to emphasize the Mt Simon interval, and the vertical scale is greatly exaggerated by 25 times. The cross sections show the locations of two well test intervals (DST1 and DST2) and the modeled perforation intervals for all five single-well simulation cases.

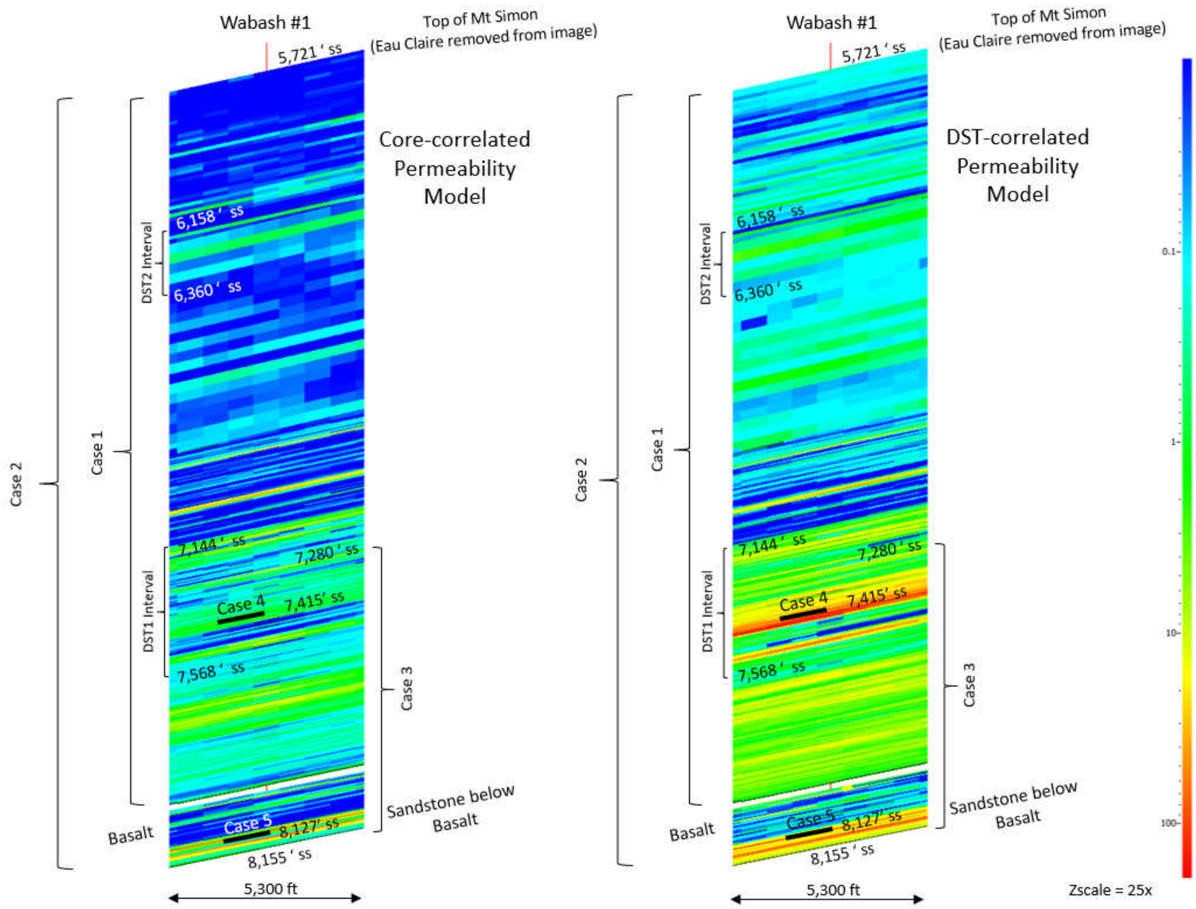

Figure 11. Partial cross section through Wabash #1 from both the Core-correlated and DST-correlated models showing horizontal permeability on a log scale, with well perforation and DST locations denoted.

The results show that Case 3 has the highest injectivity relative to the other vertical well cases. Figure 12 and Figure 13 show simulation results from Case 3 after 30 years of injection for both the DST-correlated and Core-correlated models; respectively. In the DST-correlated model: after 30 years of injection, a total a 34.8 million tonnes of CO_2 is injected at an average rate of 1.16 MMTA, resulting in a CO_2 plume radius of 1.51 miles (2.4 km). In the Core-correlated model: After 30 years of injection, a total a 6 million tonnes of CO_2 is injected at an average rate of 0.2 MMTA, resulting in a CO_2 plume radius of 1.32 miles (2.1 km). The DST-correlated model is able to inject 5.8 times the volume of the Core-correlated model over the 30-year injection period. Even though the DST-correlated model injects 5.8 times more CO_2 than the Core-correlated model, the plume radius is similar: 1.51 vs. 1.32 miles (2.4 vs 2.1 km) for the DST-correlated and Core-correlated models; respectively. The similar CO_2 plume radius is related to the injection profile, which is a result of the permeability distribution. The thin sandstone interval below the basalt captures the largest quantity of CO_2, and results in the large CO_2 plume radius at 30 years.

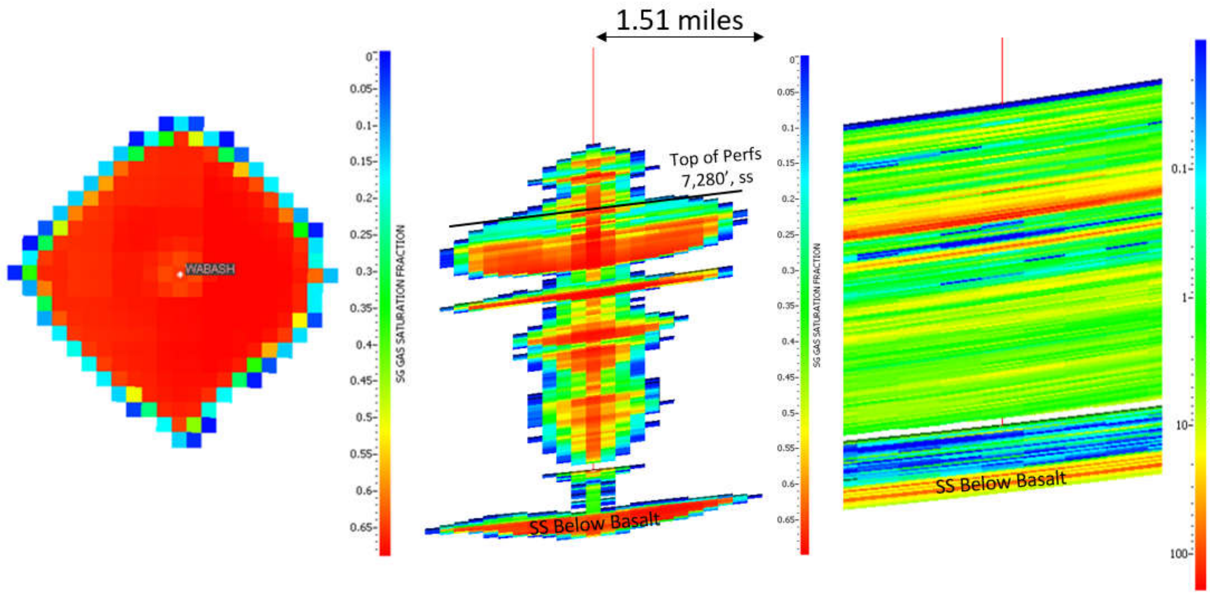

Figure 12. Case 3, DST-correlated permeability model results after 30 years of injection, showing plume radius (map view), plume cross section and permeability cross section.

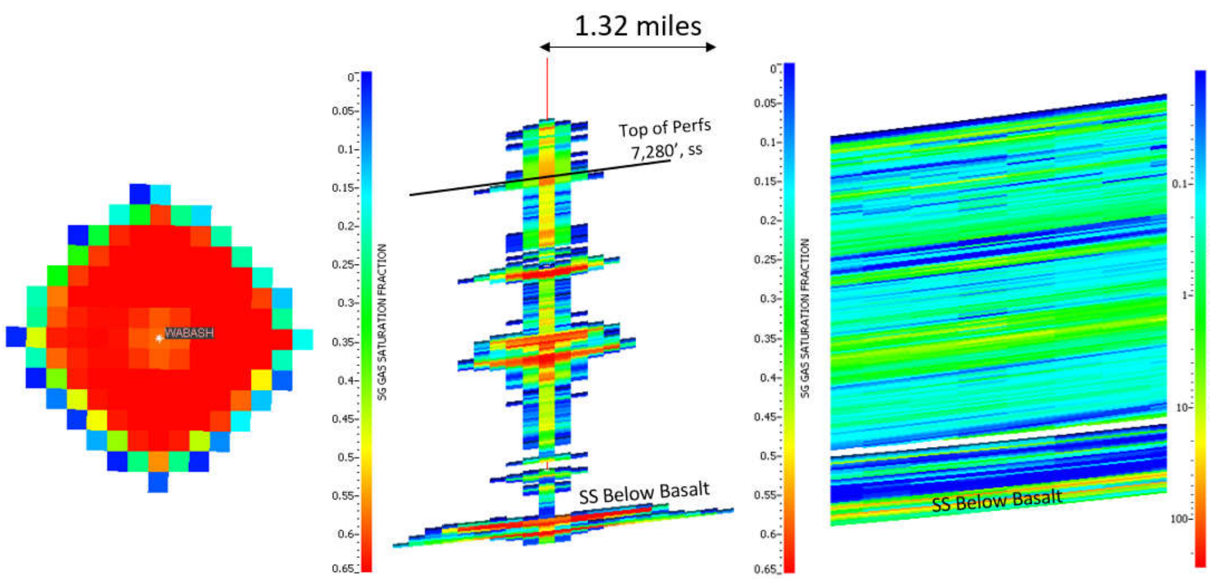

Figure 13. Case 3, Core-correlated permeability model results after 30 years of injection, showing plume radius (map view), plume cross section and permeability cross section.

Unfortunately, none of the single well injection scenarios (Table 9) are capable of injecting 1.67 MMTA of CO_2 for 30 years. Thus, additional simulations were run using multiple vertical wells and the perforated interval is 7,280 ft – 8,155 ft (2,219 m – 2,486 m) ss, same as Case 3 from the single-well modeling which showed the largest injectivity. It is possible to inject 1.67 MMTA of CO_2 for 30 years into the Mt Simon with multiple wells, but the well count differs substantially between the DST-correlated and Core-correlated permeability models.

Overall, multi-well injection simulation results based on the DST-correlated permeability model indicate that two wells spaced 1.5 to 3 miles (2.4 to 4.8 km) apart are capable of injecting 1.67 MMTA of CO_2 for 30 years into the Mt Simon. Core-correlated permeability model simulation results indicate that considerably more wells are necessary for the injection of 1.67 MMTA of CO_2 for 30 years into the Mt Simon.

Due to the lower injectivity of the Mt Simon at Wabash #1 (relative to the higher injectivity typically observed in the central portion of the Illinois basin), the focus of this project was shifted toward injection of 1.67 MMTA of CO_2 for 30 years into the Potosi Dolomite storage complex.

Characterization of the Potosi Dolomite

Geologic Data and Petrophysical Analyses

The Potosi Dolomite was initially a secondary storage target in the Wabash #1 well. Characterization of the Potosi Dolomite and its confining units is discussed in detail in Technical Report DOE-FE0031626-10 (Khosravi et al., 2022); the separate report, *Geologic Analysis of the Potosi Dolomite Reservoir Interval and Potential Confining Units at the Wabash #1 Well, Vigo Co., Indiana,* is included as Appendix D, and a summary is presented here.

For storage and containment evaluation an extensive suite of geophysical logs and drilling cuttings were collected throughout the Wabash #1 borehole, and whole cores were obtained from the Mt. Simon Sandstone, Eau Claire Formation, and Maquoketa Group. The Maquoketa Group is identified as a regionally extensive secondary sealing interval above the Mt. Simon Sandstone and as a primary seal for the Potosi Dolomite storage complex (Figure 14). Due to concerns over potential lost circulation zones in the Potosi Dolomite during drilling, no core samples or Formation Micro Imager (FMI) logs were acquired in the Potosi Dolomite. However, cased hole well testing was performed over a 20 ft (6 m) interval within the Potosi Dolomite during which a fluid swab sample was obtained. Approximately 35 miles (56 km) of 2D seismic information was acquired locally in the project area near Wabash #1 to aid in reservoir and caprock characterization.

The Cambrian Potosi Dolomite is present throughout the Illinois Basin (Figure 15, Figure 16); it is a fine to coarsely crystalline, commonly dense, dolomite, but contains characteristic drusy quartz and intercalations of vugular, brecciated, fractured and/or cavernous intervals; deep wells drilled throughout the Illinois Basin have encountered the Potosi's lost circulation zones and several wells have exploited these reservoir characteristics for fluid disposal.

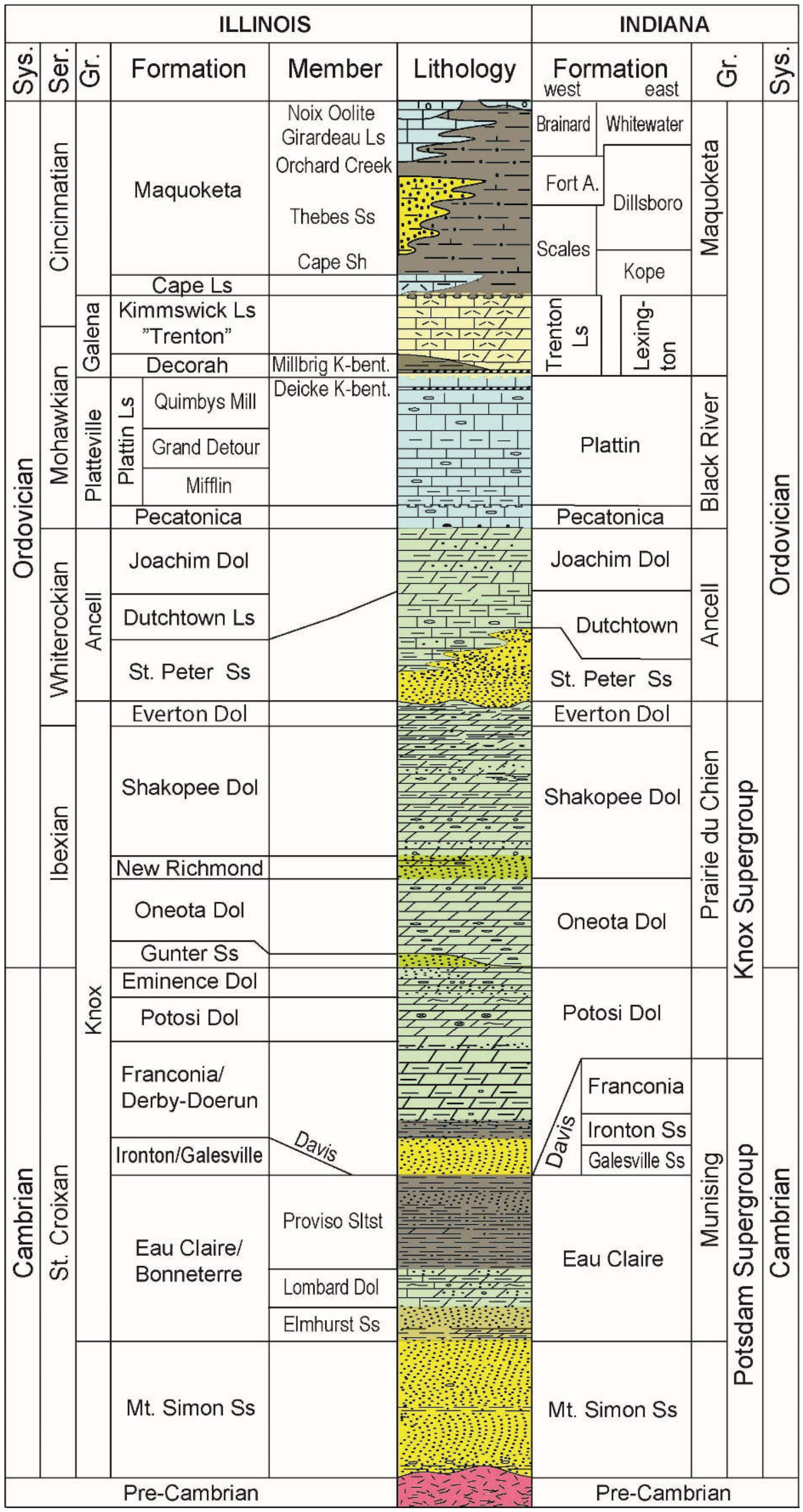

Figure 14. Stratigraphic column of the Cambro-Ordovician succession in southern Illinois (from Kolata, 2005) and southwestern Indiana (from Thompson et al., 2016). Note: in southern Illinois the Prairie du Chien Group is not differentiated and the correlative interval is considered as part of the Knox Group.

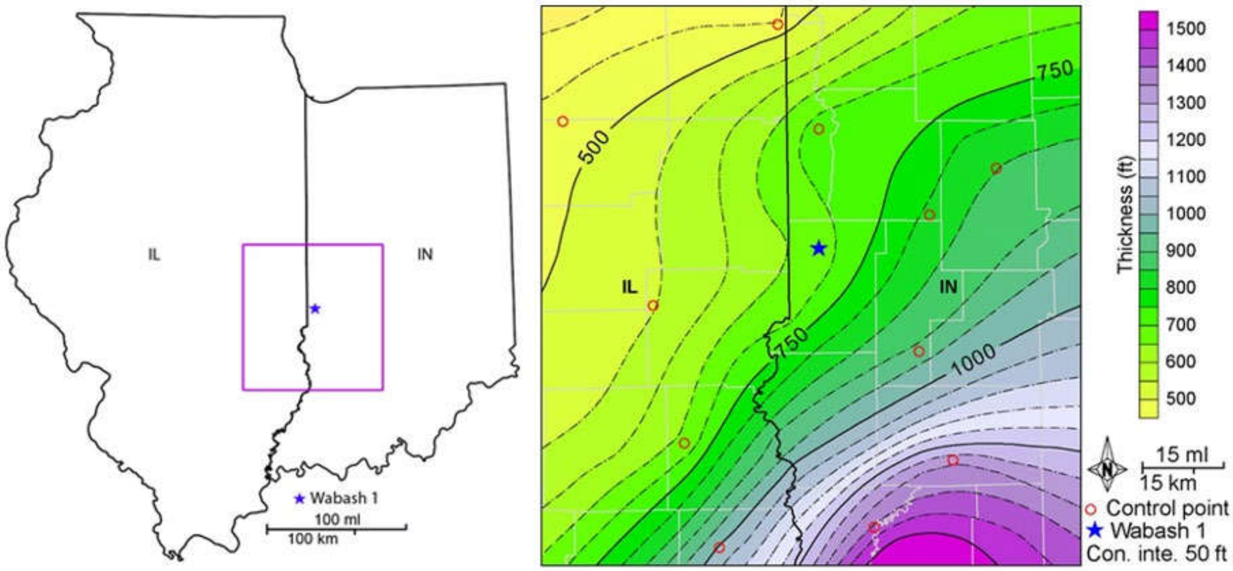

Figure 15.Thickness of the Potosi Dolomite around the study area of the Wabash #1 Well.

