Evaluation of Class VI Readiness

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SCENARIO ANALYSIS

Introduction. Project OASIS is approximately 30 miles southeast of Birmingham, Alabama, and approximately 5 miles north-northwest of Alabama Power Company's Plant Gaston. Geologically, the Project area is in the Alabama fold and thrust belt province. This work builds on the initiatives of the Southeast Regional Carbon Utilization and Storage Acceleration Partnership (SECARB-USA, DE-FE0031830) that identified nearly 500 million metric tonnes of CO_2 emitted on an annual basis that is not collocated with prospective storage geology (the Coastal Plain of the Southeastern US in this context). This observation suggests costly investments in connective infrastructure (e.g., pipelines) or exploratory well drilling campaigns to identify CO_2 storage opportunities in under explored areas. While not traditionally thought of for saline storage, these studies suggest that storage prospects in the Valley and Ridge Province occur in relatively flat lying structural panels between thrust faults. For the Project OASIS region, available geologic studies related to hydrocarbon exploration suggest that Cambro-Ordovician carbonates and Cambrian clastic units offer multiple potential storage intervals, and that regional confining systems are present, such as the tectonically thickened Floyd-Parkwood Shale. The Project OASIS surface property is owned by a timber and land stewardship company, The Westervelt Company, Inc., who worked with the Project Team to select and prepare adequate sites for geologic assessment. The purpose of drilling the Westover Stratigraphic Test Well #2 was to collect geologic data to model the feasibility of commercial scale CO_2 injection and storage in an under explored region. This initiative benefits the regions emitters as the data generated from this study can inform their own internal decision making. The field program included geological and geophysical evaluations, reservoir engineering analyses, and risk assessments. This report evaluates existing data, as well as a variety of modeling scenarios to evaluate project readiness. Importantly, the impact of this study is not limited to Alabama as there are numerous large emitters throughout Appalachia, in similar geologic settings, contemplating their decarbonization options.

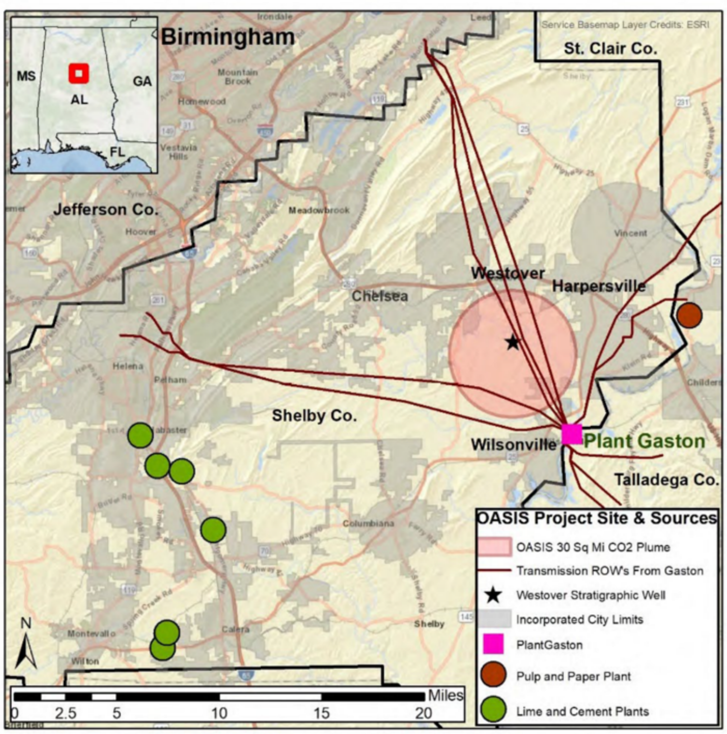

Figure 1. Location of Project OASIS and regional emitters.

Prior to Project OASIS, a stratigraphic test wellbore (Westover #1) was attempted as part of the SECARB-USA partnership, but the target formations were never reached due to a combination of factors. Additionally, 17-line miles of 2D seismic data were acquired (Figure 2). The information gathered from the first wellbore, as well as the geologic structure inferred from the seismic interpretation were used to determine the location, well design, and drilling plan for a new stratigraphic test well (Westover #2). For the OASIS CarbonSAFE Phase II project, one stratigraphic test well was drilled to reach the target formations and characterize the geologic properties of the prospective reservoirs for commercial scale storage of CO_2.