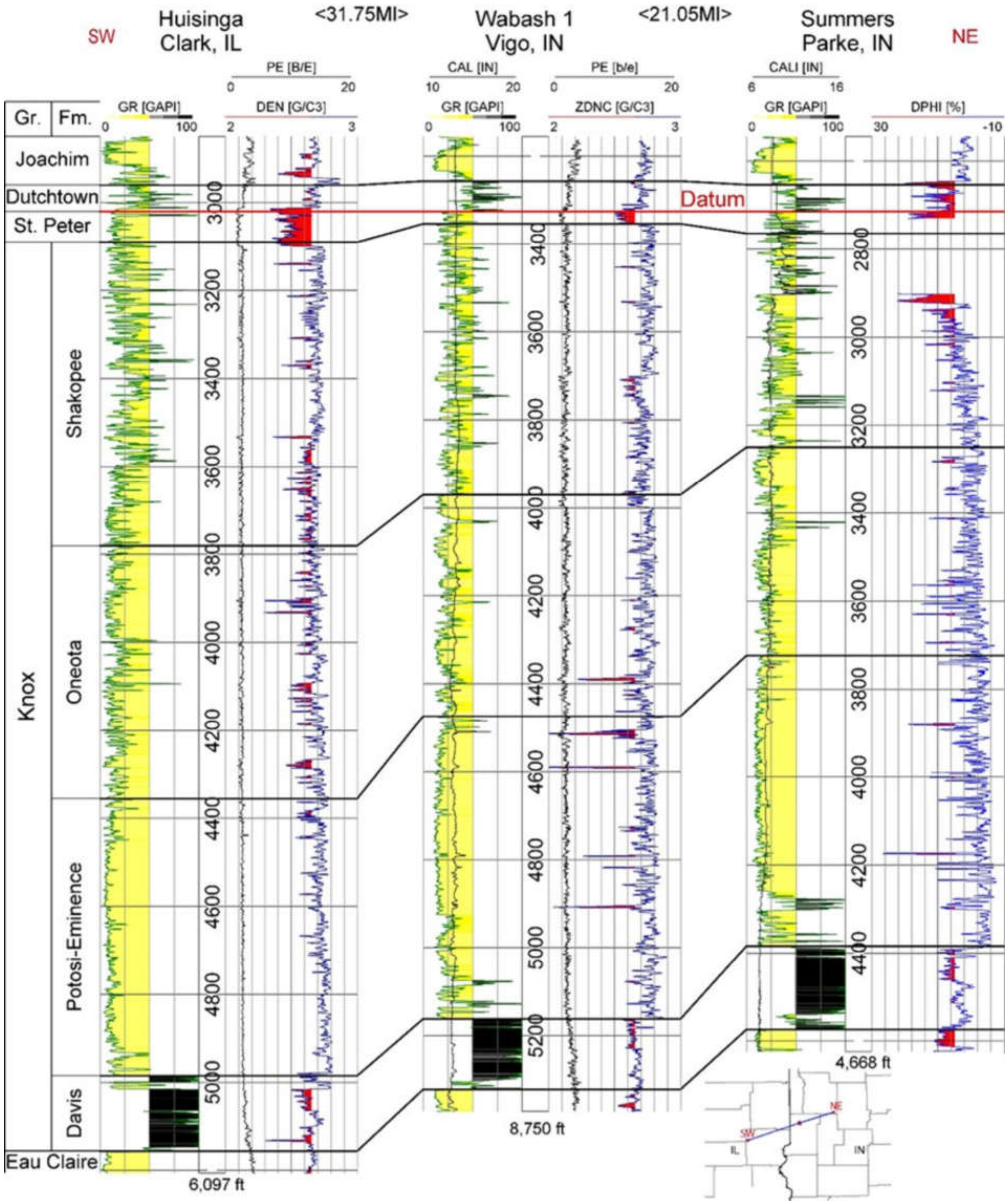

Figure 16. Southwest-northeast correlation of the units in the Knox Group from east-central Illinois to west-central Indiana (Datum top of the St. Peter Sandstone).

Wireline Log Analysis

Potosi Dolomite reservoir interval

The top of the Potosi Dolomite is very difficult to identify using wireline logs. In this study the highly porous and permeable zones in the Potosi Dolomite and lower Oneota Dolomite, within the Wabash #1 well, are considered the same reservoir interval and are referred to as the Potosi reservoir interval. In the Wabash #1 well, there are a total of six porous zones in the reservoir interval (Figure 17) that range from up to about 20 ft (6 m) to less than 5 ft (1.5 m) in thickness. Note that the top of the Potosi reservoir interval from log interpretations used in reservoir modeling differs from the top of the Potosi Dolomite as shown in regional stratigraphic cross sections; the top of the Potosi reservoir interval described herein includes 95 ft (29 m) of the lower Oneota Dolomite.

Wireline log evaluation of the 20-ft (6 m) test interval of the Potosi in the Wabash #1 well suggests that the zone consists primarily of dolomite and diagenetic quartz (Figure 18); the neutron-density porosity of the test interval is estimated to be over 30 percent with a permeability determined through well testing of potentially greater than 45,000 md (discussed below). From log analysis, the top of the Potosi reservoir interval in the Wabash #1 well is at 4,378 ft (1,334 m); the reservoir interval thickness is 784 ft (239 m) thick, of which a total of 149.5 ft (45.6 m) is greater than 10% porosity.

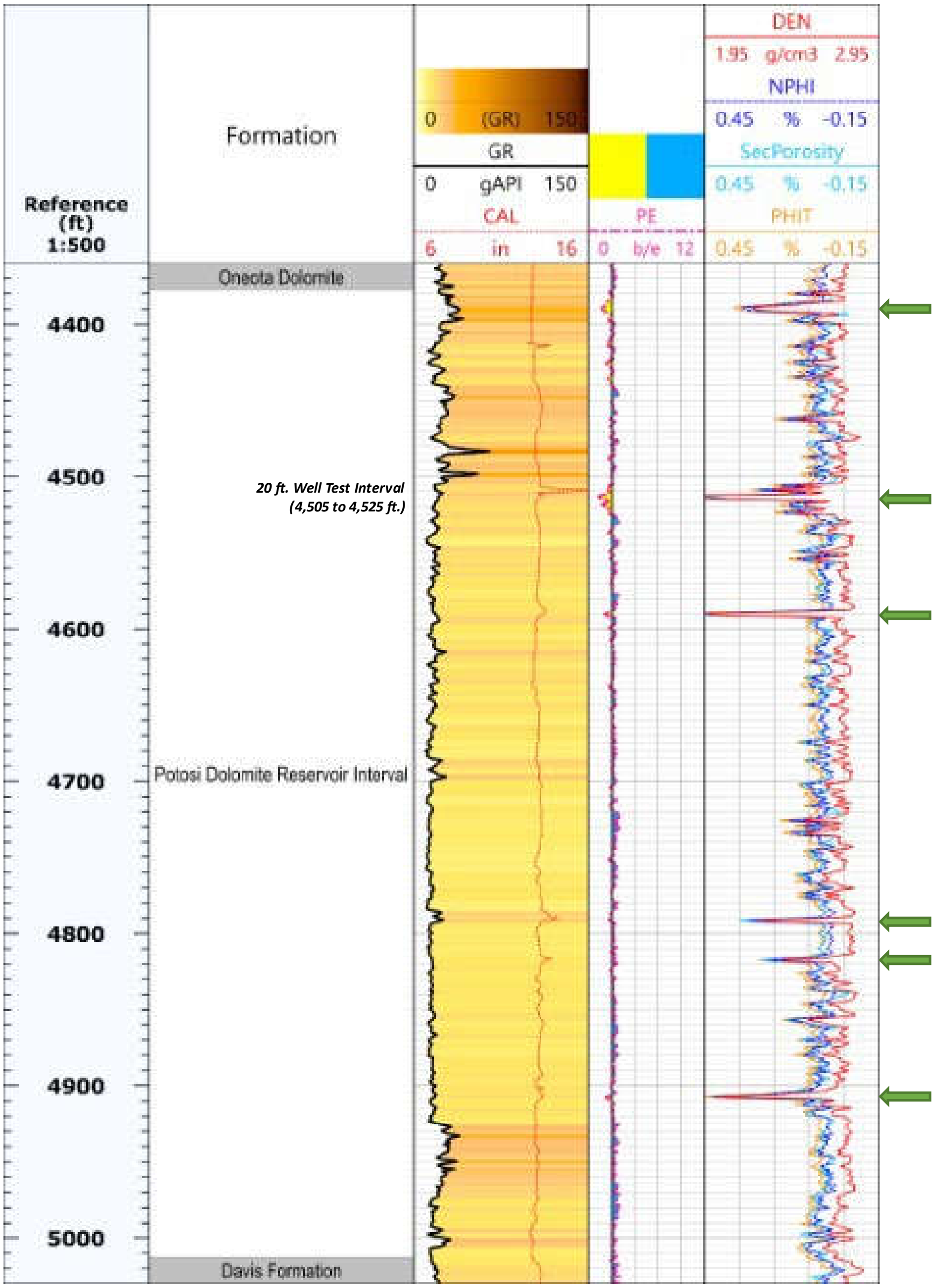

Figure 17. Geophysical log of the Potosi Dolomite reservoir interval in the Wabash #1 Well, Vigo County, Indiana. Note the top of the Potosi reservoir interval includes 95 ft of the lower Oneota Dolomite. The green arrows highlight zones with high porosity.

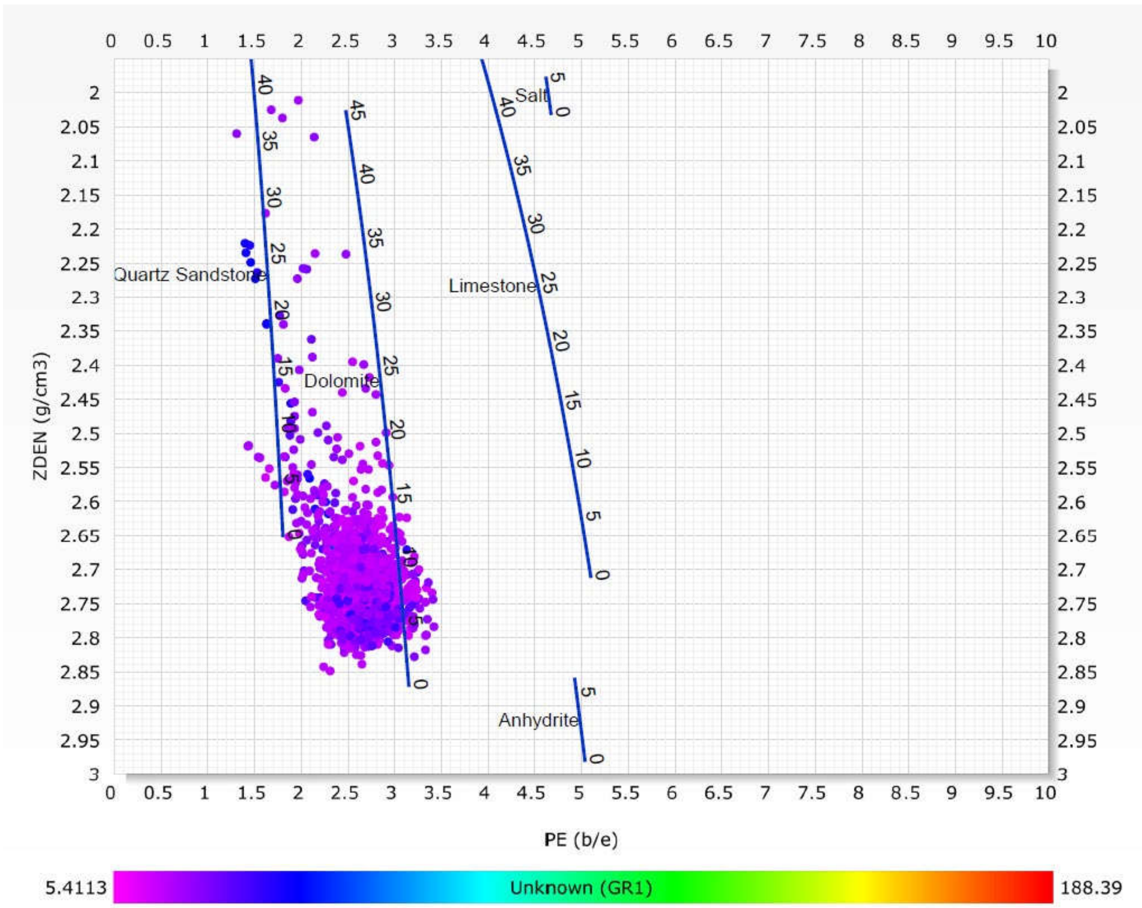

Figure 18. Cross plot of the density measurements compared with the Pe curve. This plot shows the porosity and lithology of the Potosi Dolomite tested interval in the Wabash #1 Well, Vigo County, Indiana. Note: there is no quartz sandstone in the Potosi Dolomite, but rather, mineralized quartz in the Potosi plots along the general Quartz Sandstone line as labeled above.

<u>*Confining units above the Potosi Dolomite*</u>

The thick, dense intervals of the Knox Group, including the Eminence Formation, Oneota and Shakopee Dolomites, contain strata that exhibit characteristics for effective restriction of vertical movement of fluids through negligible permeabilities. These stratigraphic units comprise a confining zone for the Potosi Dolomite reservoir interval that is cumulatively over 1,900 ft (580 m) thick in the Wabash #1 well (Table 10, Figure 19). It is notable that the Potosi Dolomite outside of the relatively thin reservoir zones is itself dense with minimal permeability. Thick shale intervals, however, are considered to be the most effective confining units within this package because they are more ductile and thus have less tendency to fracture and have extremely low vertical permeabilities. The Maquoketa Group contains 312 ft (95 m) of shale in the Wabash #1 well and is considered a regional seal for the Potosi Dolomite reservoir interval (Figure 20).

Table 10. List of significant confining intervals above the Potosi Dolomite reservoir zone, as identified in the Wabash #1 well.

Confining Zone	Formation Thickness (ft)	Depth (ft)	Avg. Porosity (%)	Avg. Permeability (md)	Shale Thickness (ft)
Maquoketa Group	314	2,386	3.0	0.0001	312
Trenton Limestone	163	2,700	1.3	0.00000273	3.5
Platteville/Black River Group	379	2,863	1.2	0.00000475	16
Dutchtown Limestone	84	3,242	2.8	0.0000840	70.5
St. Peter Sandstone	28	3,326	4.0	0.0039	3.5
Shakopee Dolomite (upper)	346	3,354	2.8	0.022360406	101
Shakopee Dolomite (lower)	270	3,700	9.1	0.098032	71
Oneota Dolomite*	408	3,970	7.1	2.585488	15

**Note the formation thickness of the Oneota Dolomite in this table excludes the portion of the lower Oneota (95 ft), which was included in the Potosi Dolomite reservoir interval for reservoir modeling purposes (see Dessenberger et al., 2022).*

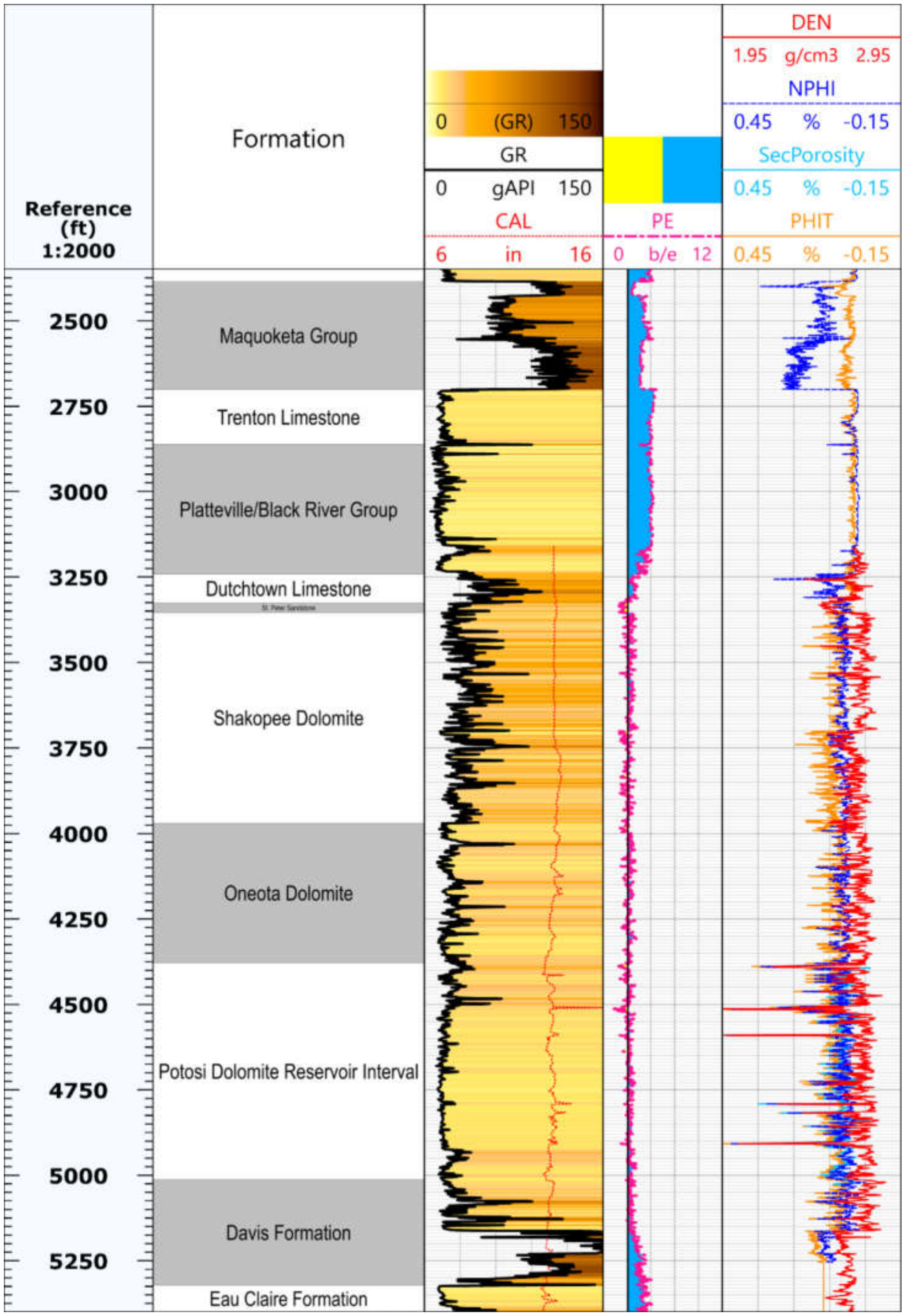

Figure 19. Geophysical log of the Cambro-Ordovician rocks from Davis Formation through Maquoketa Group, Wabash #1 Well, Vigo County, Indiana.

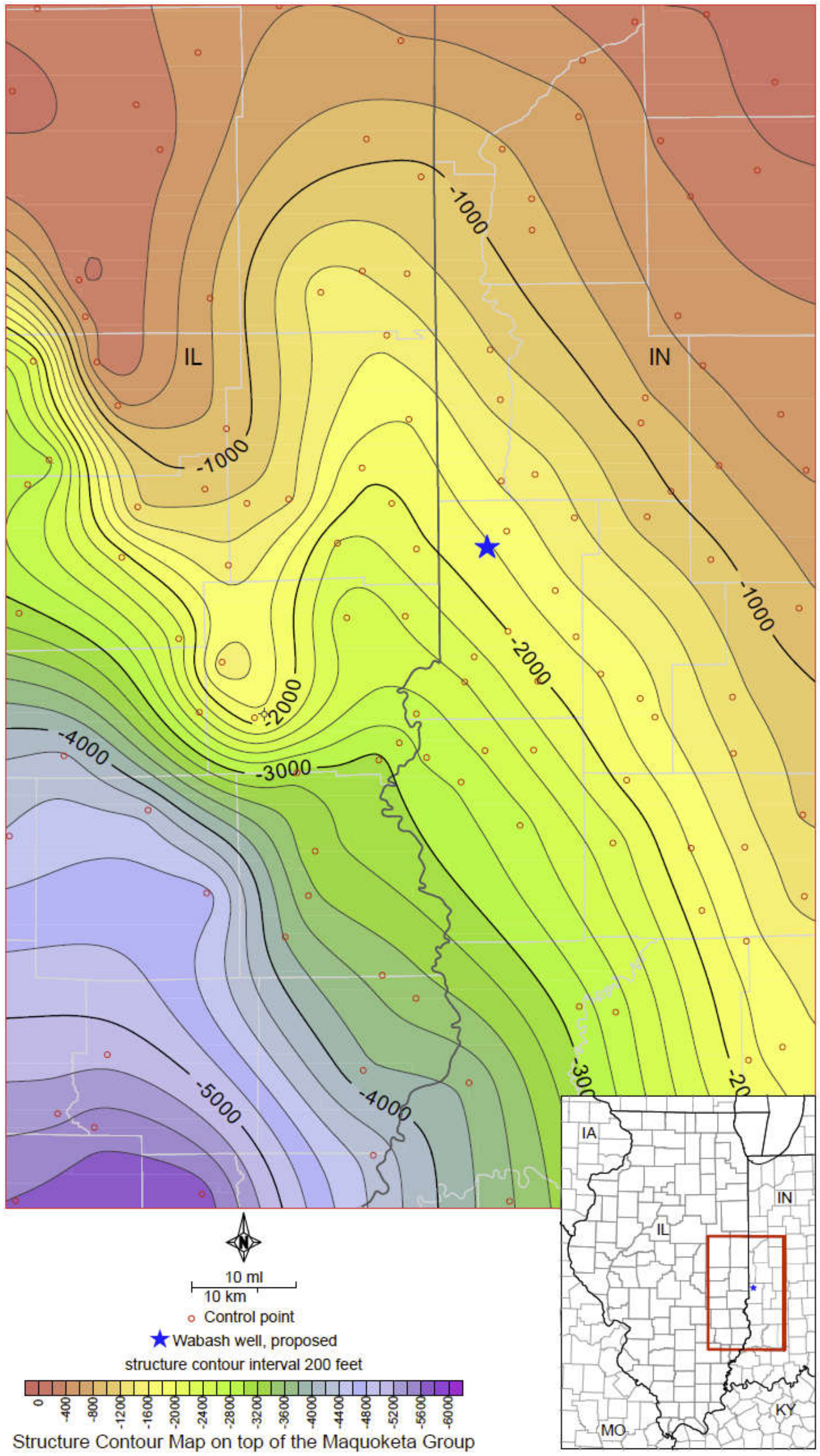

Figure 20. Regional structure map of the top of the Maquoketa Group. The Wabash #1 well is denoted by the star.