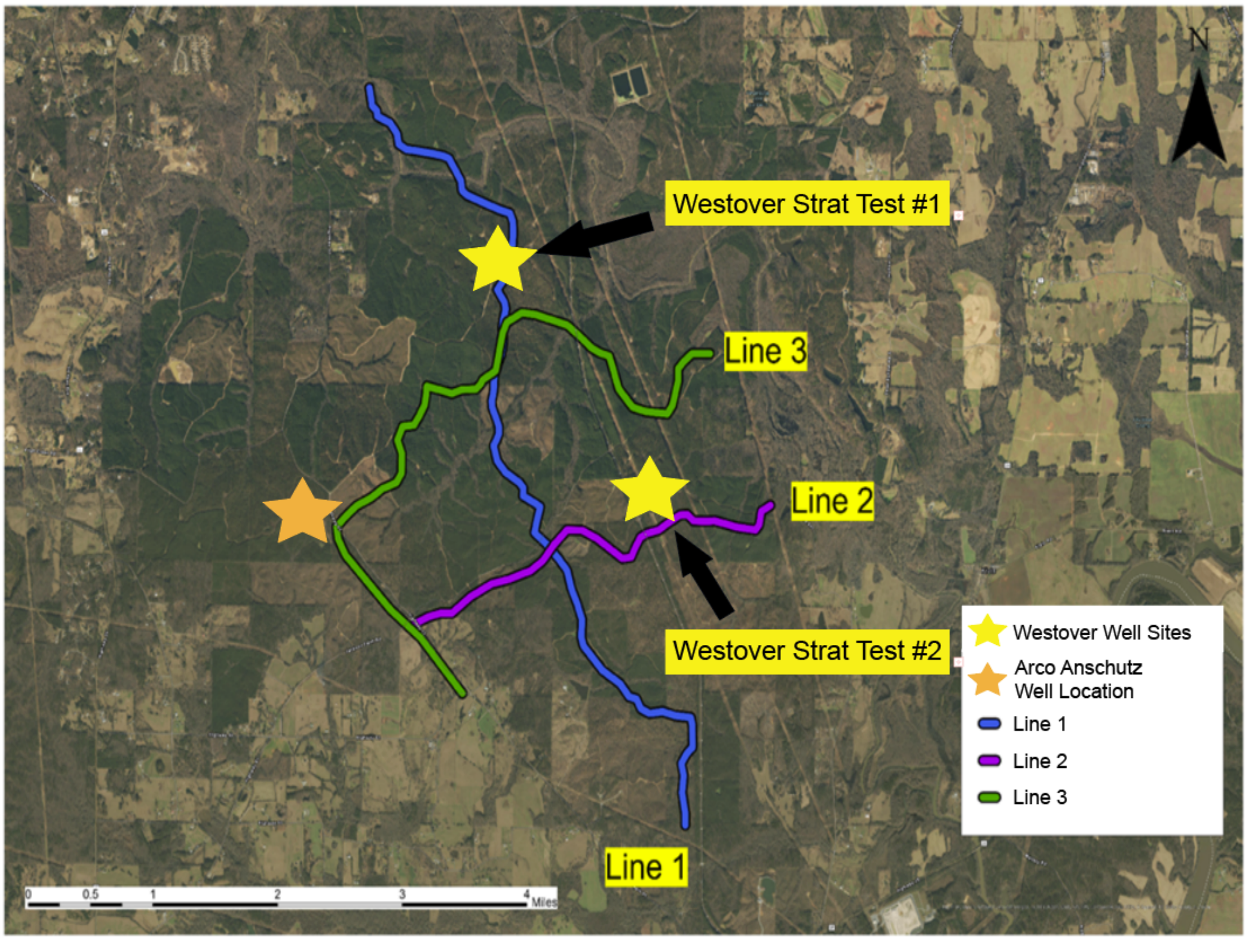

Figure 2. Location of the Westover Well Sites and Previously Collected 2D Seismic.

CO2 Sources. There are several regional emitters including pulp and paper facilities, lime and cement facilities, and Alabama Power's Plant Gaston (see Figure 1). Significant amounts of CO_2 are emitted by these power and industrial facilities. According to data available through the US Environmental Protection Agency's Greenhouse Gas Reporting Program FLIGHT database, Plant Gaston emitted 2.9 million metric tons (MMmt) of CO_2 in 2023. The seven cement plants emitted 4.1 MMmt of CO_2 in 2023. In sum, over 7 MMmt tons of CO_2 were emitted in 2023 within 20 miles of the Project OASIS site location. Figure 1 shows the "next-door" position of the Project OASIS location in Shelby County to the CO_2 sources from Plant Gaston, from the seven cement plants (20 miles), and from the pulp and paper plant (5 miles). The map also shows rights-of-way (ROW) that could be utilized for CO_2 transportation.

TECHNICAL SUBSURFACE DATA EVALUATION

Depositional System and Stratigraphic Framework. The Alabama Valley and Ridge Province extends across much of the northeastern portion of the state. It is a distinct geological region characterized by a series of parallel valleys and ridges running southwest to northeast and featuring rolling hills and elongated ridges consisting of sedimentary rock layers. The thrust belt is situated above an intracontinental rift complex locally called the Birmingham Graben and referred to at Project OASIS as Basement.

The Coosa Deformed Belt is approximately 13,000 feet thick and ranges in age from Cambrian to Lower Pennsylvanian. It follows the orientation of the Valley and Ridge with dips to the southeast. It is bounded to the northwest by the Coosa Synclinorium which ends at the Yellowleaf thrust fault. Additionally, the Coosa Synclinorium is bounded to the southeast by the Pell City thrust fault which also strikes northeast until its strike shifts to the southeast at Harpersville. There are several other bounding faults and features that create a complex triangle zone in the field area (Figure 3). The triangle zone consists of heavily deformed Mississippian-Pennsylvanian sedimentary formations and thick brittle Cambro-Ordovician carbonates.