Well Testing in the Potosi Dolomite
A 20-ft (6 m) thick (4,505-4,525 ft [1,373-1,379 m]) interval showing high porosity in the Wabash #1 well was perforated to test the Potosi Dolomite for permeability, initial pressure, fracture gradient, and any large-scale geologic features affecting rate and pressure. Step rate tests (SRT) were used to determine fracture gradient. Pressure fall off (PFO) tests were used to evaluate permeability, initial pressure, and large-scale geologic features. Multi-rate tests (MRT) were used for permeability. All tests injected freshwater.

Step Rate Tests: Seven successful step rate tests using variations in rate increments (0.25 and 1.0 bpm) and duration (1, 2, 15, and 30 mins) were conducted: four tests before and three tests after acid stimulation. Test durations were 7, 15, 30, and 90 mins. Tests were relatively consistent and resulted in a fracture gradient range of 0.70-0.74 psi/ft. As an example, Figure 21 shows one of the six step rate test analyses.

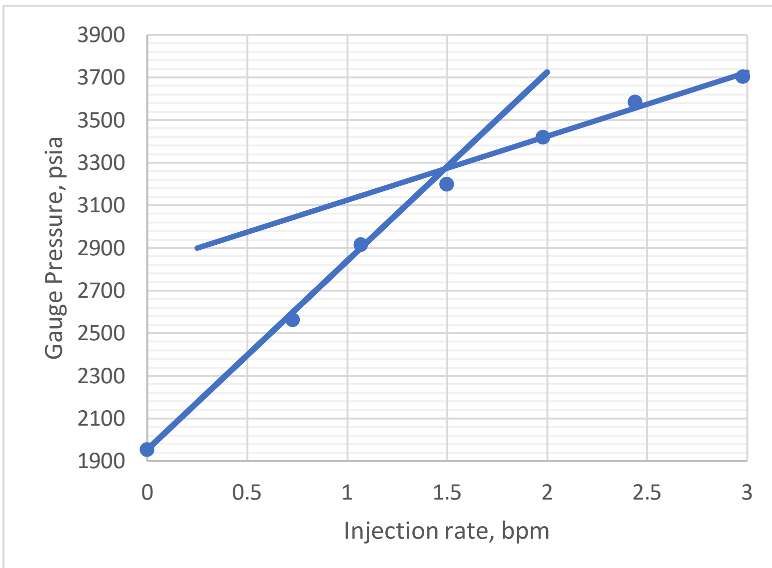

Figure 21. Example of one of the step rate tests in the Wabash #1 well. Gauge pressure is shown. The intersection of the two lines is interpreted as the fracture propagation pressure, which was corrected 5 ft (1.5 m) to the top of the perforated interval. The initial pressure is the y-axis value at 0 bpm.

Multi-Rate Tests: The pre-frac injection rates of a SRT can be analyzed as a MRT for which permeability can be estimated. The MRT rates were held constant for increments of 15 mins and ranged from 1 to 4 bpm (1,440 to 5,760 bpd). The pre-acid stimulation range of permeability, from applying steady-state flow principles to the MRT, was 275-375 md, while the post acid stimulation range of permeability from the MRT was 400-450 md.

Pressure Fall Off tests: Following each SRT, injection ceased for a short period (0.33 to 2.75 hrs) prior to the next SRT. It was noticed that within 30 mins after shut-in, pressure decreased to within 0.1 psi of the initial pressure. This was recognized as a challenge for a PFO. Consequently, a longer injection period (4 and 9 hrs) was used for the PFO; however, these tests also resulted in the shut-in period returning to within 0.1 psi of initial pressure. The derivative plot (Figure 22 example) has an early ½ slope (0.003 to 0.03 hrs), which is typically interpreted as a linear flow from a hydraulic fracture. Because the well was not hydraulically fractured, this may be related to the fracture created during the preceding SRTs. Fracture half-length is estimated at < 5 ft (1.5 m).

The large separation between the pressure curve (upper) and derivative (lower) is caused by very high, positive skin which may or may not be mechanical skin. The approximately horizontal trend in the derivative at time > 1hr represents radial flow, from which permeability can be calculated. This trend gave a permeability range of 45 to 72 D (45,000 to 72,000 md).

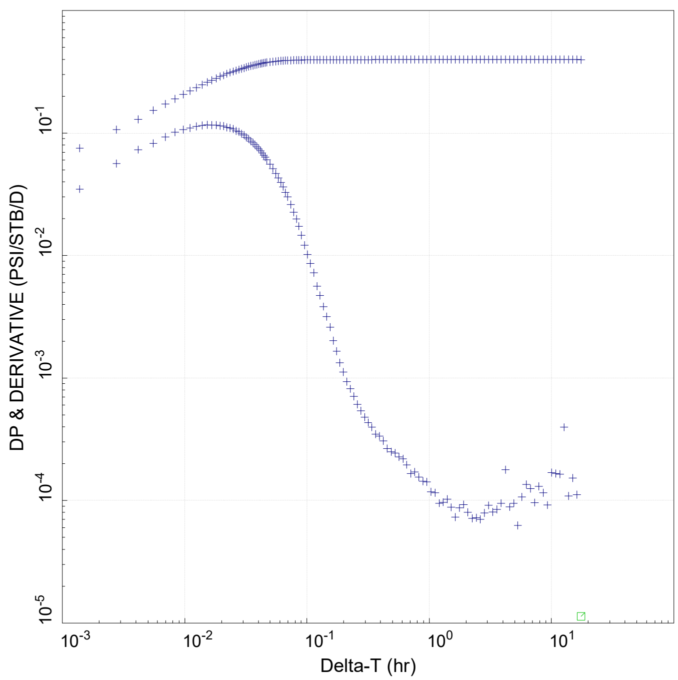

Figure 22. Example of shut-in period following injection period. (Upper curve is pressure and lower curve is derivative.) All derivative plots of shut-in periods had similar appearances: a very early ½ slope, a sharp negative slope, and stabilization. Half-slope indicates linear flow very near the wellbore, which may be a single vertical fracture induced during the preceding SRT. The stabilization after 1 hr is indicative of a radial flow from which permeability can be calculated. The large separation between the pressure and derivative curves indicates very large positive apparent skin (a logarithmic smoothing factor of 0.14 was used to calculate the derivative).

Discussion: The results of the three types of tests are inconsistent if a homogenous, infinite-acting, high permeability, 8 ft (2.4 m) formation is assumed. A homogeneous model results in a skin of 2500, which is essentially impossible for a perforated interval that accepts an injection equivalent of 1000s of barrels per day. If a high skin is not causing the large separation between the pressure and derivative curves (Figure 22), then a radial composite model can explain this, but requires a relative lower permeability near wellbore and a relative very high permeability further form the wellbore. Two unique scenarios can support the radial composite model: 1) the well was drilled within a lower permeability (100s md) area of the Potosi and near to the well laterally is an area of much higher permeability (>10s Darcy), or 2) the perforated interval, which was a lost circulation zone, also took a large volume of cement around the casing deeper into the formation and created a lower permeability zone around the well.

A lower permeability zone near the well (whether due to geology or cement), would result in successful SRTs and the lower permeability from the MRTs. If the inner zone was not present and only Darcy-scale permeability was present, the SRTs (with maximum injection rate of 6 bpm) would not have adequate resistance to injection and would be unable to reach the fracture pressure. If the inner zone is from cement, then the fracture pressure would be that of cement in the cavernous porosity and the in-situ stresses. Similarly, the permeability from the MRTs reflects radial series flow—and if a lower permeability zone was near the well, the MRT would be strongly influenced by this zone. The PFO, a shut-in analysis, is initially dominated by the near wellbore low permeability zone, but at later time is dominated by the higher permeability zone away from the well. Results of all tests support the radial composite model with an inner permeability zone (100s of md permeability) and a higher permeability outer zone (10s Darcy). Two zones with a large contrast of permeability, with the inner zone much lower than the outer zone, will cause the large separation between the pressure and derivative curve appearing as large positive skin. A summary of the results of the well tests are provided below in Table 11.

Table 11. Summary of well tests of Potosi test interval: 4505-4525 ft (1373-1379 m).

Perforated Interval	Interval Name	k, Darcy (md)	Initial pressure, psia (mid-perf)	Feature present	Comments on k and initial pressure	Fracture gradient, psi/ft	Comments on fracture gradient
4,505-4,525	Potosi	45-72 (45,000-72,000)	1955 (0.430 psi/ft)	Linear early trend; large skin	The multi-rate tests were used for kh; pi was used as a direct measurement	0.70-74 psi/ft @4505 ft (top perf)	Range based on SRTs at various rates and durations

Potosi Dolomite Fluid Sample from Wabash #1

Fluid samples were collected at Wabash #1 stratigraphic well for the Potosi Dolomite well test interval (4,505 to 4,525 ft [1,373 to 1,379 m]) on June 8 and 9, 2020. Produced fluids were collected at the well head approximately every 10 minutes and density measurements were recorded on unfiltered samples. A total of 24 swab runs were completed prior to collection of the final swab sample (approximately 3 liters).

The final swab sample was filtered, preserved, and submitted for analysis (per procedures in Locke et al., 2013) at the Illinois State Water Survey Analytical Laboratory. The sample was analyzed for major, minor and trace element composition using Ion Chromatography (IC) and Inductively Coupled Plasma-atomic Emission Spectrometry (ICP-ES). The Potosi fluid sample had a Total Dissolved Solids (TDS) of 34,250 mg/L.

Structural, Geomechanical, and Seal Analyses: Potosi – Maquoketa storage complex

Material in this section is discussed in detail in Khosravi et al., 2022 (see Appendix D), and Freiburg et al., 2022 (see Appendix B), and a summary is presented here.

2D Seismic Interpretation

Local 2D seismic reflection data indicate that there are no faults penetrating the Potosi Dolomite reservoir or confining zones within the study area (Figure 23). Approximately 35 miles (56 km) of 2D seismic information was acquired in the project area near Wabash #1 to aid in evaluating reservoir and caprock continuity; two profiles were acquired under the Wabash CarbonSAFE Project (Lines Wabash 1000 and 2000), and a separate acquisition was made by Wabash Valley Resources (Line WVR 20).

The geologic formation contacts observed in the Wabash #1 well were correlated with the seismic reflections using synthetic seismograms created with sonic and density wireline logs from the Wabash #1 well. The north-south seismic profile (Figure 23) shows the correlation of the seismic reflectors with the geologic data acquired from the Wabash #1 well. The seismic reflection data is relatively noisy (high signal to noise ratio) due to near-surface conditions.

Based on seismic profiles there are no faults identified in the study area that transect the Potosi Dolomite, overlying confining beds, or Maquoketa Shale. There is no specific Potosi Dolomite seismic reflector as the few highly porous and permeable zones (ranging from less than 5 ft [1.5 m] to up to 20 ft [6 m] in thickness) in the reservoir interval are too thin to be resolvable on seismic reflection data. However, there are no faults observed within this sedimentary package including overlying strata.

The only resolvable faults in the study area occur in the Precambrian and lower Mt. Simon Sandstone as shown on seismic line 2000 in the circled area (see Figure 24, showing a three-dimensional perspective of the well and seismic data within the Mt. Simon Sandstone). The faults appear to be related to Precambrian structures and terminate within the lower Mt. Simon Sandstone. The northernmost seismic profile WVR 20 has no indication of faulting above the Precambrian (Figure 25).

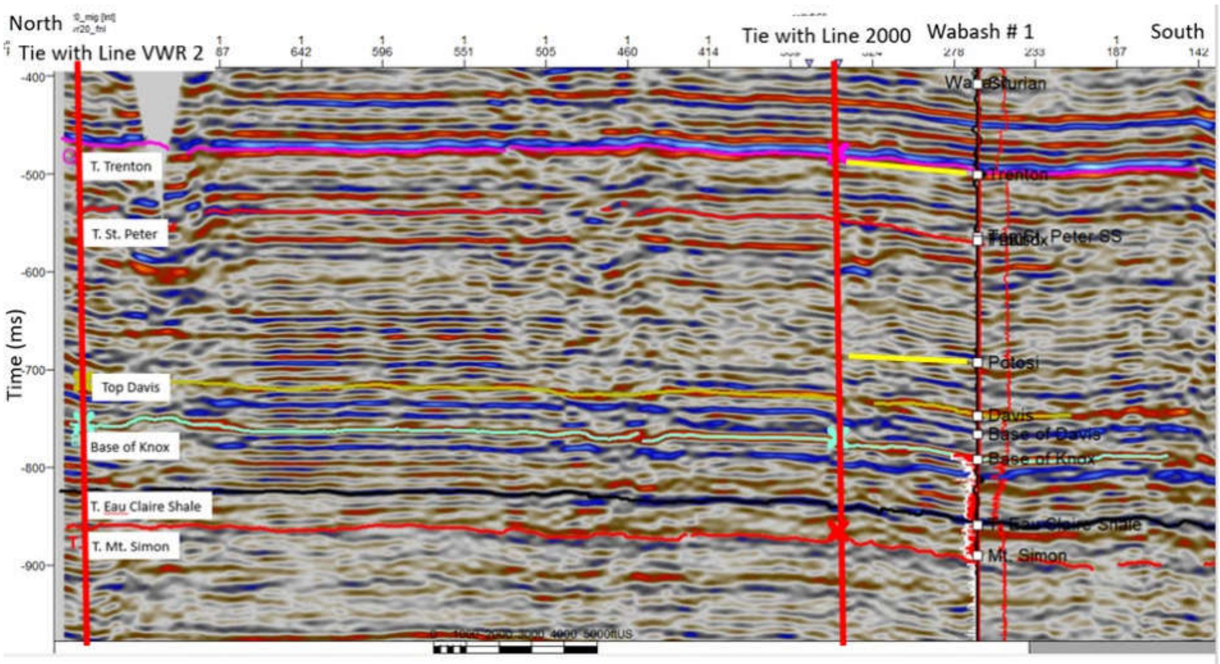

Figure 23. 2D Seismic line acquired over approximately 10 miles (16 km) in north-south direction and running along the east side of the WVR facility; seismic reflection data is correlated with the Wabash #1 well. The top of the Potosi Dolomite is the lower heavy yellow line, and the top of the Trenton Limestone (base of the Maquoketa Group) is the heavy yellow line above.

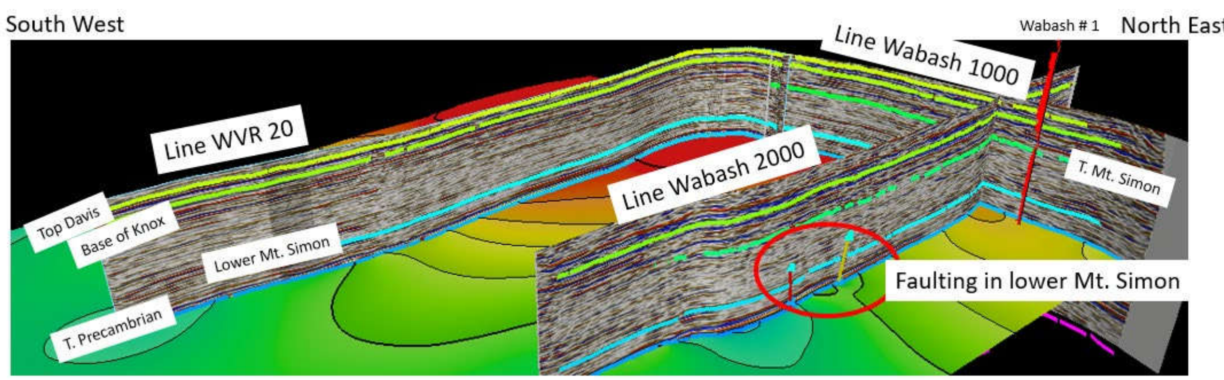

Figure 24. Three-dimensional view of the Precambrian through the Eau Claire Formation. The basal surface is the top of the Precambrian correlated from the three seismic lines. The circle on Wabash 2000 is the area with faulting in the lower Mt. Simon and Precambrian.

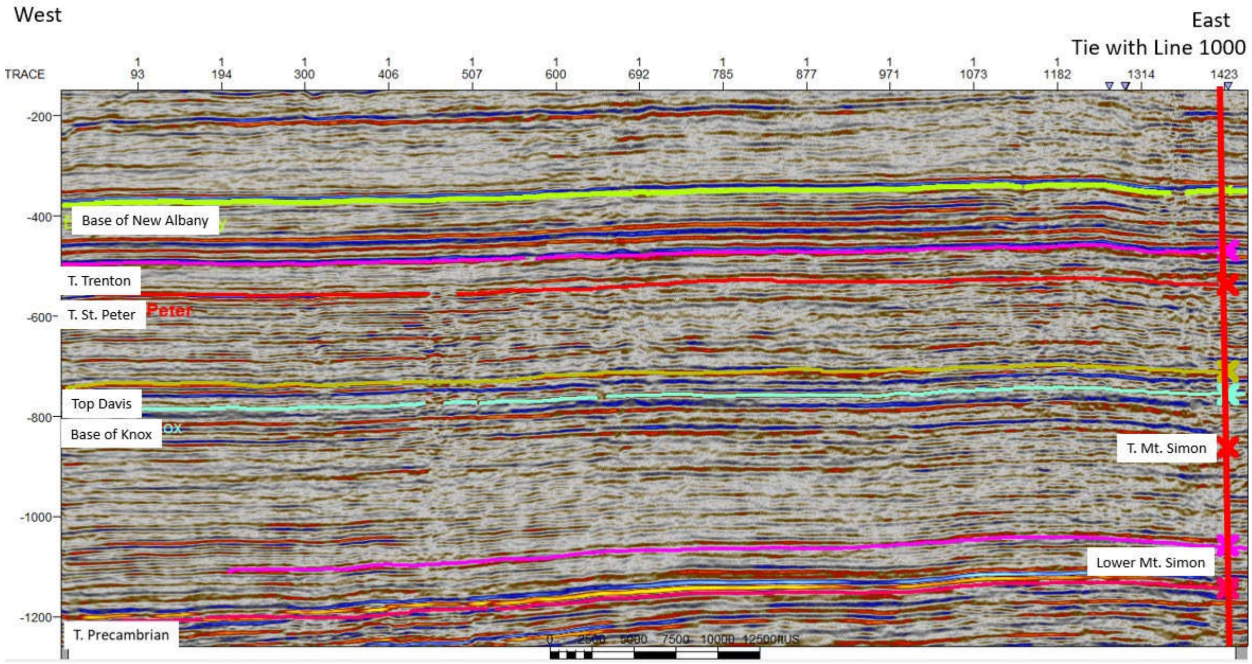

Figure 25. Seismic line WVR 20 illustrating the stratigraphy and structure in the Ordovician and Cambrian strata. No resolvable faults were observed on this line.