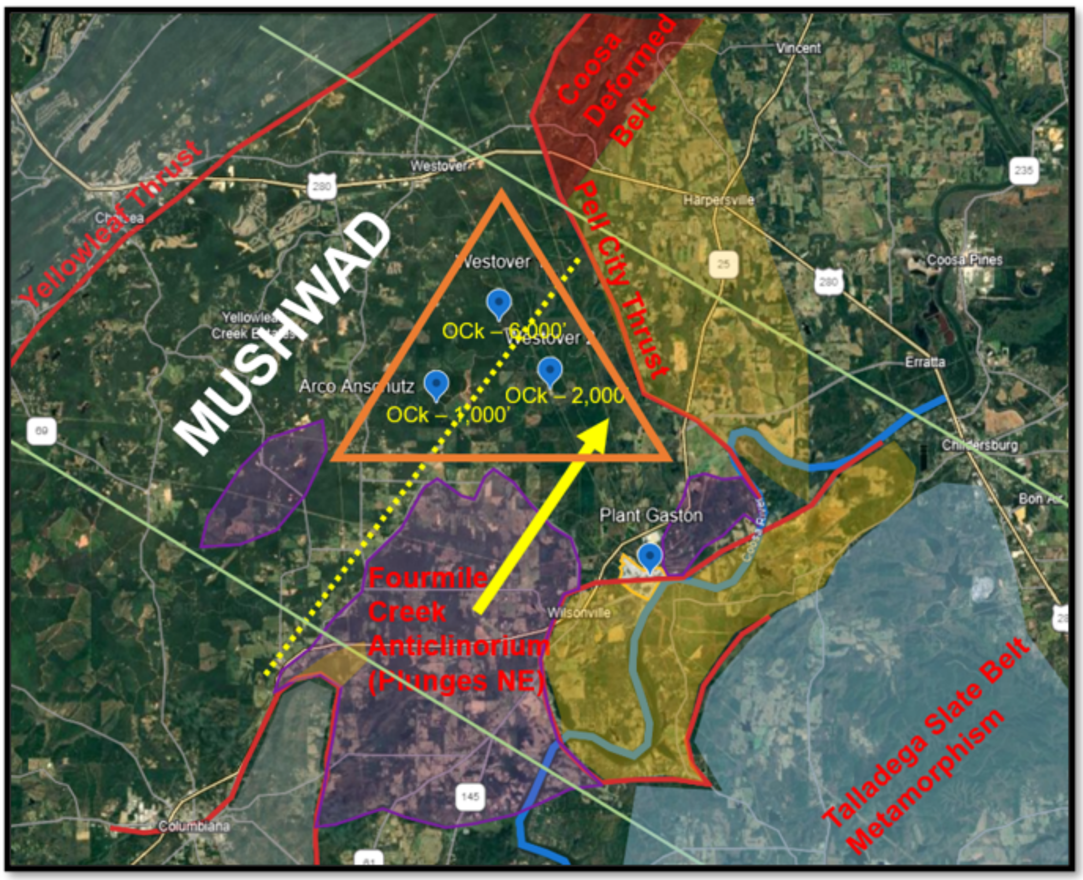

Figure 3. Structural setting of Project OASIS (orange triangle) located between bounding thrust faults in the Alabama Valley and Ridge.

Prospective/Contingent Storage Resources. Thirty miles of 2D seismic lines were shot and interpreted for this project to delineate the overall structure of the valley and ridge section in the Westervelt acreage and showed a complex structural setting typified by nearly flat stratigraphy to the northwest west and a thrust ramp to the southeast which creates a stacked duplex of potential reservoir carbonates with basement graben faulting creating accommodation for deeper reservoirs as well. Some within the storage zone could serve as potential leakage pathways for CO_2. All deep structural features appeared to be confined to the underlying Paleozoic section.

Static storage resource estimates were calculated for the more porous and permeable intervals within the Knox Group and for the deeper Rome Formation. The U.S. DOE methodology, written by Goodman et. al[1], was utilized to create the estimates on a per-square-mile basis. The calculation involves multiplying the area, thickness, porosity, CO_2 density at reservoir temperature and pressure, and a storage efficiency to generate a volumetric storage resource estimate. Efficiencies vary based on lithology. For example, clastics (Rome Formation) use an efficiency factor of 7.4%, 14%, and 24% for a P10, P50, and P90 storage estimate, respectively. The limestone efficiency is 10%, 15% and 21% for P10, P50, and P90 storage estimates, respectively. CO_2 density was calculated based on the midpoint depth, using a pressure gradient of 0.433psi/ft and a temperature gradient of 0.0107°F/ft +70°F.

Table 1. Static Storage Resource Estimate for each Formation.

Formation	Net Thickness (ft)	Reservoir Depth (ft)	Average Porosity	P10 G(CO_2) Mmtonne/ mile^2	P50 G(CO_2) Mmtonne/ mile^2	P90 G(CO_2) Mmtonne/ mile^2
Knox Newala	20	2,650	7.0%	0.03	0.05	0.07
Knox Longview	20	3,900	3.0%	0.03	0.05	0.06
Knox Chepultepec	25	4,600	6.0%	0.08	0.12	0.17
Knox Copper Ridge	25	5,800	6.0%	0.08	0.13	0.18
Rome	500	14,900	10.0%	2.23	4.22	7.23

The CO_2 storage resource of the Storage Complex was estimated using the following: (1) a storage area of 16,000 acres; (2) a formation gross thickness of approximately 10,000 feet and porosities (0 to 3%) from the Westover #2 well; (3) depths of 2,000 to 12,000 feet; and (4) a standard subsurface pressure (0.8 psi/ft) and temperature gradients (0.0107 °F/ft + 70°F) to estimate CO_2 density, as shown on Table 1.