Fracture Analysis in the Wabash #1 Well

A Formation Micro Imager (FMI) log acquired in Wabash #1 from the Maquoketa Group to the Oneota Dolomite interval (it did not extend into the Potosi Dolomite) provided information regarding smaller-scale fracturing in the stratigraphic succession above the Potosi Dolomite. In general, the strata have irregular to isolated fractures, with no distinct indication of interconnectedness. Fracture orientations broadly trend along N-NE and S-SW orientations, with dips of 45 degrees or greater. In the lower part of the Shakopee, the fractures tend to be more numerous and throughgoing (i.e., cutting across multiple beds). The Oneota Dolomite (above the Potosi Dolomite) is exhibiting more fractures than the Shakopee, but the fractured intervals are separated by non-fractured beds. Overall, in the Maquoketa Group interval, no significant natural fractures, drilling induced tensile fractures (DITFs) or wellbore breakouts (WBOs) were observed.

Core collected from the Wabash #1 well (61 ft [19 m]) from the Maquoketa Group exhibited some fractures in the boxed core as examined by Bauer (2020). Nearly all the fractures are clearly drilling- or handling-induced, based on morphological features such as hackle marks (Figure 26) or bullet-shaped "impact marks." Only a few fracture planes do not show drilling-induced fracture patterns; these planar, vertical fractures are not cemented and can extend for several feet. However, artificial fracture initiation in the calcareous shale may have occurred preferentially, along possible pre-existing planes of weakness, producing full core width fractures. Evidence of in situ fracturing was not observed at these depths on the FMI log indicating the bulk of fractures observed are due to coring or handling during core recovery. The lack of faulting or fracture network in the Potosi Dolomite through Maquoketa Group succession indicates CO_2 containment would not be compromised by natural structural features.

Figure 26. Example of Maquoketa Group core from the Wabash #1 well. Off the bottom of this picture is another bullet shaped impact at 2,487.6 ft (758.2 m) depth. Fracture initiated from there moving up through the core, forming this fracture face as shown by the hackle lines which are annotated on the right. The impact also produced another fracture plane that was about 60 degrees to this plane and ended at this plane (from Bauer, 2020).

Geomechanical Testing and Analysis of the Maquoketa Group

Geomechanical testing of the Maquoketa Group was performed in September 2020, on wax-preserved core samples obtained from the Wabash #1 well. At the Wabash #1 well, the Maquoketa Group is ~315 ft (96 m) thick and occurs from 2,386 to 2,700 ft (727 to 823 m) in depth. A 61 ft (18.6 m) interval was cored (3-1/2 inch [9 cm] diameter) from 2,435 to 2,496 ft (742 to 761 m) in depth. A 2 ft (0.6 m) section of core from 2,446.92 to 2,448.45 ft (745.82 to 746.29 m) was preserved in wax.

Triaxial compressive strength tests and ultrasonic velocity measurements were conducted on Maquoketa core plug samples (3 vertical core plugs, 1 horizontal plug, and one inclined plug [oriented 45-degrees to horizontal]) to determine geomechanical (dynamic and static) and petrophysical characteristics. The tests were conducted under confining pressures of S3 = 675, 1350, and 2025 psi (Table 12; ~4.6, ~9.3, and ~14.0 MPa) and results were interpreted based on Mohr-Coulomb failure criteria.

Table 12. Confining pressures used for testing at Schlumberger Reservoir Laboratory.

Formation	Sample depth (ft)	TZSG (psi/ft)	TXSG_ANISO (psi/ft)	TXYSG_ ANISO (psi/ft)	PPG (psi/ft)	MES (psi)	MES x 0.5 (psi)	MES x 1.5 (psi)
Maquoketa	2447.25	1.100	0.743	1.114	0.430	1350	675	2025

*TZSG=Vertical stress, TXSG_ANISO=Anisotropic min. horizontal stress, TXYG_ANISO=Anisotropic max. horizontal stress, PPG=Pore pressure gradient, MES=Mean effective stress

Uniaxial or unconfined compressive rock strength (UCS) of ~26,000 psi (~180 MPa) for the Maquoketa Group was extrapolated (based on triaxial testing of 5 cores) from the best fit line to the relationship between σ3 and resulting yield strength (Figure 27; Zoback, 2007). The slope (i.e. m = 3) of the best fit line is used to determine a coefficient of internal friction (μ_i) of ~0.58, an angle of internal friction (ϕ) of 30° and a cohesive or shear strength (C_0) of ~7514 psi (~52 MPa). Measurements of compressional velocities (V_p), shear velocities (V_s), dynamic and static Young’s modulus (E), and dynamic and static Poisson’s ratio (υ) are presented in Table 13. Elastic properties which typically correlates with UCS show nearly consistent values at this depth (see Figure 28).

The triaxial test results show the Maquoketa to have a high Young's modulus (~42-46 GPa), suggesting very stiff rock. In addition, it has high UCS (~180 MPa) compared to the Eau Claire shale UCS value (~76 MPa) observed at this location (see Freiburg et al., 2022), and also at the IBDP site in the central IL Basin (Bauer et al., 2016; Babarinde et al., 2021) where shale within the Eau Claire Formation forms the primary seal (Leetaru and Freiburg, 2014). The high strength values in the Wabash #1 Maquoketa Group results suggest that a sufficiently high pore pressure change will be required (depending on the in situ stress field)—i,e. above the fracture gradient of the reservoir—to induce a tensile failure in any layer of the Maquoketa with similar strength values.

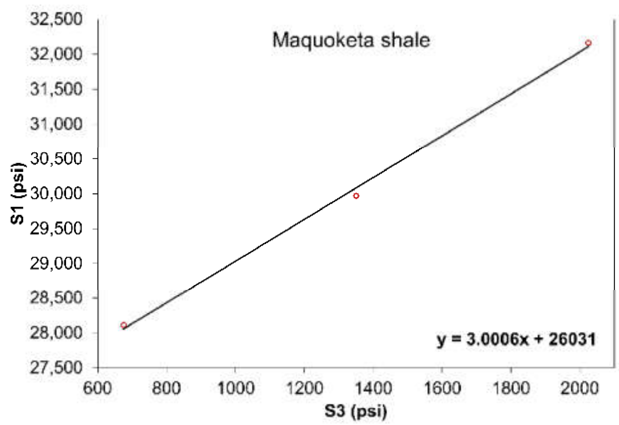

Figure 27. Plot of confining stress versus the resulting yield strength. Note that 3 measurements were used to create a best-fit line.

Table 13. Measured parameters from the triaxial tests and ultrasonic measurements.

	Petrophysical properties	Ultrasonic velocities		Dynamic elastic properties		Static elastic properties				
Sample orientation	ρ (g/cc)	Vp (km/s)	Vs (km/s)	E (GPa)	υ	E (GPa)	υ	UCS (MPa)	C_0 (Mpa)	φ (°)
Vertical	2.61-2.71	4.9-5.5	2.6-3.0	45-62	0.30	42-46	0.23-0.3	180	51.8	30
45 degrees	2.71	5.5	2.9-3.0	60-62	0.30					
Horizontal	2.63-2.70	5.2-5.7	2.6-3.0	48-63	0.30-0.32					

* (ρ) = Density, (ϕ) = angle of internal friction, (C_0) = cohesive or shear strength, (V_p) = compressional velocities, (V_s) = shear velocities, (E) = dynamic and static Young's modulus, (υ) = dynamic and static Poisson's ratio, (UCS) = uniaxial or unconfined compressive rock strength.

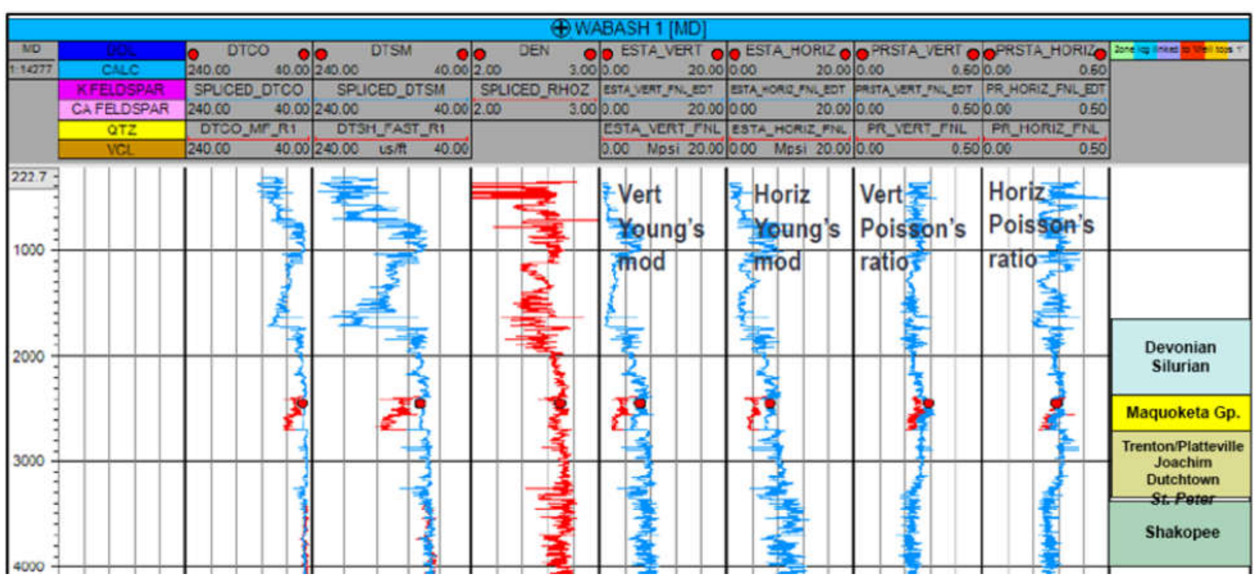

Figure 28. Cross section showing core calibrated elastic properties (in blue) estimated from well log data. Laboratory measurement of static elastic properties (red dots) are also shown on the section.

Seal Capacity of the Maquoketa Group

Discussed in Freiburg et al. (2022), theoretical scCO_2 column heights across a range of permeabilities were determined for the Maquoketa Shale. In addition, detailed Mercury Injection Capillary Pressure (MICP) data were used to create a range of minimum to maximum scCO_2 column heights based upon a distribution of CO_2 contact angles and Hg/air threshold pressures. Results from the MICP analysis for one Wabash #1 Maquoketa shale sample are shown below in Table 14; at a formation pressure of 1,080 psi and an assumed contact angle (CA) range between 20º and 40º, the sample data indicate the Maquoketa can hold a scCO_2 column height of 2,020 ft (616 m). Both the theoretical approximations and detailed MICP data indicate that the Maquoketa Shale is an effective caprock to scCO_2 migration based upon membrane capillary behavior.

Table 14. Calculated minimum, sample value, and maximum scCO_2 column heights relative to caprock capacity based upon MICP analyses of one sample from the Maquoketa Shale from the Wabash #1 well. The variability in the column heights was calculated using a range of contact angles (CA) and threshold pressures (20% variability relative to sample value).

Formation	**CO_2 Column Height ft. (m) @ CA 0º**	**CO_2 Column Height ft. (m) @ CA 20º**	**CO_2 Column Height ft. (m) @ CA 40º**	**CO_2 Column Height ft. (m) @ CA 60º**
	min – sample - max	**min – sample - max**	**min – sample - max**	**min – sample - max**
Maquoketa	**1891**(576) - **2365** (721) - **2844** (867)	**1777** (542) - **2223** (678) - **2673** (815)	**1449**(442) - **1812** (552) - **2179**(664)	**946**(288) - **1183**(361) - **1422**(433)

Storage Complex Modeling Results

The objective of the Wabash CarbonSAFE project's static and dynamic modeling was to assess the feasibility of storing 50 million tonnes (1.67 million metric tonnes annually; MMTA) of industrially sourced carbon dioxide (CO_2) in a commercial-scale geological storage complex at the WVR gasification facility near Terre Haute, Indiana over a period of 30 years. The secondary target formation for storing CO_2 was the Potosi Dolomite (Knox Group). Also evaluated was storing 20 million tonnes (1.67 MMTA) of CO_2 over 12 years, to address current commercial scenarios based on 45Q laws, which are driving commercial activity generally.

Results from the geological characterization of the Potosi Dolomite in the Wabash #1 well, now plugged and abandoned, served as a basis for the development of static and dynamic models to evaluate the commercial potential of storage using the Potosi Dolomite – Maquoketa Group as a storage complex. Static and dynamic modeling of the Potosi storage complex is discussed in detail in Technical Report DOE-FE0031626-8 (Dessenberger et al., 2022; see Appendix C), and a summary is presented here.

Potosi Geocellular Model

The geocellular model for the Potosi Dolomite was built using Petrel™, Schlumberger's reservoir modeling software. The input data for the Potosi model comprise: the petrophysical log data of Wabash #1 at half-ft (0.15 m) intervals including Gamma ray, resistivity, porosity, photoelectric, and sonic logs, and structure surfaces, thickness maps, well test data, and permeability data. The Potosi static model is a layer cake model, and the grids were propagated with the porosity and permeability data of Wabash #1. The model boundary covers a surface area of about 22 x 22 miles (35 x 35 km) and includes Wabash #1 and two proposed wells (Well 1-North; Well 2-South) locations (Figure 29).

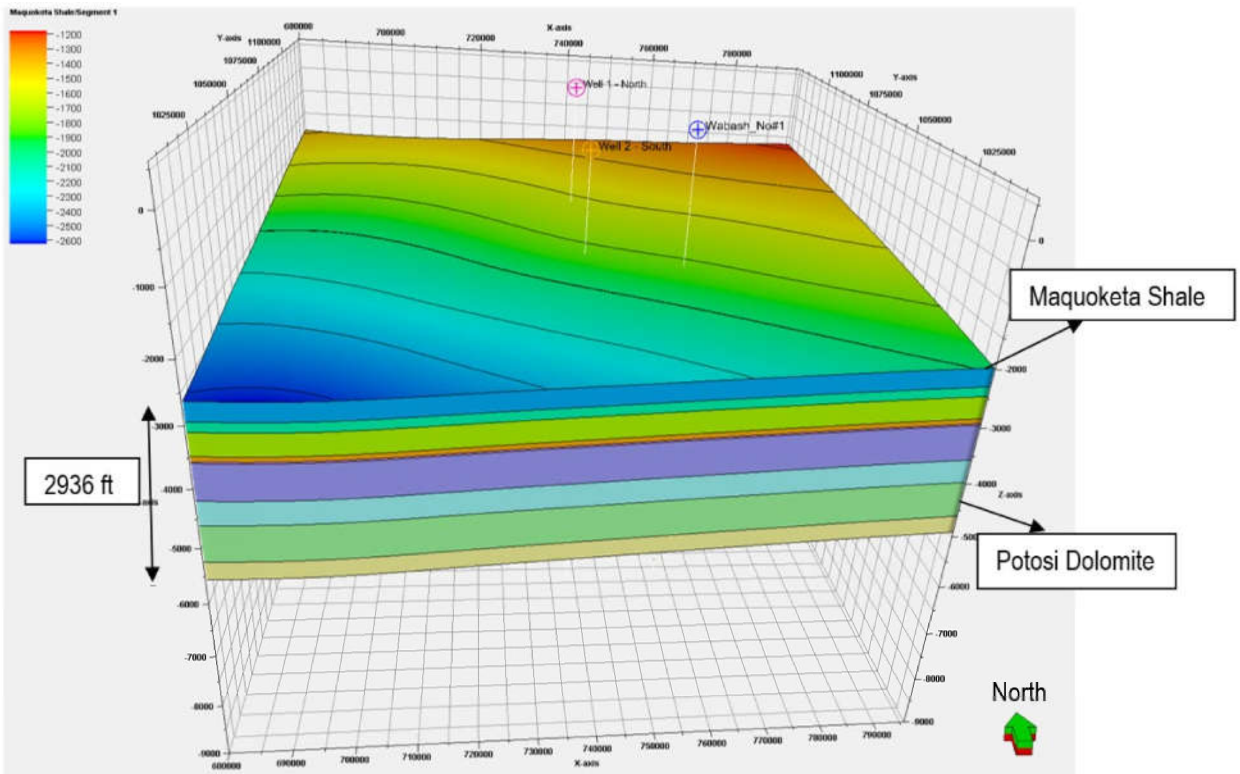

Figure 29. 3-D structural framework of the Potosi model, the top of the project is the Maquoketa Shale structure surface, and the base is the top of the Eau Claire formation. The Potosi Dolomite interval is shown with green color.

The Potosi Dolomite consists of streaks with high porosity and permeability values and thick dolomite intervals with lower property values, therefore the Potosi zones were subdivided into thinner layers to reproduce the reservoir properties from the 0.5-ft (0.15 m) porosity and permeability data from Wabash #1 logs. It is uncertain if the permeability of the Potosi Dolomite is consistent within the project boundary, but the presence of vuggy intervals and lost circulation zones in almost all wells that encounter the Potosi throughout the Illinois Basin suggest that the pore throat systems of vuggy intervals are highly connected. Thus, the Potosi model was built by assuming the spatial connectivity of the vugs in the horizontal direction and discontinuity of pore systems in the vertical direction (Figure 30).

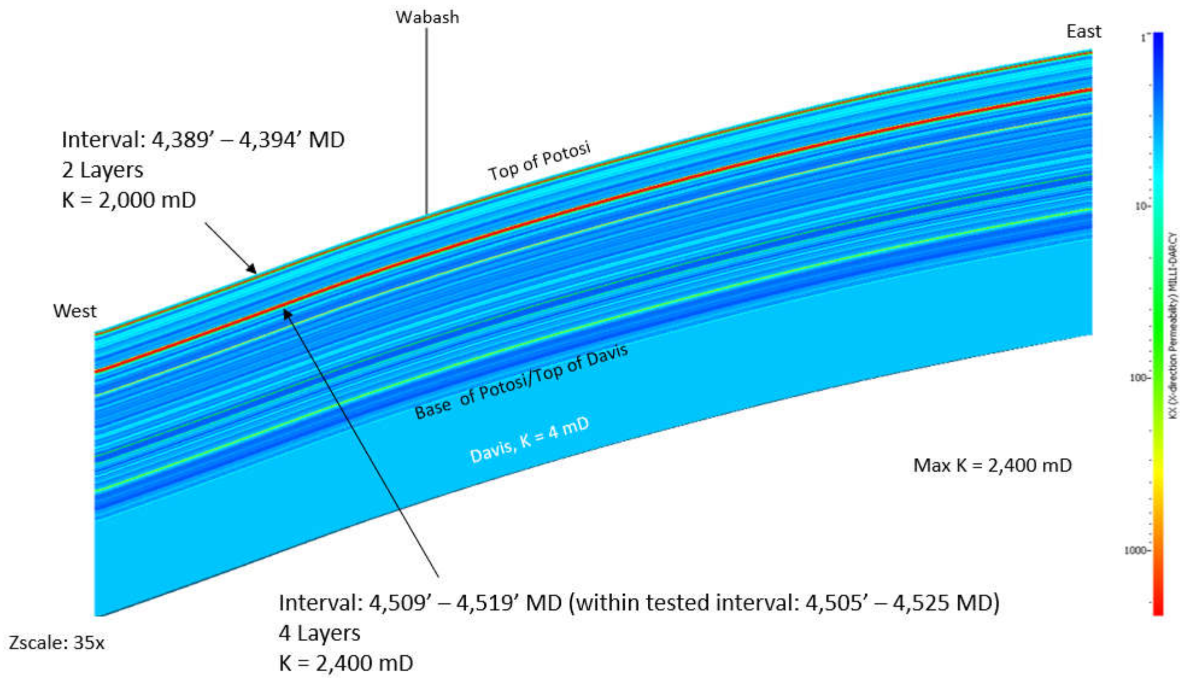

Figure 30. West-east cross section through the model at Wabash #1 showing the horizontal permeability in the Potosi Dolomite and the underlying Davis formation.