[1] Goodman, A., Sanguinito, S., and Levine, J.S. 2018 Prospective CO_2 Saline Resource Estimation Methodology: Refinement of Existing US-DOE-NETL Methods Based on Data Availability

The project then undertook an initial dynamic estimate of CO_2 storge using a reservoir model to calculate the extent of the CO_2 plume and to estimate CO_2 storage resource for the 16,000-acre storage complex. The Computer Modeling Group Ltd.'s GEM equation of state reservoir simulation software was used for the study. CO_2 was injected into the Copper Ridge member of the Knox Group which has an abundance of conductive and non-conductive fractures and the Knox Group as a whole. The reservoir properties used were the same as set forth in Table 1 with permeabilities of <.001 mD to 3 mD (based on porosity-permeability cross-plots developed from Westover #2 rotary sidewall core data). Dynamic modeling was conducted for four injection scenarios: vertical well injection into the Copper Ridge member of the Knox Group, horizontal well injection into the Copper Ridge member of the Knox Group, vertical well injection into the whole Knox Group, and injection into the Rome Formation. In all scenarios, CO_2 was injected at the maximum allowable bottomhole pressure, which is assumed to be 90% of a 0.8psi/ft gradient. The structure of the modeled area is relatively flat, and thus CO_2 migration up dip is not significant over the modeled time period.

For the first modeling scenario, approximately 20,000 metric tons of CO_2 were injected into the Copper Ridge through a vertical well for 30 years (550,000 tonnes total), followed by 20 years of monitoring. The CO_2 plume radius is approximately 2,700 feet at the end of injection. The second modeling scenario injects approximately 140,000 metric tons of CO_2 per year for 30 years (4.31 million metric tons CO_2) into the Copper Ridge member via a 5,400-foot horizontal well. The CO_2 plume extends approximately 3,000 feet beyond each end of the wellbore, in the direction of the wellbore. Perpendicular to the wellbore, the CO_2 plume extends approximately 3,200 feet. Please refer to Figure 4. The third modeling scenario injects approximately 28,000 metric tons of CO_2 per year for 30 years (840,000 metric tons of CO_2) via a vertical well into the entire Knox Group. The CO_2 plume radius is approximately 2,700 feet at the end of injection. The fourth and final modeling scenario injects CO_2 at a rate of 1.6 million metric tons of CO_2 per year for 30 years (48.02 million metric tons of CO_2) into the Rome Formation through a vertical well. The CO_2 plume extends approximately 5,200 feet. The first three modeling scenarios, in the Knox Group, are shown in Figure 4, the CO_2 mass rate and total mass graphs below. Additionally, Figure 5 shows the CO_2 mass rate and total mass for the fourth Rome injection scenario. In contrast to the first three modeling scenarios, the Rome Formation is permeable enough for the boundary effects to notably decrease the injection rate as the reservoir increases in pressure.