An early in situ well test at Wabash #1 was interpreted to indicate a permeability value of 2,400 md for an injection unit within the Potosi Dolomite (24,000 md-ft over 10 ft [3 m]). Subsequent, longer well testing (described earlier in this report) indicated much higher permeabilities of 45,000 md or greater exist within the Potosi Dolomite. The low permeability value of 2,400 md was used in dynamic simulations of CO_2 injection into the Potosi Dolomite reservoir interval. For regional comparison, a Class I well using the Potosi Dolomite for waste injection near Tuscola, IL, approximately 50 miles (80 km) west-northwest of the Wabash location, has a permeability of 9,600 md (Texas World Operation, 1995).

Injection Simulations

A *Nexus*® dynamic simulation model for the Potosi Dolomite was constructed using the geologic model exported from Petrel™. The model includes the Potosi Dolomite, underlying Davis Formation, and the overburden formations (listed in descending order) the Maquoketa Group, Trenton Limestone, Platteville (Black River) Group, Dutchtown Limestone, St. Peter Sandstone, Shakopee Dolomite, and Oneota Dolomite.

Dynamic reservoir simulations were performed to assess CO_2 injectivity, plume radius and pressure distribution as a function of time for several injection scenarios using the Wabash #1 Potosi Dolomite reservoir model. For the scenario of injecting 50 million tonnes over 30 years (1.67 MMTA) into a single well, the predicted maximum CO_2 plume radius was 3.8 miles (6.1 km) at the end of injection (Figure 31). A 50-year post-injection period showed no further lateral migration of CO_2, while upward movement of CO_2 was restricted to the lower Oneota Dolomite

Figure 32). The pressure increase from injection does not substantially propagate vertically past the Dutchtown Limestone; which results in a negligible increase in pressure in any overlying formations above the Dutchtown Limestone (Figure 33).

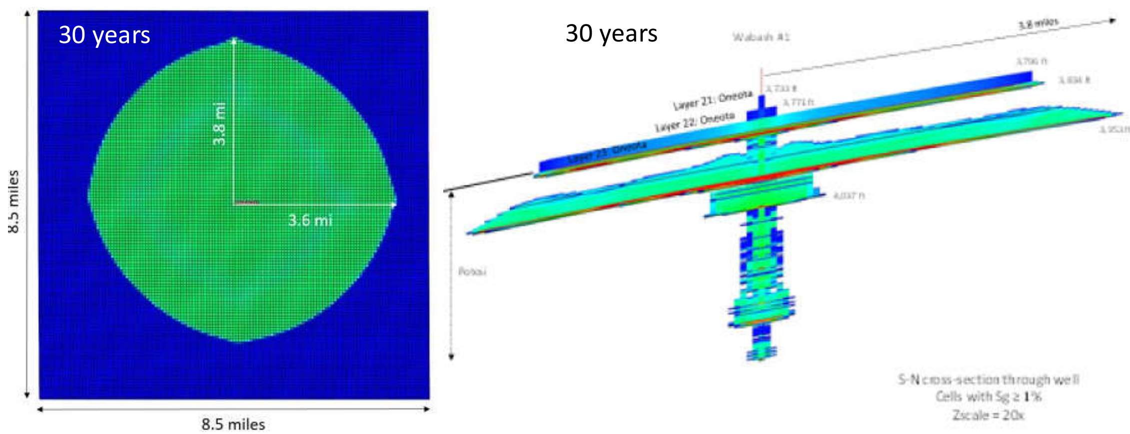

Figure 31. Map view (left; at top of Potosi tested interval) and cross-sectional view (right) of CO_2 plume after 30 years of injection (1.67 million tonnes annually). The predicted areal extent of CO_2 at the end of the injection period is indicated by green pixels (left) and colored pixels (right).

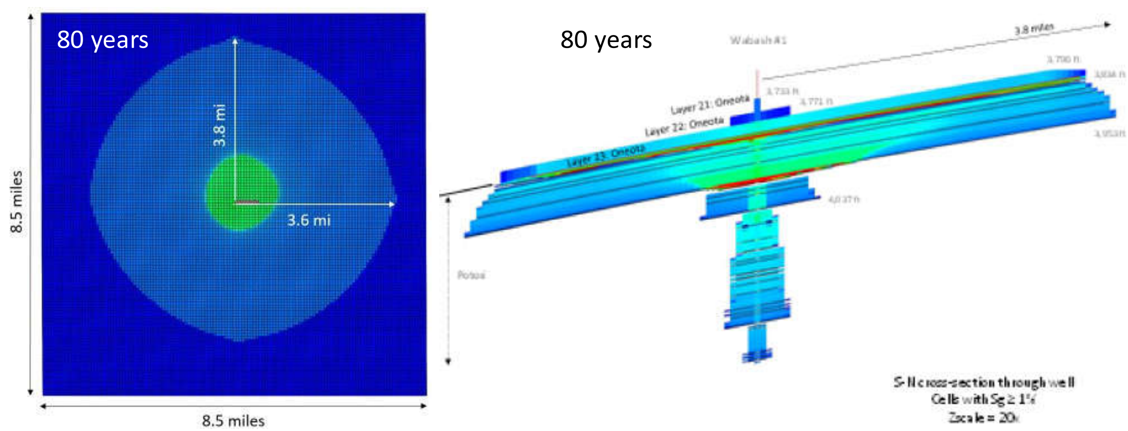

Figure 32. Map view (left; at top of Potosi tested interval) and cross-sectional view (right) of CO_2 plume at year 80 (after 30 years of injection at 1.67 million tonnes annually, plus 50 years post-injection). The predicted areal extent of CO_2 at the end of the injection period is indicated by green pixels (left) and colored pixels (right).

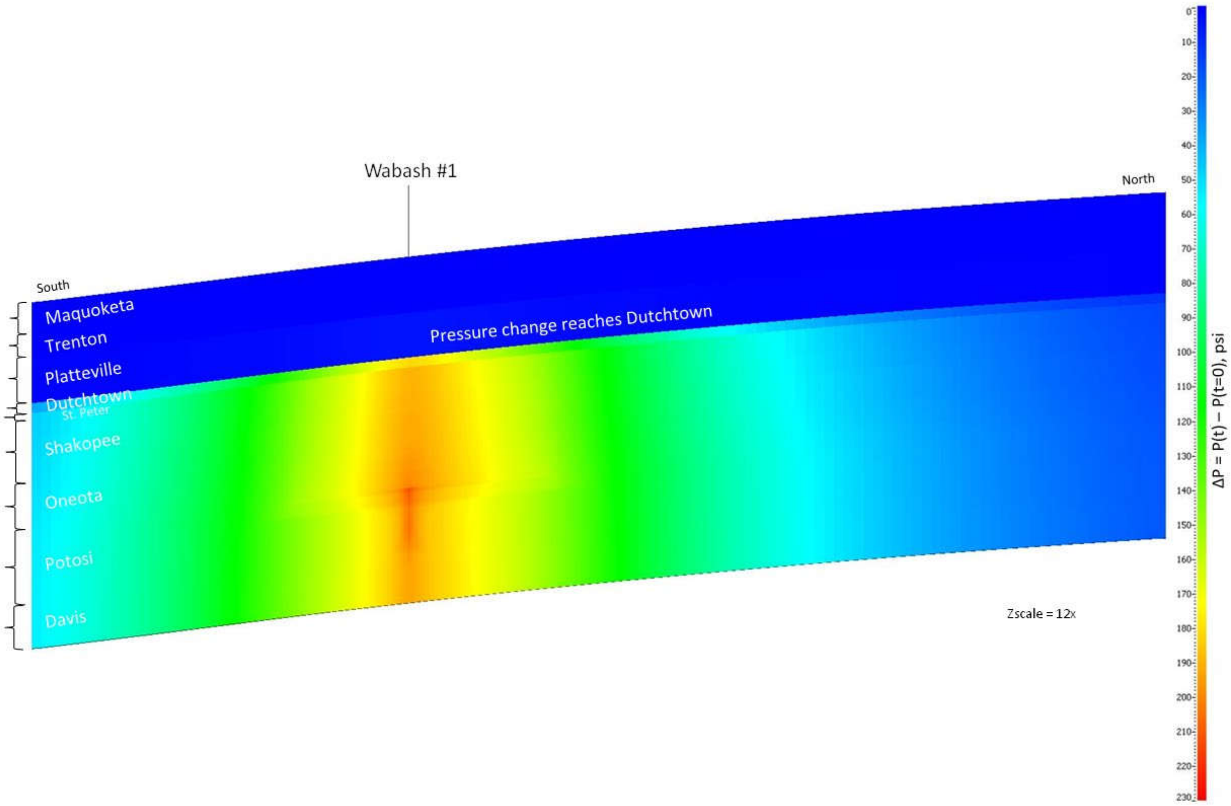

Figure 33. South-North cross section through Wabash #1 showing the change in pressure (ΔP) after 30 years of injection.

Pressure and temperature conditions of the Potosi Dolomite and confining units expected during CO_2 injection have been examined during dynamic reservoir modeling. A summary of reservoir conditions is provided below in Table 15:

Table 15. Potosi Dolomite reservoir conditions from the Wabash #1 well used in dynamic reservoir modeling.

Parameter	Value
Initial Pressure	1,954 psia at 4,500' MD
Resevoir Temperature	108F at 4,500' MD
Salinity	34,250 ppm
Frac Gradient	0.71 psi/ft

For the scenario described above of injecting 50 million tonnes over 30 years (1.67 MMTA) into the Potosi Dolomite using a single well, the maximum bottom-hole pressure (BHP) injection constraint of Pmax = 0.9 * 0.71 psi/ft (90% of the fracture gradient) was applied at the top of perforated interval (which equates to 2,804 psia at 4,381 ft [1,335 m] in depth).

BHP over the 30-year injection period is shown in Figure 34; while the BHP increases by 282 psi over the 30 years of injection, the maximum well BHP of 2,182 psia is significantly below the maximum BHP constraint of 2,804 psia. Thus, the CO_2 injection operation never reaches pressures high enough to fracture the reservoir. Injection well BHP can be seen to fall immediately after injection ceases and returns toward the initial reservoir conditions over the modeled 50-year post-injection period.

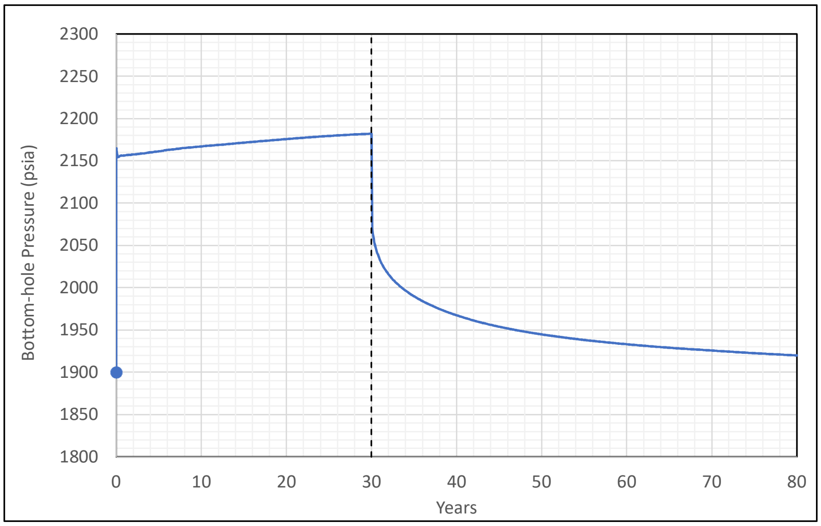

Figure 34. Potosi Dolomite reservoir bottom-hole pressure conditions from one dynamic modeling scenario (30-year period of CO_2 injection at the WVR site, at a rate of 1.67 MMTA for a total of 50 million tonnes).

Overall, the various injection simulations considered an injection period of either 12 or 30 years, followed by a 50-year post-injection observation period. The four Potosi Dolomite injection scenarios simulated for Wabash CarbonSAFE include: two-well injection of 1.67 MMTA of CO_2 for 30 years and 12 years, and single-well injection of 1.67 MMTA of CO_2 into Wabash #1 for 30 years and 12 years.

All four cases show that the Potosi has adequate injectivity at the Wabash site to support a large-scale CO_2 injection project of 1.67 MMTA for 30 years (i.e., rate-constrained cases) totaling 50 million tonnes. The pressure increase from injection does not substantially propagate vertically past the Dutchtown Limestone, which results in a negligible increase in pressure in any overlying formations above the Dutchtown.

Simulation of pressure-constrained cases (discussed in Dessenberger et al., 2022) in which injection of CO_2 is at maximum rate (i.e. BHP is 90% of fracture gradient) indicated it is possible to inject over 5 MMTA for 30 years without exceeding the fracture pressure of the Potosi Dolomite.

Application of NRAP Tools for Risk Assessment

Technical Report DOE-FE0031626-3 (Sarathi et al., 2021) documents a risk assessment of CO_2 containment loss and induced shear failure due to geologic carbon storage at the Wabash CarbonSAFE site; the separate report, *Application of the NRAP Tools to the Wabash CarbonSAFE Site for Risk Assessment Associated with Geologic Carbon Storage Activities,* is included as Appendix E, and a summary is presented here.

The purpose of this work was to assess (1) CO_2 sequestration performance relative to the CarbonSAFE goals of storing 50 Mt over 30 years, (2) the risk of containment loss due to leakage along a wellbore and into an overlying aquifer, and (3) the state of stress and risk of reactivating existing fractures. This study relied upon the initial Potosi Dolomite characterization and Potosi modeling work for the Wabash CarbonSAFE site (described above) along with analogue data collected from other carbon sequestration projects in the region.

The National Risk Assessment Partnership (NRAP) analytical tools were applied to quantify the risk of CO_2 and brine leakage into an overlying aquifer (in particular, underground sources of drinking water), and to identify injection-related geomechanical risks. Stochastic leakage risk analyses were performed varying subsurface permeabilities, aquifer porosity, and well properties using the open-source NRAP Integrated Assessment Model (NRAP-Open-IAM). Geomechanical risks resulting from the injection of CO_2 were analyzed with the aid of SOSAT (State-of-Stress Analysis Tool).

Potosi Dolomite injections simulations were performed using the STOMP (Subsurface Transport Over Multiple Phases) simulator, which agree with the *Nexus*® Potosi CO_2 injection simulation modeling results (described above) showing that injection in the Potosi Dolomite would meet the rates necessary to inject 50 million tonnes over 30 years. Based on the Petrel™ Potosi Geocellular Model (described above), the large injectivity is primarily due to multiple high-permeability vuggy intervals within the Potosi Dolomite.

NRAP-Open-IAM Tool

Building on the STOMP model, two scenarios were analyzed using the NRAP-Open-IAM tool: leakage through hypothetical uncemented wells and leakage through hypothetical damaged cemented wells. Key findings are as follows:

- For the conservative case of leakage through a hypothetical uncemented well, the 90% quantile results estimate cumulative leakage of 0.08 Mt of CO_2 and 0.08 Mt of brine over 80 years (injection plus monitoring period), which amounts to less than 0.2% of the injected CO_2. This leakage amount is considerably below the 1% leakage value commonly proposed to ensure storage effectiveness. The plume size for detectable water quality impact to an underground source of drinking water are constrained to within a radius of 0.5 mi (0.8 km) around the leaky well.
- Leakage risks are even smaller when considering leakage along the cemented annulus of a hypothetical damaged well. The 90% quantile results estimate a cumulative leakage of 8.2×10^{-3} Mt of CO_2 to the overlying aquifer and atmosphere and insignificant brine leakage. As a result, detectable water quality impact plumes have negligeable sizes for

total dissolved solids; for pH and dissolved CO_2 the radii do not exceed 0.4 mi (0.6 km) from the leak source.

- The aforementioned results apply to leakage at the injection well location. The leakage amounts and groundwater impacts decrease as the distance between the injection well location and the hypothetical leaky well location increases.

SOSAT Tool

Geomechanical risks resulting from the injection of CO_2 were analyzed with the aid of SOSAT (State-of-Stress Analysis Tool), a computational tool that incorporates subsurface geomechanical uncertainties to evaluate the state of stress probability distribution along a depth profile. For the Wabash site, SOSAT computes a relatively high variance of the probability distributions for minimum and maximum horizontal stresses and estimates a low risk of inducing shear failure.

The current level of knowledge of the site indicates that the risk of reactivation of any potential existing faults is very limited. This is largely due to a combination of (1) the a priori assumption that a normal faulting stress state was unlikely based on regional information, and (2) the low values of the minimum horizontal stress indicated by the step rate tests (SRTs). These analyses highlight the importance of investing in geomechanical characterization efforts, with particular focus on measuring the principal stresses in the sealing formation, to reduce geomechanical uncertainties.

Regional 2D Seismic Survey

The regional seismic information obtained by the Wabash CarbonSAFE project provides a linkage with a region having known storage characteristics (in east-central Illinois) through the transition to the deeper Wabash location to better evaluate and interpret the basin features significant to storage at this site. Preliminary interpretations of the Vermilion-Champaign-Piatt (‘Champaign’ line) and Wabash-Paris (‘Paris’ line) 2D seismic reflection data were performed, and are summarized below:

<u>Champaign 2D Seismic Line</u>

The east-west Champaign seismic line (Figure 35) is located in east-central Illinois and runs west-east for almost 38 mi (61 km) through Piatt, Champaign, and Vermilion Counties. The line can be broken up into the Paleozoic section above the interpreted Precambrian unconformity and the Precambrian section below the unconformity. The Paleozoic section has semi- to continuous high amplitude reflectors generated by variable carbonate/shale/sandstone stratigraphy and is a broad low-relief structure approximately 25 mi (40 km) across (Figure 36). It is bounded on the west by unfaulted, shallow west-dipping Paleozoic stratigraphy, and bounded on the east by a monocline cored by a west-dipping high angle reverse fault. Since there are no deep wells present along the Champaign line to tie the Paleozoic stratigraphy to the seismic, existing interpretation from nearby well and seismic data was extrapolated to the Champaign line. This data includes the 2021 One Earth Energy (OEE) seismic data and OEE #1 test well (26 mi [42 km] north), the Hinton Brothers #7 well (18 mi [29 km] north) and the 2014 Manlove seismic line (19 mi [31 km] north).

Within the Precambrian section, the Champaign seismic line shows two distinct features. First, spread out across most of the seismic section are a series of high angle normal faults with relatively small offsets ranging from <0.25 to about 1 seismic wavelength. Assuming 45 Hz frequency and a Precambrian interval seismic velocity of 18,000 ft/s (5,486 m/s), this equates to a range of offsets of about seismic detection (1/4 wavelength) at 50-100 ft (15-30 m) to about 400 ft (122 m). These faults are truncated at the Precambrian unconformity and are, therefore, older than the overlying Argenta sandstone, which is likely Lower Cambrian in age (Monson et al, 2018). One exception is the black fault which is nearly vertical and is a younger fault with both strike-slip and reverse movement. This fault is younger than the other Precambrian normal faults since it appears to tip out just above the top of the Mt. Simon Sandstone within the Eau Claire Formation.

The second Precambrian feature is a series of dipping Precambrian reflectors throughout the deeper section (below the Precambrian unconformity and down to about 4 seconds). These reflectors are possibly packages of basalt dikes or sills related to the latest stages of rifting that eventually lead to the formation of the Illinois Basin (Freiburg et al., 2022), or the reflectors represent part of the Centralia sequence of Pratt et al. (1992).

Seven key Paleozoic surfaces were mapped across the seismic line (Figure 36). Most stratigraphic intervals show relatively constant thickness across the seismic line or subtle thickness changes. The Mt. Simon Sandstone shows a gentle thickening to the east. The thicker Knox and Mt. Simon intervals show lower overall reflectivity due to the lack of significant lithology differences within the zones. The Precambrian unconformity surface appears to show some relief, indicating areas of differential erosion into the Precambrian rocks.

<u>Paris-Wabash 2D Seismic Line</u>

The east-west Paris-Wabash seismic line is located about 39 mi (63 km) southeast of the Champaign line, crossing from Illinois to Indiana just north of the recent Wabash #1 well (Figure 35 and Figure 37). The line is about 30.4 mi (49 km) long and runs west-east, primarily through Edgar County, IL, and part of Vigo County, IN. Existing 2019/2021 Wabash 2D seismic lines were tied to the Wabash #1 well; the Paris-Wabash 2D line intersected two of these lines, resulting in a high confidence seismic tie. Since the Wabash well did not penetrate the Precambrian unconformity, the mapped Precambrian horizon is estimated. Additionally, a deeper intra-Precambrian surface was mapped to delineate an angular unconformity within the Precambrian and is also unpenetrated.

In the Paleozoic section, the most significant feature is a monocline cored by a high angle west-dipping reverse fault, with a high angle east-dipping normal fault just to the west (Figure 37). The Paleozoic stratigraphy is nearly unfaulted except for the Mt. Simon, which is where the normal fault tips out. The reverse fault tips out at or just below the Precambrian unconformity.

There are three units that show significant thickness changes. The Eau Claire Formation and the Mt. Simon Sandstone both thin to the east. The Argenta sandstone also thins to the east, but shows abrupt thickening across the normal fault from west to east, indicating relative timing of the movement of the fault. Visible within the Argenta are a series of very bright reflectors, which may indicate the presence of flood basalts. A 20 ft (6 m) thick basalt, interpreted as a flood basalt (Freiburg et al., 2022), was penetrated in the Wabash #1 well at the base of the Argenta. These bright reflectors are not present in the thinned Argenta in the upthrown side of the normal fault on the western part of the line. This could be interpreted as either the basalts were not deposited on the west upthrown side of the block, or they were eroded during Argenta time shortly after deposition.

Below the intra-Precambrian unconformity lie a significant number of Precambrian reflector packages that, like the Champaign line, could be related to the latest stages of rifting that lead to the formation of the Illinois Basin (Freiburg et al., 2022), or represent part of the Centralia sequence of Pratt et al. (1992). Two broad folds are present in these packages, one at each end of the line at about 1500-2500 ms two-way travel time (twtt). The fold on the east side of the line is imaged well enough to see growth on the west limb of the fold.

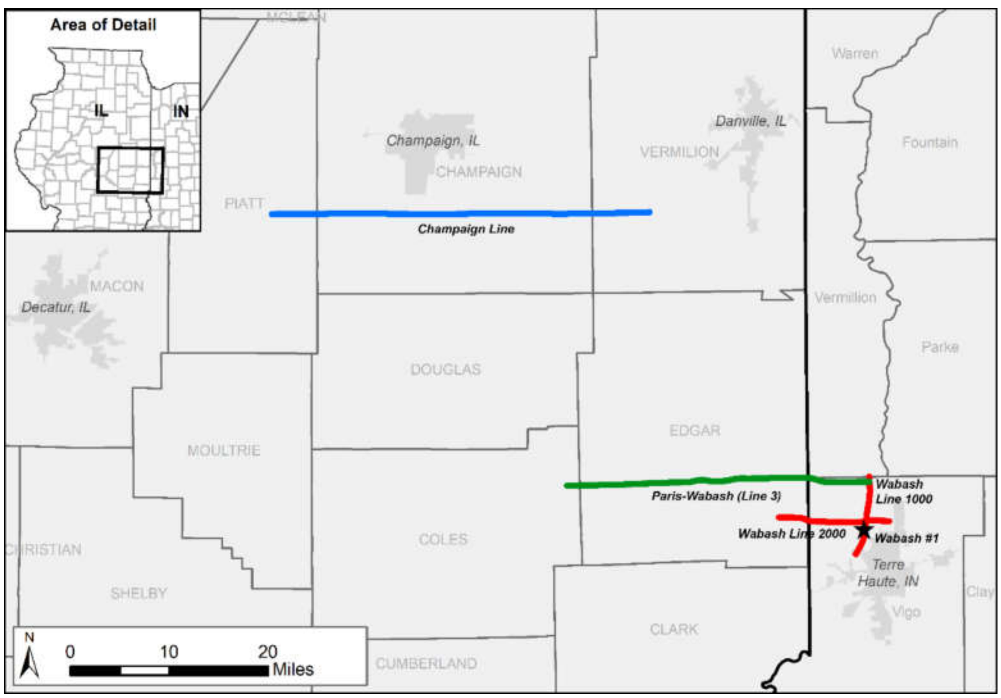

Figure 35. Location of recent Wabash CarbonSAFE 2D seismic acquisitions (Paris-Wabash, and Champaign 2D lines) in relation to earlier project acquisitions (Lines 1000 and 2000) in the vicinity of the Wabash #1 well.

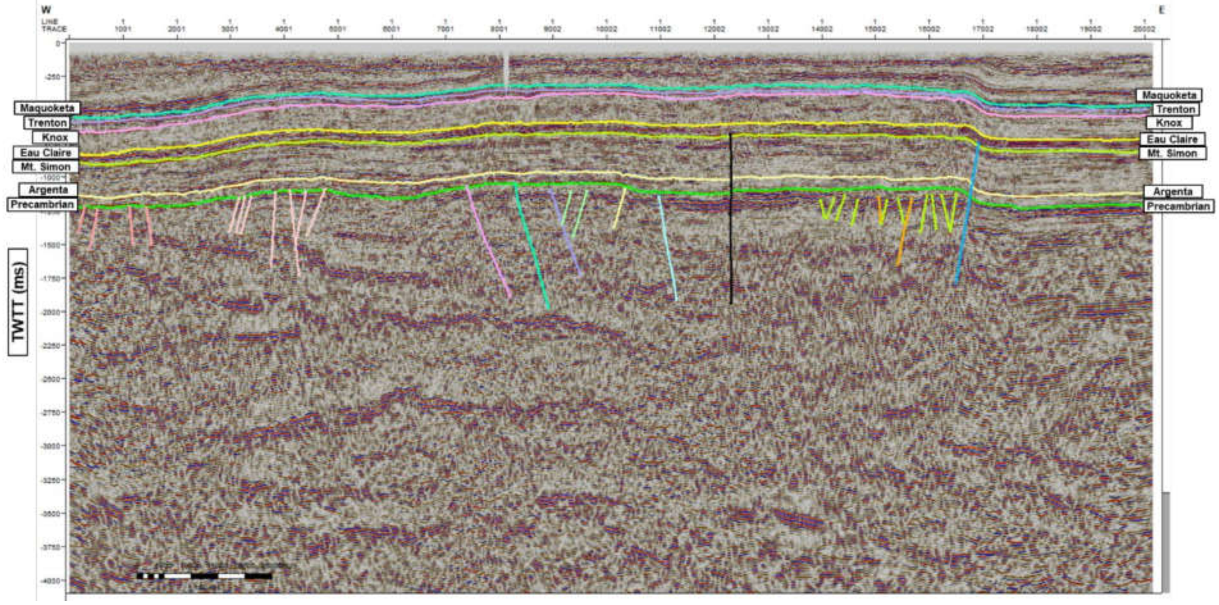

Figure 36. Champaign 2D seismic reflection profile showing a series of high angle normal faults with relatively small offsets in the Precambrian. One exception is the black fault which is nearly vertical and is a younger fault with both strike-slip and reverse movement. Also shown is a series of dipping Precambrian reflectors throughout the deeper section (below the Precambrian unconformity and down to about 4 seconds).

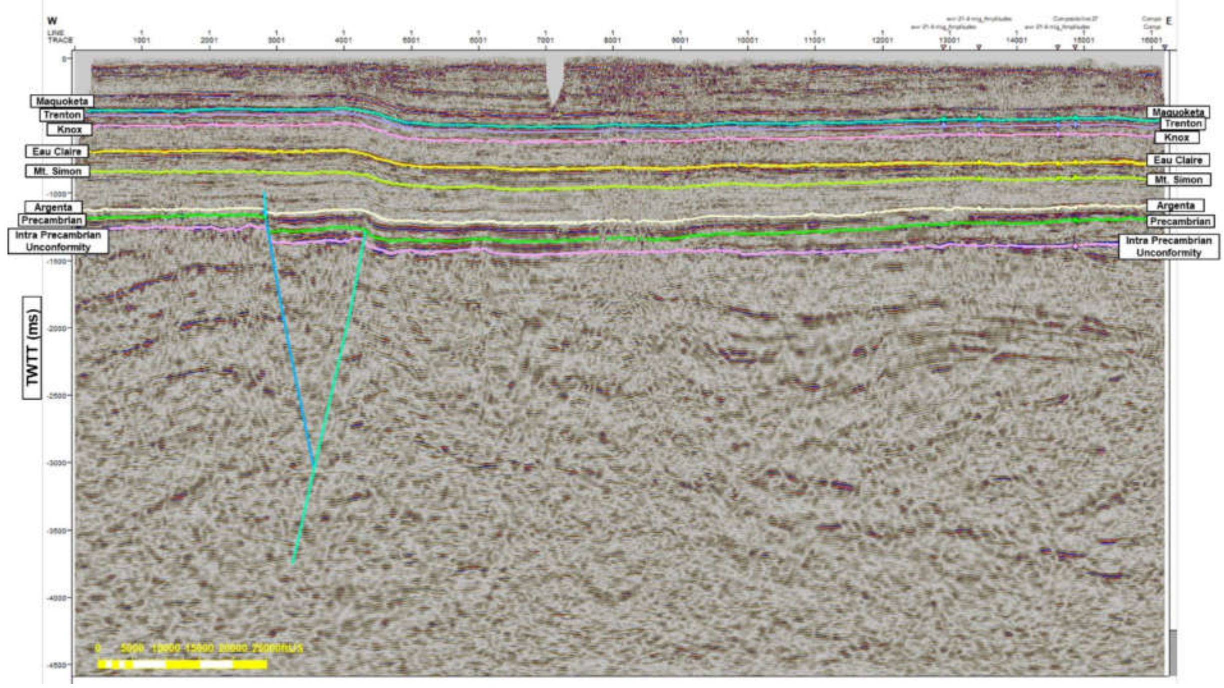

Figure 37. Paris-Wabash 2D seismic profile showing a monocline (in Paleozoic section) cored by a high angle west-dipping reverse fault, with a high angle east-dipping normal fault just to the west. The Paleozoic stratigraphy is nearly unfaulted except for the Mt. Simon, which is where the normal fault tips out. The reverse fault tips out at or just below the Precambrian unconformity.

CO_2 SOURCE AND INFRASTRUCTURE DEVELOPMENT

Wabash Valley Resources Facility Summary

The primary source of CO_2 for this project, the WVR Integrated Gasification Combined Cycle (IGCC) facility, and former power plant, is now being retrofitted and converted into a hydrogen production facility that will capture, compress, and inject up to 2 million tons of CO_2 annually. This is the first hydrogen production facility in the United States to implement carbon capture and storage (CCS) technology. With the goal of net-zero carbon emissions, WVR is focused on producing a clean hydrogen fuel, generating up to 300MW of electricity using a hydrogen power block, and sequestering the greenhouse gas emissions in geologic formations (Koenig, 2021). The current WVR IGCC plant configuration and CCS designs are discussed in detail in Technical Report DOE-FE0031626-5 (Blakley et al., 2021); the separate report, *Wabash CarbonSAFE CO_2 Source Assessment,* is included as Appendix F, and a summary is presented here.

Retrofitting the existing gasification facility reduces the technical risk and capital costs associated with the project, leading to a higher probability of implementation and more competitive product prices. The Wabash gasification facility has successfully produced syngas for over 20 years; adding CO_2 separation and capture to the plant configuration maintains the existing plant as-is with minimal modifications (Figure 38).

Carbon dioxide sequestration will be integrated into the design of the new facility, allowing the site to have a low greenhouse gas (GHG) emission rate. Carbon dioxide from the new Dual Refrigeration CO_2 Fractionation Unit (DRCF) will be directly forwarded via pipeline to the injection field. Due to the favorable geology of western Indiana, the carbon dioxide injection well(s) can be located very close to the production site, lowering the investment costs for CCS. A summary of plant performance and CO_2 product specifications are provided in Table 16 and Table 17, respectively.

The Wabash Gasification plant has successfully produced syngas for over 20 years, utilizing petroleum coke (petcoke) or coal as the feedstock. The solid feedstock is milled with recycled water to produce a slurry solids concentration that varies depending on the feedstock selected, then the slurry is routed to the Gasifier. The Gasifier is the E-Gas^{TM} gasification technology. Several processes are combined in the integrated facility to produce hydrogen and power. Byproducts of the facility include carbon dioxide, elemental sulfur, and vitrified slag.

The supercritical carbon dioxide stream generated in the Hydrogen Purification section (Figure 38) will be forwarded via pipeline to the injection field from the new DRCF. One major advantage of the DRCF hydrogen purification process is that the resultant carbon dioxide stream is generated as a liquid product, allowing for the use of pumps to elevate the pressure to the required level for sequestration; this avoids the cost, complexity, and electrical usage penalty of a large compressor. Planned injection well(s) would be designed and permitted per US EPA Underground Injection Control (UIC) Class VI (Wells used for Geologic Sequestration of CO_2) specifications (EPA, 2021).

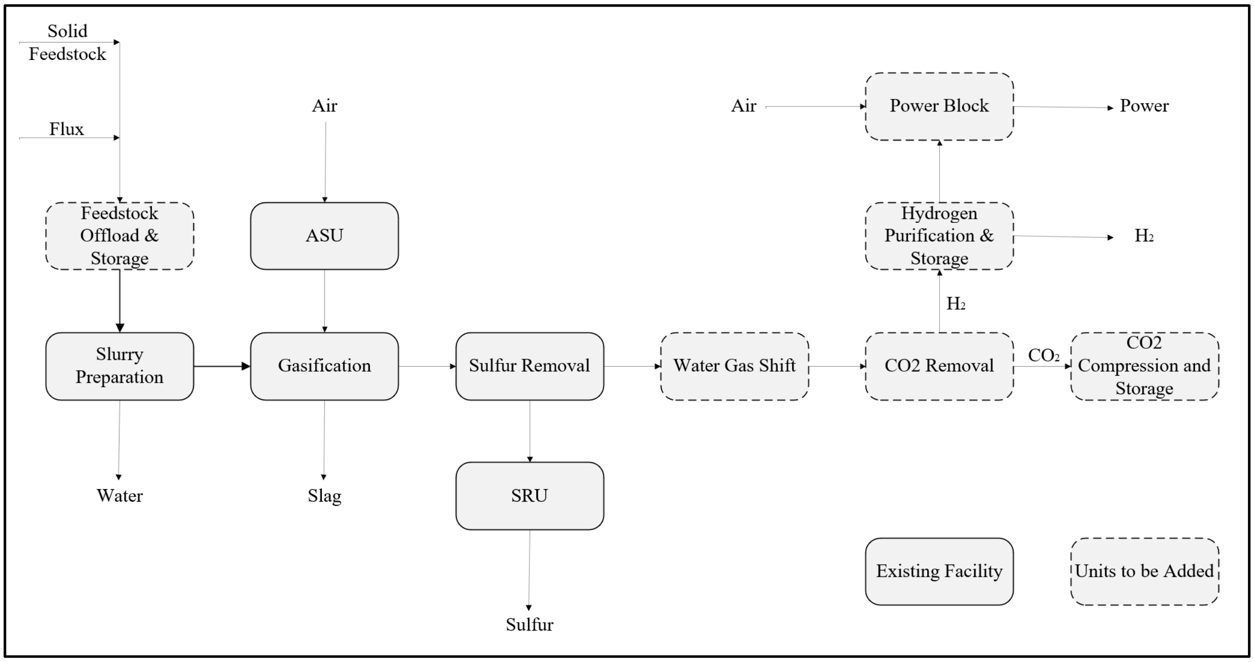

Figure 38. WVR facility block flow diagram.

Table 16. WVR Plant Performance Summary.

Petcoke Fuel Consumption	2,000 stpd
Natural Gas Usage	15 mmbtu/hr
Power Consumption	60 MW
Raw Water Consumption	2,816 gpm
Hydrogen Production	14,000 kg/hr

Table 17. CO_2 product specification.

Temp. Deg F	114
Pressure PSIG	2,000
CO_2	>99%
Water	<400 PPM

Business Environment

As part of a plan to commercialize capture, compression, and sequestration operations, regional business considerations leading to specific business plans are necessary for successful implementation at commercial scale. Technical Report DOE-FE0031626-4 (Koenig, 2021) explores the outside influences and the business plan of the Wabash Valley Resources facility to implement a commercial, large-scale CCS project; the separate report, *Wabash CarbonSAFE Business Environment Study,* is included as Appendix G, and a summary is presented here.

WVR's commercial project is influenced by two legislative bodies: the Indiana General Assembly and the United States Congress. Indiana has shown continued, bipartisan support of the Wabash commercial project. Indiana Senate Bill 442, signed into Public Law 291 in 2019, established carbon storage as a publicgood. As part of Indiana Law 291, the project has access to the established eminent domain laws for the construction of CO_2 pipelines and access to storage formations. The legislation also allows the State of Indiana to assume long term ownership of the sequestered CO_2 after site closure. The federal government has little regulation of CCS, only regulated directly by the United States Environmental Protection Agency's (EPA) Underground Injection Control Class VI (wells used for Geologic Sequestration of CO_2) permit, which requires an extensive application process. Additionally, Congress has established the Section 45Q tax credits, providing tax credits on a dollar amount-per-metric ton (tonne) basis.

Terre Haute, Indiana, has a business climate full of industry. The surrounding region has oil and gas field operations, with subsurface operation familiarity in the area. Located between Indianapolis and the state border with Illinois, Terre Haute has an interstate, two U.S. highways, and other Indiana state roads providing a road transportation corridor familiar with heavy trucking activity. The Wabash project will require estimated \$355 million in capital expenditures for the carbon capture, compression, and sequestration facilities, and an estimated \$32 million annual operational cost. The project is funded via equity investments and debt obtained through commercial loans, bonds or other debt instruments. It is anticipated that up to \$300 million of the project capital requirements would be obtained through debt. By utilizing §45Q tax credits, WVR will capitalize on the injection of CO_2. The §45Q credits will allow for a realized economic internal rate of return (IRR) sufficient to allow the project to proceed.

Network Expansion, Transportation, and Infrastructure

In addition to storing its own captured CO_2, the geographic location and subsurface geology at Wabash Valley Resources suggest it may be an advantageous site for a carbon storage hub.

<u>CO_2 Source Network Expansion Modeling</u>

Technical Report DOE-FE0031626-7 (Kammer, 2022) analyzes the potential of nearby sources to transport their captured CO_2 to Wabash Valley Resources through an optimal pipeline network; the separate report, *Wabash CarbonSAFE Roadmap for Network and Storage Deployment,* is included as Appendix H, and a summary is presented here.

In this study, an aggregation of the inputs for dynamic models from the Illinois State Geological Survey (ISGS) of the Potosi Dolomite at the Wabash Valley Resources site is used in the

Sequestration of CO_2 Tool (SCO_2T) for storage and cost estimates. The estimated well injection rate from *SCO_2T* in the Potosi Dolomite is 1.0 million metric tonnes annually (MMTA) per well, at a storage cost (capture and transport costs not included) of $3.23 per tonne of CO_2 and a total storage amount of 60 million tonnes using two wells over a 30-year project period. In addition to Wabash Valley Resources, five additional capture facilities are included in this feasibility study: the Valero Linden Ethanol Plant in Linden, Indiana, Duke Energy's Cayuga Generating Station (Units 1 and 2) in Cayuga, Indiana, Lone Star Industries cement facility in Greencastle, Indiana, and the Marathon Robinson Refinery in Robinson, Illinois (Figure 39).