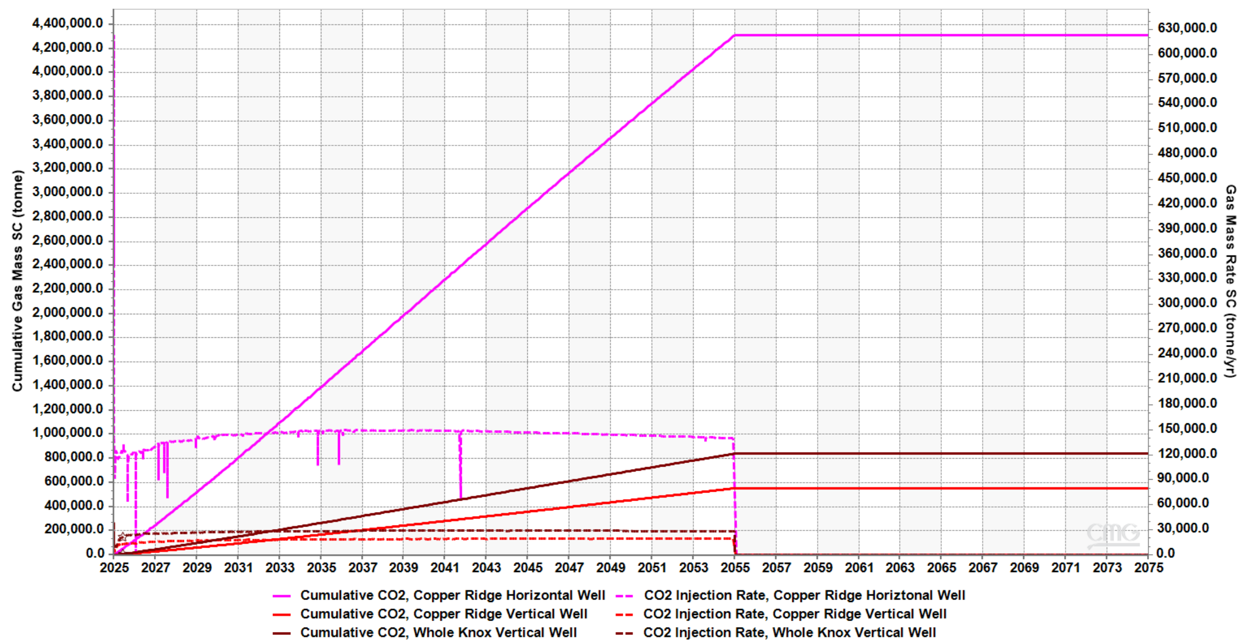

Figure 4. CO_2 Injection Rate and Cumulative Mass Graphs. Modeling the Knox Group.

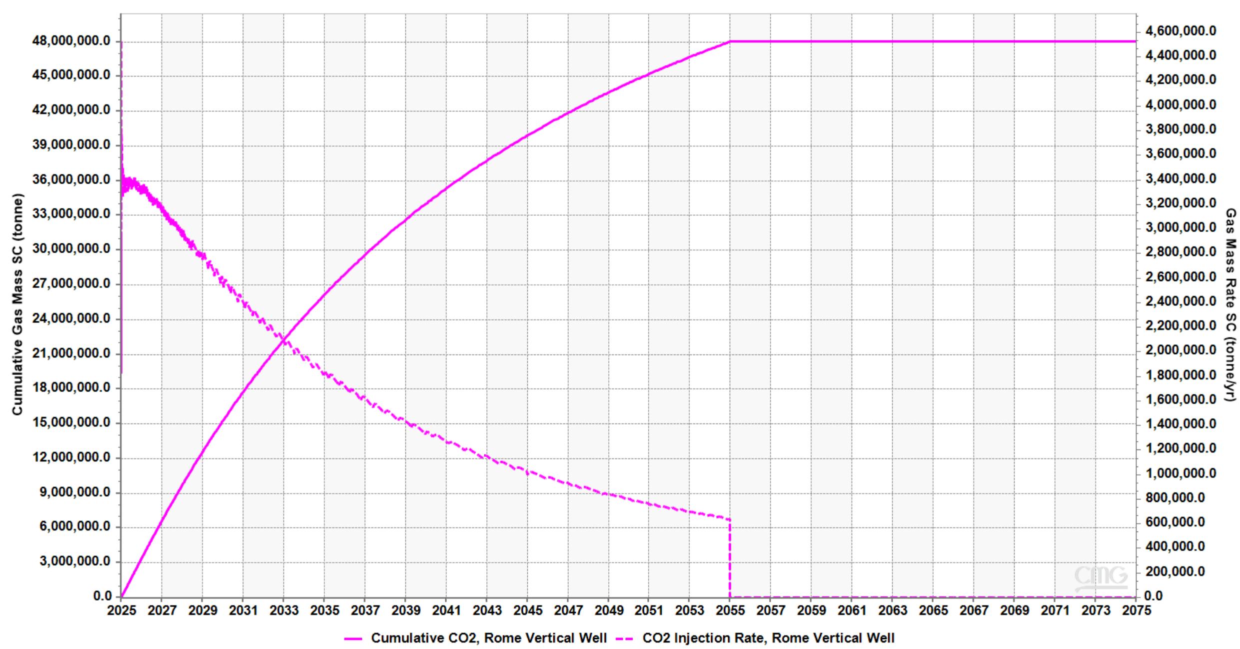

Figure 5. CO_2 Injection Rate and Cumulative Mass Graphs. Modeling the Rome Formation.

Multiple scenarios for estimates of CO_2 storage resource show the Storage Complex could provide adequate space to store 50 MMmt of CO_2 over a 30-year injection period only with a package of multiple injection wells.

Storage Reservoirs. The Alabama Valley and Ridge Province is underlain by a series of grabens in the Precambrian crystalline basement associated with the Appalachian Orogeny and locally referred to as the Birmingham Graben or Basement. This rock is predominately granite.