After parameterizing the CO_2 capture and storage facilities, *SimCCS Gateway*, a cloud computing service developed at Indiana University that provides an online platform for the community open-source version of the *SimCCS* software, was used to generate the optimal candidate network and develop optimal deployment scenarios for CCS with Wabash Valley Resources as a storage hub.

Two cases were considered for CCS deployment among the six capture facilities in this study, each using low, average, and high capture costs among their scenarios.

Case 1 included project capture targets ranging from 0.5 to 2.0 million metric tonnes annually (MMTA). Wabash Valley Resources and the Valero Linden Plant were the only two capture facilities used across all capture cost scenarios and project capture target rates for Case 1. The total unit cost (annualized cost of all capture, transport, and storage costs combined) for Case 1 ranged from $22.20 to $31.31 per tonne of CO_2, with a mean total unit cost of $27.82 per tonne of CO_2.

Case 2 allowed for the maximum injection rate at Wabash Valley Resources to extend beyond the currently modeled injection rate to allow all capturable CO_2 among the six facilities to be transported to Wabash Valley Resources for injection. In this Case, the project capture target rate varied from 3.0 to 8.23 MMTA in increments of 1.0 MMTA. The *SimCCS Gateway* results continued to favor Wabash Valley Resources and the Valero Linden Plant for initial deployment, followed by the remaining capture facilities, with their order of deployment depending on the capture cost scenario (Figure 40). The total unit cost for Case 2 ranged from $26.72 to $58.44 per tonne of CO_2, with a mean total unit cost of $45.63 per tonne of CO_2.

The *SimCCS Gateway* model scenarios as defined in this study suggest that CCS network and storage deployment could be economically viable in the current tax credit scenario from Internal Revenue Code (IRC) § 45Q, which provides $50 per tonne of CO_2 sequestered in saline formations, and would certainly merit further consideration if the tax credit were to be increased.

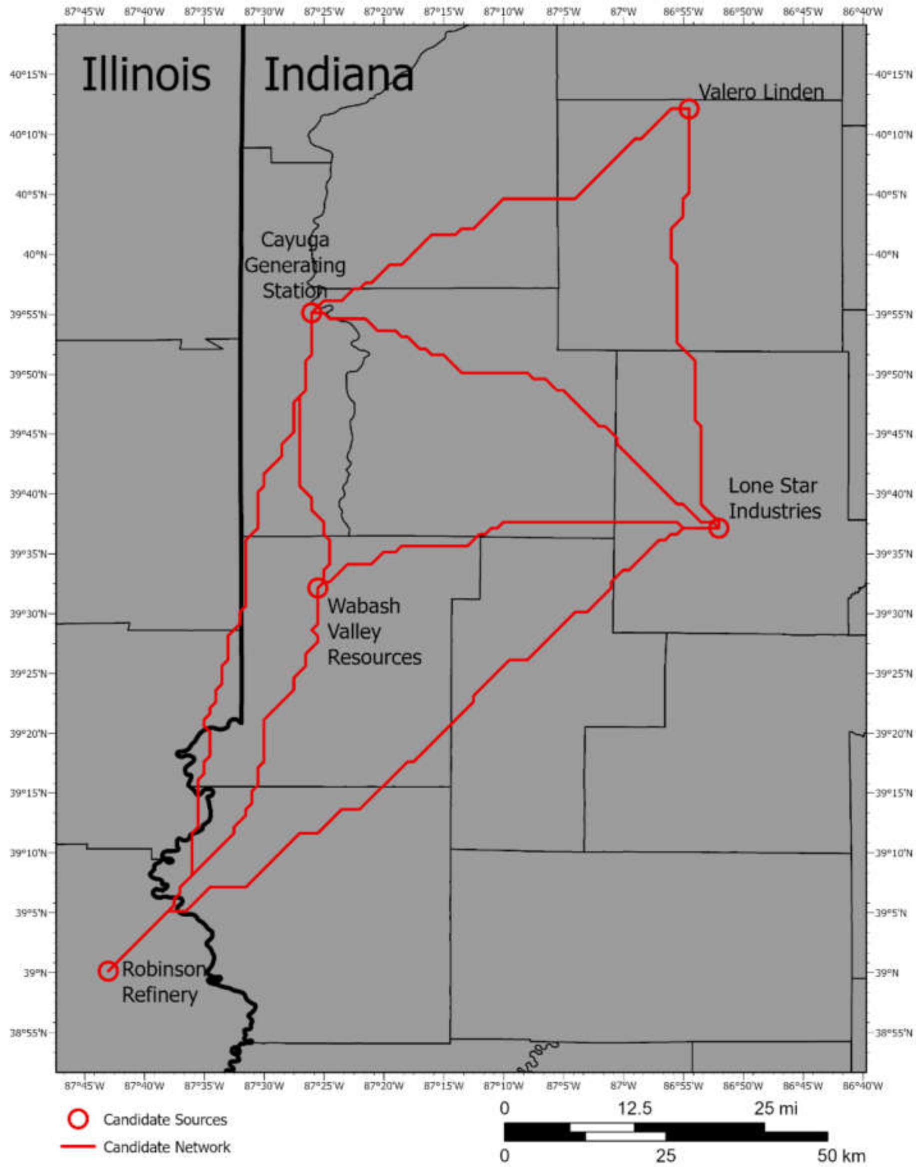

Figure 39. Candidate sources and pipeline network for SimCCS Gateway simulations. Cayuga Generating Station Units 1 and 2 coincide. Storage facility is located at Wabash Valley Resources and is not shown. Project area is roughly 130 km by 70 km (80 mi by 40 mi).

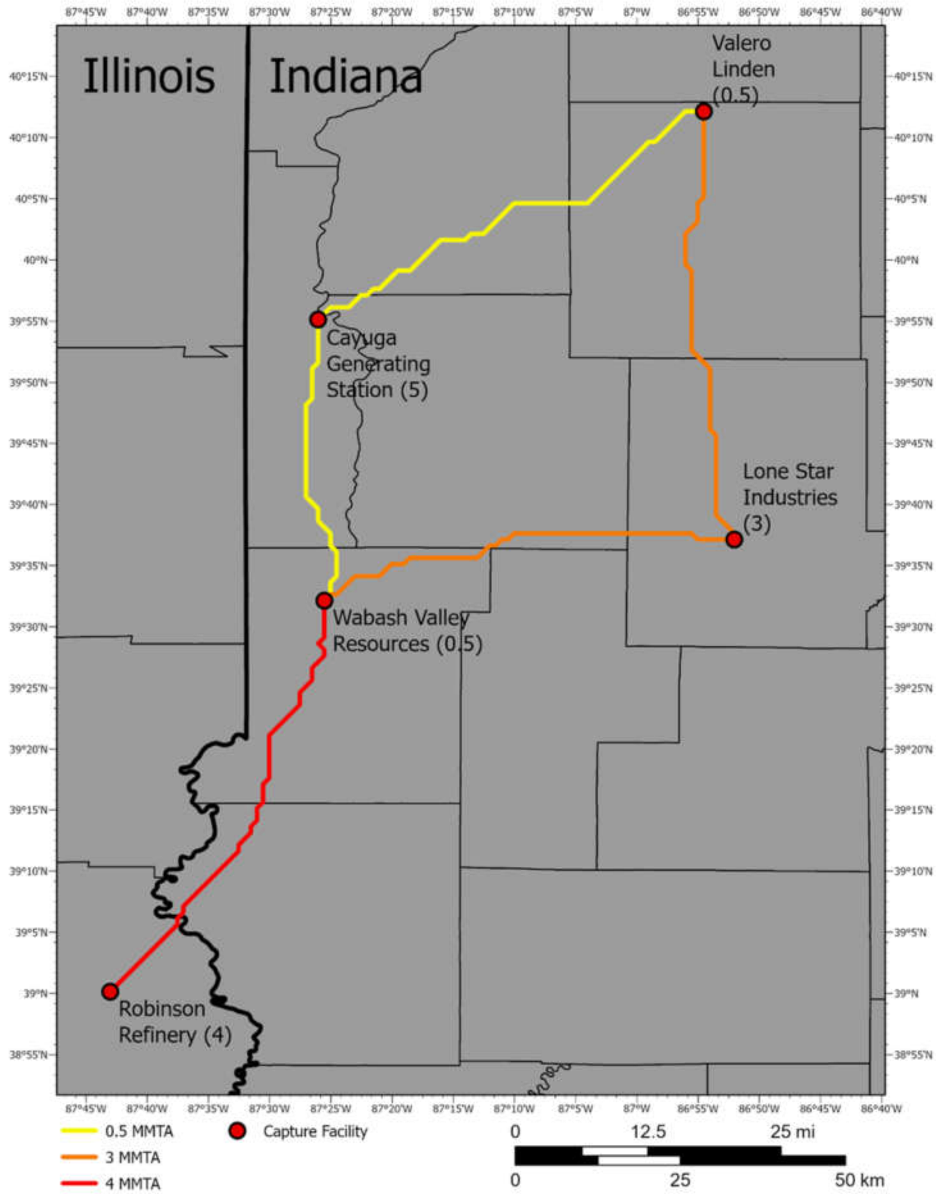

Figure 40. Example from Case 2 deployment scenarios. Order of deployment of capture facilities and pipeline network for average capture cost scenarios. Number in parentheses next to capture facility names denotes the lowest annual project capture amount where the respective facility is utilized. The value provided at Cayuga Generating Station is for Unit 1, Unit 2 is utilized beginning at 7.0 MMTA. Color of pipeline network denotes the lowest annual project capture amount where the respective pipeline is utilized.

Conceptual Tie-ins for CO_2 Source Expansion

Whereas the network expansion study referenced above assessed nearby sources regardless of facility type, a second study assessed higher-purity CO_2 sources at a more regional scale (McKaskle et al., 2021), and included an overview of equipment and instrumentation required to tie-in the additional CO_2 to the surface facilities at the WVR site; the separate report, *Conceptual Study of Expansion CO_2 Source Tie-ins at the WVR Injection Facility,* is included as Appendix I, and a summary is presented here.

Broadly, Trimeric evaluated the high-level pipeline, equipment, and instrumentation requirements for bringing additional sources of CO_2 into the WVR facility injection site.

CO_2 Source Assessment:

High-purity CO_2 sources were identified and cataloged in the region surrounding the WVR facility and representative cases for future CO_2 source expansion were included for CO_2 flow rates of 300,000 and 1,000,000 tonne/yr and for straight-line distances of 50 and 150 miles (80 and 240 km) to WVR. These flow rates and distances represent likely bounds for high-purity CO_2 sources such as ethanol, fertilizer, and hydrogen facilities in the region.

Pipeline Sizing and Costs:

Pipelines sizes (diameters) and costs were developed for four cases bracketed by the CO_2 flow rates and pipeline lengths described above:

- 300,000 tonne/yr, 50 mile (80 km) pipeline.
- 300,000 tonne/yr, 150 mile (240 km) pipeline.
- 1,000,000 tonne/yr, 50 mile (80 km) pipeline.
- 1,000,000 tonne/yr, 150 mile (240 km) pipeline.

For 300,000 tonne/year Cases (Typical biogenic CO_2 generation rate for average size ethanol plants in the region):

- The nominal diameter was 6” for both the 50-mile (80-km) and 150-mile (240-km) pipeline length cases.
- The screening-level installed cost estimate for a 6”, 50-mile (80-km) pipeline was $41 million.
- The screening-level installed cost estimate for a 6”, 150-mile (240-km) pipeline was $122 million.
- For the 50-mile (80-km) pipeline, a 4” line was evaluated, but the CO_2 can only be transported ~20 miles (32 km) before reaching the 1,200 psig minimum pressure threshold for this study. Booster stations were not considered in this study for the shorter, 50-mile (80-km) pipeline cases since the cost-benefit of booster stations is more clearly illustrated for the longer pipeline cases (i.e., more significant cost savings for the longer pipeline size reduction).
- Adding booster pump stations was deemed impractical for the 150-mile (240-km) pipeline because approximately five booster stations would be need to reduce the pipeline size to the next smallest nominal diameter (4”) while meeting the operational constraints defined for this study.
- Therefore, a 6” pipeline appears to be a reasonable choice for these cases.

For 1,000,000 tonne/year Cases (Typical for hydrogen production facilities or the largest ethanol plants in the region):

- The nominal diameter was 8” for a 50-mile (80-km) pipeline.
- The nominal diameter was 10” for a 150-mile (240-km) pipeline.
- The screening-level installed cost estimate of an 8”, 50-mile (80-km) pipeline was $54 million
- The screening-level installed cost estimate of a 10”, 150-mile (240-km) pipeline was $203 million.
- Adding a single booster station for the 150-mile (240-km) pipeline was deemed feasible based on the hydraulic analysis. The booster station was located at approximately the mid-point of the pipeline and reduced the nominal diameter of the pipeline from 10” to 8”.
- Adding this booster station allowing the use of the smaller diameter pipeline reduced the estimated installed cost of the 150-mile (240-km) pipeline to approximately $162 million (~$41 million less than the 10” pipeline without a booster pump station).
- The costs savings from a smaller diameter pipeline with a booster station must be weighed against the installed cost for the booster pump station (~$2.4 million), annual operating costs of the booster pump station (~$0.20 million/yr), and several other costs/considerations that were not evaluated as part of this study. These include land acquisition costs/availability, land disturbance, cost of providing electricity to the booster station site, etc. In some cases, these additional factors may dictate the choice to install a booster station regardless of the potential cost savings with a smaller diameter pipeline. Another part of the tradeoffs to be considered - Installing a larger diameter pipeline initially also allows more room for future expansion.
- Adding more than one booster pump station was deemed impractical since several booster stations would be required to reduce the pipeline diameter further from 8” down to 6” or less.
- Therefore, an 8” pipeline with one booster pump station or a 10” pipeline without booster stations appear to be the practical lower limit for these cases.

The installed CO_2 pipeline costs reported in this study are order-of-magnitude estimates developed from publicly available data; the cost data for installed pipelines highlighted a high degree of variability in costs due to site-specific and project-specific requirements.

CO_2 Distribution and Injection Site Facilities:

The study includes a description of example CO_2 distribution and injection facilities (with diagrams) to give the reader an idea of the general requirements and the type of equipment, piping, and instrumentation required to connect the CO_2 trunk line arriving at the WVR site to the injection wells (see example Figure 41).

Once the main CO_2 trunk line arrives at the injection site, the CO_2 will be distributed, metered, measured, and controlled for safe and reliable injection of the CO_2 at each injection well. This study provides a high-level, general description of CO_2 distribution and associated surface facilities that may be required at WVR. The injection site description can be broadly organized into the following categories:

- Equipment located near the main CO_2 trunk line at WVR.
- Field injection system and distribution network.
- Equipment located at each injection well.

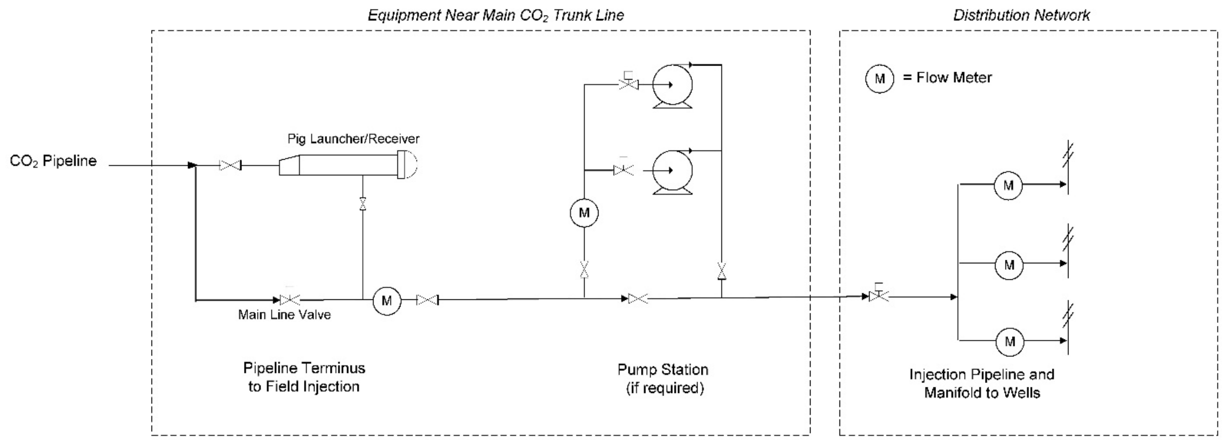

Figure 41. Example of general equipment located near the main CO_2 trunk line and distribution network at WVR for conceptual CO_2 source expansion study.

This conceptual study defined representative cases to facilitate analysis an understanding of the approximate costs and general requirements of adding additional CO_2 sources to the WVR injection site; the study is not intended to replace or represent the detailed engineering design work that must be completed specifically for the WVR injection facility and operation and any subsequent source additions. Additional engineering work would be needed to incorporate specific CO_2 sources. Future studies would also need to perform a more detailed engineering evaluation of the injection facility, including CO_2 distribution and surface facilities: this conceptual study provided general examples of the piping configurations, instrumentation, and equipment required for the distribution and injection facilities.

STAKEHOLDER ENGAGEMENT AND PUBLIC OUTREACH

Outreach Activities

Early in the Wabash CarbonSAFE project, discussions had taken place between WVR and ISGS on stakeholder engagement goals and approaches, and differentiation between the Wabash CarbonSAFE characterization project and the larger co-located WVR industrial project. As the projects progressed, ISGS staff were generally available to meet with visitors to the WVR site to further explain the Wabash CarbonSAFE project specifically, and/or geologic sequestration in general.

One such meeting hosted by WVR on February 19, 2019, involved industry representatives (Oil and Gas Climate Initiative) and Indiana State legislators. Approximately 15 people were in attendance, and general questions pertaining to geologic CO_2 storage were answered by the ISGS and discussed, e.g. relative depths of potential CO_2 storage reservoirs and sealing units vs. oil production reservoirs, degree of risk for induced 'earthquakes' or CO_2 leakage near Terre Haute, and subsurface CO_2 plume radius estimation and number of surface land owners to account for.

Legislators were interested in how they could best communicate the answers to these questions to their constituents.

On another occasion on October 28, 2019, ISGS assisted in a CCS presentation at the WVR facility and answered questions from local stakeholders, the Terre Haute mayor, chamber of commerce, city council, and others from local government who expressed an interest in topics such as: natural gas storage in the Illinois Basin, the geology of reservoirs and seals, and generally in the history of carbon capture and how it has been demonstrated successfully at other sites such as Decatur, Illinois.

During 2D seismic reflection acquisition, project staff and contractors interacted with interested individuals and nearby landowners, providing them with informational flyers developed for the Wabash CarbonSAFE project characterization and seismic data collection efforts. During drilling, newer staff from the Indiana Department of Natural Resources visited the site and were shown the core collection operations in progress at the Wabash #1 well.

Stakeholder Analysis and Social Site Characterization
Stakeholder engagement and public outreach research focused on conducting a stakeholder framework comparison study that highlights the particular methodologies and theories applicable (and best suited) for stakeholder engagement at Wabash CarbonSAFE. The following material is excerpted from Report DOE-FE0031626-2 (Brumbaugh and Rupp, 2020); the separate report, *Application of Policy Frameworks for Improved Carbon Capture and Storage Social Site Characterization & Stakeholder Engagement,* is included as Appendix J.

Initial stakeholder identification in this region (Greenberg et al., 2019) revealed a range of possible local, state, and national interest groups ranging from government, community groups, environmental organizations, industry, utilities, educational institutions, and media outlets, and concluded that effective stakeholder analysis and engagement is essential for the success of this emerging opportunity for CCS demonstration in the Midwest of the United States.

However, more research was needed to adequately characterize the core beliefs and fundamental principles of relevant stakeholders, as well as identify optimal outreach teams, mechanisms for engagement, and key messages and materials tailored to certain stakeholder values. Application of various analytical approaches in the social sciences, collectively termed “policy frameworks” – are tools which broadly provide a structure to evaluate policy issues, opportunities to compare research findings across projects, and often suggest specific methodologies to assess social phenomena – could provide CCS project developers with theoretically-grounded methods for enhancing efforts to elicit stakeholder concerns and perspectives (Sabatier and Weible, 2014).