The accommodation space created by these faults is filled by the Lower Cambrian Rome and Conasauga Formations. The Rome Formation consists of shales, mudrocks, sandstone, anhydrite, and carbonates. Additionally, there may be Shady Dolomite locally. In the Arco-Anschutz #1 well, approximately 2.5 miles west of the Westover #2 well, there was a higher-than-average amount of evaporites observed. The Upper Cambrian Conasauga Formation gradationally overlies the Rome Formation with gray shale, limestone, and dolostone. Near the Westover #2 well site a basal fault decollement near the top of the Conasauga separates the lower basement and Cambrian strata from the Cambro-Ordovician Knox Group. In this intermediate zone is the Ketona Dolomite, which is diagenetic, and sometimes included as a basal member of the overlying Knox Group.

The Knox Group is a thick (> 5,000 ft) carbonate sequence composed of dolomite, limestone, chert, and thin sandstones made up of several members that are difficult to differentiate based on seismic reflectors and are thus often treated as an undifferentiated stratigraphic sequence (Figure 6).

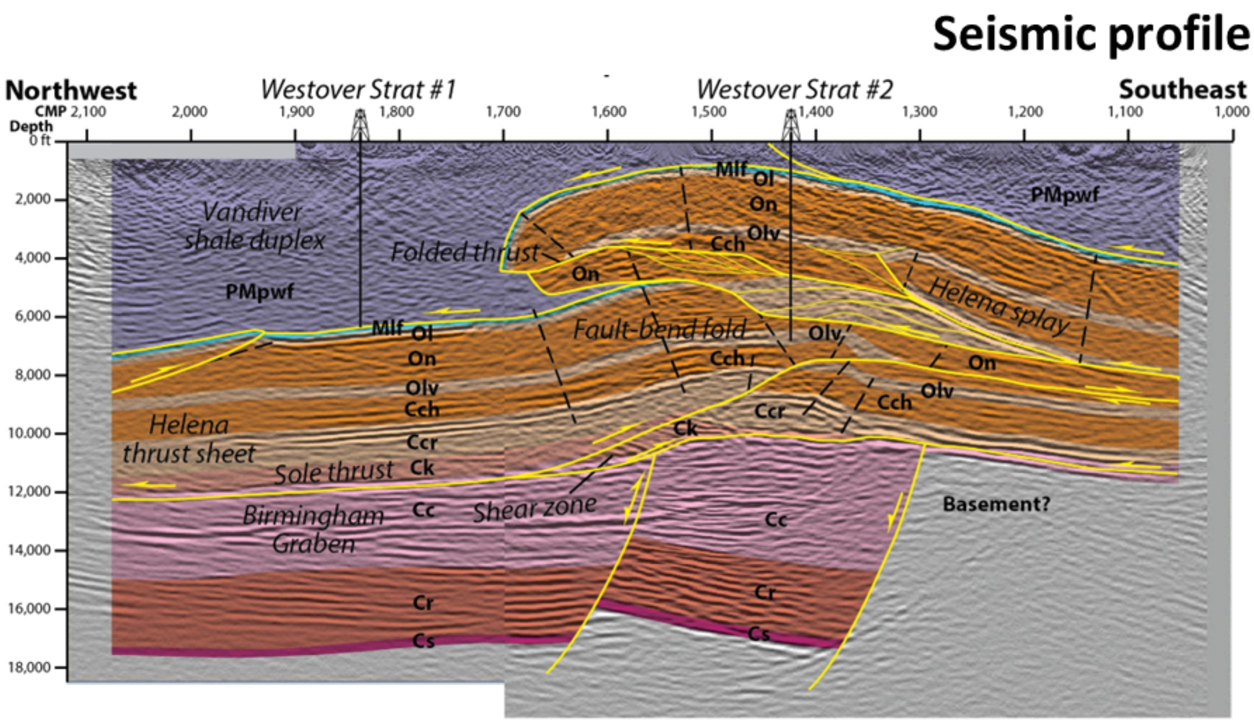

Figure 6. 2D Seismic Line 1 from north to south across the Project OASIS area images the fault bend fold and thrust ramp as well as the prospective Knox Group and the Floyd-Parkwood MUSHWAD.