Because the beliefs, values, and actions of relevant stakeholder coalitions have considerable influence on the success of energy-related projects globally (Wüstenhagen et al., 2007; Perlaviciute and Steg, 2014; Upham et al., 2015), siting of projects that use geological reservoirs for CO_2 storage requires social site characterization and stakeholder analysis efforts alongside traditional technical characterization surveys (Wade and Greenberg, 2011). The characterization of diverse and often intangible values of numerous stakeholder groups is complex, necessitating the use of theoretical “policy frameworks” to organize and apply various methods to assess and analyze stakeholder concerns and elicit their perspectives.

The Brumbaugh and Rupp (2020) study presents four prominent policy frameworks (Table 18) and associated case studies as opportunities to improve CCS social site characterization and stakeholder engagement. Overall, this report summarized relevant social policy frameworks that CCS project specialists may utilize to assess stakeholder coalition dynamics, organize outreach initiatives, and elicit the concerns and perspectives of various stakeholders.

Based on what is understood to be the most relevant to CCS projects, the report concludes that frameworks should focus on the “subsystem level of analysis” to analyze stakeholders who compromise coalitions. All of the frameworks assessed, including the Advocacy Coalition Framework, Narrative Policy Framework, Collaborative Governance Framework, and Policy Conflict Framework, are applicable for assessing the social aspects of CCS developments; decisions to utilize one of these frameworks over another depends on the central research questions sought. In this regard, each framework differs in its relative effectiveness and efficiency with respect to social site characterization and stakeholder engagement.

After comparing the relative effectiveness and efficiencies of each framework with regard to CCS, this report concludes that the Advocacy Coalition Framework, Narrative Policy Framework, and Policy Conflict Framework can improve the CCS social site characterization process, while the Collaborative Governance Framework paired with the Q-Methodology provides an ideal framework for direct stakeholder engagement.

Overall, this report finds that the Narrative Policy Framework and the Collaborative Governance Framework are most ideally suited for the purposes of CCS social site characterization and stakeholder engagement. In sum, although each framework has varying levels of effectiveness and efficiency, integration of policy frameworks into the CCS social site characterization and stakeholder engagement process is key in improving overall project success.

Table 18. Summary of Policy Frameworks.

	ACF	NPF	CGF	PCF	IAD/SES
Scope of Analysis	Interaction at the coalition and subsystem levels.	Applications at the micro, meso, and macro levels.	Particularly valuable for coalition-level collaboration, but the scope can be interpreted broadly.	Conflict at the individual and group levels.	Broad, conceptual blueprint for examining institutional-level issues.
Key Questions	"What factors influence coalition formation, policy learning, and policy change (Sabatier& Weible, 2014)."	"Do narratives play an important role in the policy process (Sabatier& Weible, 2014)?"	How can collaborative learning, dispute resolution, and cross-coalition decision-making be applied to address complex issues (Emerson et al., 2012)?	"Under what settings do policy conflicts emerge, endure, and subside and which forms have what consequences (Heikkila & Weible, 2017)?"	"How do people devise institutional arrangements to solve collective action problems and provide shared benefits (Sabatier& Weible, 2014)?"
Methodology Clarity	Clearly stated assumptions. Many case studies use consistent ACF methods and generally include surveys used as appendices.	Clear methods and codebooks available for applying the framework in various contexts.	The framework is highly conceptual, so it must be paired with specific methodologies.	Methods are defined in existing literature, but there have been few applications of this framework thus far.	Clear guidelines for laying out policy issues, but very conceptual in nature.
Extent of Application	Extensive use in multiple countries, with particular use in environmental policy-related issues.	Some applications in the United States, but the NPF is still a relatively new framework.	Many case studies cite collaborative governance broadly, but the official CGF is a relatively new development.	Very recent application for oil and gas conflict issues. Due to the recent development of the PCF, only a few applications exist.	Many cases have used the IAD/SES throughout the world to conceptually address common-pool and stakeholder issues.

*ACF = Advocacy Coalition Framework, NPF = Narrative Policy Framework, CGF = Collaborative Governance Framework, PCF = Policy Conflict Framework, IAD/SES = Institutional Analysis and Development Framework/Social-Ecological System Framework.

STORAGE COMPLEX DEVELOPMENT

Policy, Regulatory and Legal Considerations

Wabash CarbonSAFE Technical Report DOE-FE0031626-6 (Korose et al., 2022) discusses the policy, regulatory, legal, and permitting considerations to-date as related to geologic CO_2 storage at the Wabash Valley Resources (WVR) gasification plant site in Vigo County, Indiana; the separate report, *Wabash CarbonSAFE Policy, Regulatory, Legal, and Permitting Evaluation,* is included as Appendix K, and a summary is presented here.

Indiana Senate Bill 442, signed into Public Law 291 in 2019, establishes that CCS operations at WVR would be a pilot project in need of Class VI Underground Injection Control (UIC) permit by the US EPA. The law provides for the use of eminent domain, if needed, for the pooling of subsurface pore space for CO_2 injection; and provides for the assumption of long-term ownership of the injected CO_2 by the State of Indiana.

Currently, the US Federal §45Q Tax credits are the greatest monetary incentive for CCS/CCUS projects. The current dollar amounts of the Section 45Q credits per tonne were established in the Bipartisan Budget Act of 2018, expanding the maximum dollar amounts in 2026 to $50 for sequestered carbon oxide and $35 for utilized CO_X. The credits were modified as recently as December 2020 when Congress passed The Consolidated Appropriations Act, 2021, which expanded the deadline for construction to begin, now required to commence by December 31, 2026. In addition, there is a general continued interest in scaling CCS technologies toward commercialization at the Federal level via funding through the bipartisan Infrastructure Investment and Jobs Act (IIJA), which was signed into law by President Biden on November 15, 2021.

The WVR facility is located above suitable geology for storage of the anticipated capturable CO_2 (ca 1.82 million tonnes per year) with minimal transportation distance providing WVR the opportunity to reduce costs with onsite injection. In Indiana, both the Eminent Domain for Transportation of Carbon Dioxide by Pipeline (IC 14-39) and Indiana Public Law 291 established carbon storage as a public good. As part of Law 291 the WVR project has access to the established eminent domain laws for the construction of CO_2 pipelines.

Groundwater protection is addressed by the Safe Drinking Water Act and is regulated through the US EPA's Underground Injection Control (UIC) program. Protection of underground sources of drinking water (USDWs), in the context of CO_2 injection for geological storage, is achieved by geological characterization and validation of the storage complex site reservoir and seal integrity, and through successful UIC Class VI well permitting and proper injection well construction. Of primary importance to the development of a UIC Class VI permit application is the identification of the lowermost underground source of drinking water (LUSDW) to inform modeling and delineation of the Area of Review. Based on regional salinity data and sample analysis from the Wabash #1 well, it is expected that the LUSDW at the WVR site is the Silurian-Devonian Carbonate-Rock Aquifer.

A potential Class VI CO_2 injection well permit for the Wabash CarbonSAFE study site would be obtained through the US EPA Region 5, because the State of Indiana does not have UIC Class VI primacy. 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).

Potential Risks Associated with the Permitting Process

Project risks associated with UIC Class VI permit development were evaluated for Wabash CarbonSAFE (Arnott et al., 2022); the separate report, *Wabash CarbonSAFE Project Risk Assessment and Monitoring Report,* is included as Appendix L, and an overview is presented here.

This Risk Assessment work reviewed US EPA guidelines for Class VI injection wells and the Risk Register was broken down into 15 categories (listed below) with ties to US EPA guidance or other source documents:

- Area of Review
- Aquifer Exemption
- Emergency Response and Remedial Action Plan
- Financial Responsibility

- Geological Site Characterization
- Operational Conditions
- Project Plan Development
- Pre-Operational Testing
- Quality Assurance
- Stimulation
- Well Construction
- Well Plugging and Post Site Care
- Record Keeping, Reporting, and Data Management
- Well Testing and Monitoring
- Intangible Permitting Factors

Overall, 438 risks were identified associated with potential Class VI permitting at the project site. Each risk was assigned a severity and likelihood and draft actions toward mitigation were assigned to each risk. Post-action remedial risks values were then assigned. An initial scoring assessment for the risk items based on implementing the varied risk mitigation strategies showed an overall decrease in risk severity and likelihood. Key gaps and recommendations for future work were identified, and further refinement and development will be necessary as the project moves into subsequent phases.

Recommendations for the Next Steps for Site Characterization.

<u>UIC Class VI Permit Planning</u>

The next steps for site characterization and development include the identification of the location and number of injection wells required to meet project requirements, and the generation of Class VI permits for each injection well.

The general components of a US EPA UIC Class VI permit along with a Class VI Permitting Plan for Wabash CarbonSAFE are detailed in Korose et al. (2022; see Appendix K). Key sections of the UIC Class VI permit application include: Site Characterization, Area of Review (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.

The permit applications must be prepared in accordance with Class VI guidance (see Korose et al., 2022). Adhering to the regulatory guidance assures that required technical and administrative aspects of the project are addressed, and that documentation is complete.

In general, for development of Class VI permits under the US EPA Underground Injection Control (UIC) guidelines, the results of the reservoir modeling for the site can be used to estimate the AoR and initiate development of the UIC permit application (Figure 42). AoR is considered as the region encompassing the CO_2 storage site where particular attention must be paid to protection of underground sources of drinking water (USDWs). Supporting documentation is required to accompany a UIC permit application to demonstrate that the injection zone is of sufficient capacity, and the confining zone is of sufficient thickness and integrity, for the site to permanently store the CO_2 in a manner that is protective of USDWs.

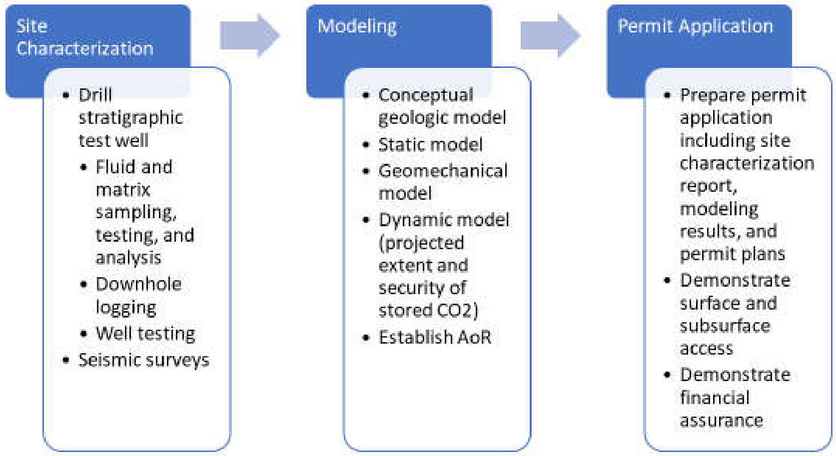

Figure 42. Site characterization and modeling needs in support of Class VI UIC permit application.

A UIC permit application should be based on regional and site-specific data typically derived from a stratigraphic well drilled specifically in support of the UIC application. The well data will be used as input to numerical models which will serve to delineate the projected AoR and to optimize the storage site design. The DOE (Department of Energy) NETL (National Energy Technology Laboratory) Best Practices Manual for CO_2 storage provides significant guidance and reference information for permit preparation (2017).

Data Gaps for Future Activities

Although the Potosi Dolomite was not the primary target for Wabash CarbonSAFE, data was collected from the Wabash #1 stratigraphic test well, and supplemented with regional data, to perform initial CO_2 injection simulations and establish feasibility of the Potosi Dolomite – Maquoketa Group storage complex for commercial-scale CO_2 at the Wabash CarbonSAFE project site.

The lateral extent and connectivity of the vuggy intervals within the Potosi Dolomite reservoir interval are uncertain, however, and the need for additional data and verification exists for the next steps in site characterization and permitting to proceed. A summary of data gaps remaining is presented here.

Additional drilling, well logging, testing, and core analyses

Due to concerns over potential lost circulation zones in the Potosi Dolomite during Wabash #1 drilling, no core samples or Formation Micro Imager (FMI) logs were acquired in the Potosi Dolomite. For future characterization efforts, a full suite of geophysical logs, including FMI, should be collected across the Potosi reservoir interval and its confining strata.

Cased hole well testing was performed over a 20 ft (6 m) interval within the Potosi Dolomite, and results of all tests support the radial composite model with an inner permeability zone (100s of md permeability) and a higher permeability outer zone (10s Darcy). Additional well testing will help to verify these results and help to confirm the lateral extent and connectivity of the vuggy intervals within the Potosi Dolomite reservoir interval.

Only 61 ft (19 m) of core was collected in the 314 ft (96 m) thick Maquoketa Group sealing interval in the Wabash #1 well; in subsequent wells, additional core should be collected for petrophysical and geomechanical analyses in the Potosi Dolomite reservoir interval as well as above the Potosi injection interval, in strata that also exhibit confining characteristics such as dense, low-porosity, sections of the Oneota Dolomite and lower Shakopee Dolomite and/or in more shale-rich portions of the upper Shakopee Dolomite.

Direct fluid sampling and verification of lowermost USDW
The US EPA Class VI permitting AoR is considered as the region encompassing the CO_2 storage site where particular attention must be paid to USDW protection and monitoring. Near the WVR site, the Silurian-Devonian carbonate bedrock aquifer is expected to be the lowermost USDW and overlies the Maquoketa Group seal (Korose et al., 2022).

In the Wabash #1 well, cased hole well testing was performed over a 20 ft (6 m) interval within the Cambrian Potosi Dolomite during which a swab sample was obtained and analyzed to be 34,250 mg/L TDS. Regional data trends project a salinity of greater than 10,000 ppm TDS through the area for the St. Peter Sandstone which lies below the lowermost USDW expected in the Silurian-Devonian. Log-based calculations may be used to estimate salinities, but there is a large variation in the results depending on the log-based calculation method employed (e.g., using resistivity or spontaneous potential logs), which underscores the need for direct sampling.

The most reliable determination of formation salinity is through chemical analysis of fluid samples; however, no samples exist from the Wabash #1 well for the shallower Silurian-Devonian formations and for the St. Peter Sandstone (Ordovician). In future wells, fluid samples in the Potosi Dolomite itself, as well as above the Potosi Dolomite, would be needed to verify that a TDS greater than 10,000 ppm is maintained through the confining intervals (including the St. Peter Sandstone) and to verify that the lowermost USDW is as expected in the Silurian-Devonian strata lying above the Maquoketa Group regional seal.

Additional seismic information
Although the local 2D seismic reflection data acquired under Wabash CarbonSAFE is relatively noisy (high signal to noise ratio) due to near-surface conditions, it is of sufficient quality to determine that there are no through-cutting features in the potential Potosi Dolomite storage complex. 3D seismic reflection data would be useful, however, to provide additional resolution to the seismic profiles and determine orientation of any features including association of lower faults with basement structures. Additional recommendations for future data acquisition include a Vertical Seismic Profile (VSP) to help tie well data with seismic reflection data.

Refinements to numerical modeling
The collection of additional data can be used to address sources of uncertainty in the Potosi Dolomite – Maquoketa Group storage complex geologic model and injection simulation results.

Several sources of uncertainty in the static and dynamic modeling (from Dessenberger et al., 2022) are listed below:

- The current Potosi storage complex models are "layer cake" models, having constant properties within layers, but heterogenous properties vertically across the layers. Layer cake models were built because of limited nearby well data. The drilling of additional wells in the area would allow for a more heterogenous geologic model.
- Lateral extent and connectivity of the vuggy intervals within the Potosi Dolomite are uncertain. The current model assumes that the vuggy intervals are continuous across the entire 22 x 22-mile (35 x 35-km) model.
- No core measured permeability, relative permeability, or capillary pressure data are available for the Potosi matrix and/or vuggy intervals from the Wabash #1 well. Laboratory measurements of permeability, relative permeability, and capillary pressure using cores from the Potosi are recommended.
- The permeability and capillary entry pressures for the formations overlying the Potosi reservoir interval were not measured; published correlations were used to calculate an average permeability from log porosity.
- CO_2 solubility in brine and chemical reactions of the CO_2 with the reservoir rock were not considered in this study.

CONCLUSIONS

Wabash CarbonSAFE has established that commercial-scale CO_2 storage in the Potosi Dolomite –Maquoketa Group storage complex associated with the WVR plant site near Terre Haute, IN is highly feasible. The CarbonSAFE project team performed this evaluation through extensive data acquisition and analysis including 2D seismic reflection data, wireline logs, well testing, and core/cuttings from the Wabash #1 stratigraphic test well (now plugged and abandoned).

Wabash #1 and the project's 2D seismic data are providing greater insight into the regional distribution of the Mt. Simon Sandstone. The Mt. Simon Sandstone was the initial target for storage evaluation and was found to have generally poor reservoir qualities in the Wabash #1 well. Focus was then placed on a secondary target, the Potosi Dolomite.

The storage units within the Potosi Dolomite strata are generally thin beds (ca 3-10 ft [1-3 m]) having high porosity and permeability values. In situ well tests at Wabash #1 over a 10 ft (3 m) interval within the Potosi Dolomite indicated that permeability of 2,400 md to 45,000 md or greater exists within the Potosi Dolomite at this location. The thick dense intervals of the Knox Group, including the Eminence Formation, Oneota and Shakopee Dolomites could serve as immediate confining intervals as they exhibit characteristics for effective restriction of vertical movement of fluids through negligible permeabilities. The Maquoketa Group has 312 ft (95 m) of shale and is considered a regional seal for the Potosi Dolomite reservoir interval.

There are no faults identified seismically in the study area that transect the Potosi Dolomite, overlying confining beds, or Maquoketa Group, and the Formation Micro Imager (FMI) log and Maquoketa core from the Wabash #1 well show little to no natural fractures within the Maquoketa interval. Triaxial test and MICP results indicate the Maquoketa exhibits geomechanical characteristics and membrane capillary behavior supportive of highly effective sealing capacity.

Due to concerns over potential lost circulation zones in the Potosi Dolomite during Wabash #1 drilling, no core samples or Formation Micro Imager (FMI) logs were acquired in the Potosi Dolomite. For future characterization efforts, a full suite of geophysical logs, including FMI, should be collected across the Potosi reservoir interval and its confining strata.

In subsequent wells, additional core should be collected for petrophysical and geomechanical analyses in the Potosi Dolomite reservoir interval as well as in the confining units above the Potosi injection interval. Similarly, fluid samples in the Potosi Dolomite itself, as well as above the Potosi Dolomite, would be needed to verify that a TDS greater than 10,000 ppm is maintained through the confining intervals (including the St. Peter Sandstone) and to verify that the lowermost USDW is as expected in the Silurian-Devonian strata lying above the Maquoketa Group regional seal.

Simulation indicates the Potosi Dolomite can accept more than 50 million tonnes CO_2 injected over a period of 30 years (1.67 million metric tonnes annually); a 50-year post-injection period showed no further lateral migration of CO_2, while upward movement of CO_2 was restricted to the lower Oneota Dolomite (1,270 ft [390 m] below the base of the Maquoketa seal). The pressure increase from injection never reaches pressures high enough to fracture the reservoir, and does not substantially propagate vertically past the Dutchtown Limestone; this results in a negligible increase in pressure in any overlying formations above the Dutchtown Limestone. However, lateral extent and connectivity of the vuggy intervals within the Potosi Dolomite is uncertain. The current model assumes that the individual vuggy intervals are in communication across the entire 22 x 22-mile (35 x 35-km) reservoir model. Additional well data in the area would allow for a more heterogenous geologic model.

WVR plans to develop a commercial CCS project in the Illinois Basin. Retrofitting the existing gasification facility reduces the technical risk and capital costs associated with the project, leading to a higher probability of implementation and more competitive product prices. The WVR facility is located above suitable geology for injection of the full amount of CO_2 expected to be captured (ca 1.82 million tonnes per year) with minimal transportation distance providing WVR the opportunity to save on transportation costs with onsite injection.

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LIST OF APPENDICES

Wabash CarbonSAFE Final Report