In the Coosa Deformed Belt several members have been described from core and outcrop which include from base to top: the Copper Ridge Dolomite, the Chepultepec Dolomite, the Longview Limestone, and the Newala Limestone. While the Knox contains both limestone and dolomitic sequences, the latter is worth noting for operational purposes as it is a harder rock to drill through. Porosity in the Knox is found in thin zones created by chemical dissolution of marine fossils, known as moldic porosity. There are also fractures that create porosity and permeability predominately in the Copper Ridge member. The Knox is disconformably overlain by the Middle Ordovician Lenoir Limestone. An idealized stratigraphic column of the Alabama Valley and Ridge Province is shown in Figure 7.

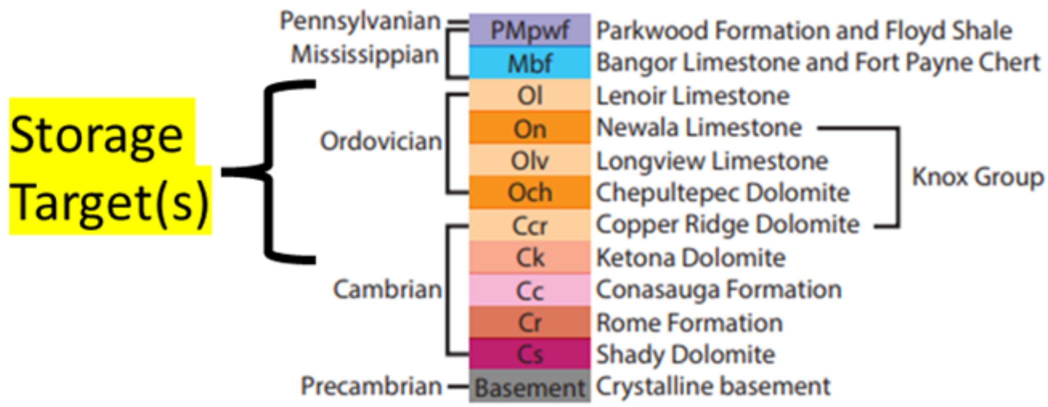

Figure 7. Idealized Stratigraphic Column of the Alabama Valley and Ridge Province.

Confining System. Overlying the Knox Group and Lenoir Limestone is the Mississippian Floyd-Parkwood marine shales that are locally deformed and known as MUSHWAD (Malleable Unctuous Shale Within a Ductile Duplex). The MUSHWAD is difficult to drill due to its ductile nature and variable dip direction. Total thicknesses range from 800 feet at the crest of the fault ramp and fault bend fold to more than 6,000 feet off structure in the flat lying structural panels between thrust faults.

Prediction of Site Performance. The Knox Group and repeat Knox section in this area has a total thickness of approximately 10,000 ft with an average porosity of 0.54% and an average permeability of 0.24 mD. In some thin zones, porosity and permeability values are higher, 3 to 6% and 2.0 mD, respectively, and this observation is incorporated into the whole Knox Group model. These reservoir properties were established by log analysis of the ARCO-Anschutz Well and the Westover #1 and #2 Stratigraphic Test Wells as well as sidewall core samples collected at the Westover #2.
For the first model, 0.018 Mt of CO_2 (18K tonnes/year per well) was injected for 30 years (0.55 Mt in total) into the Copper Ridge member of the Knox Group, followed by 50 years of post-injection monitoring to establish the shape and stabilization of the CO_2 plume. The CO_2 plume remained within the storage complex covering an aerial extent of 0.82 square miles at the end of injection, migrating updip toward the top of the grid at the end of 30 years of post-injection monitoring (see Figure 8 and 9).
Commercial reservoir engineering software GEM from Computer Modeling Group was used to characterize geologic modeling work to date and create a prediction of the storage site's performance in terms of CO_2 injectivity, CO_2 plume size, and pressure increase. A 25-square-mile initial storage area targeting the Knox Group carbonates was established on the crest of the structural duplex in the Westover area. The storage area is represented in the GEM model using 169,065 grid blocks with the ramp dipping to the southeast. Vertical and horizontal injection well scenarios were modeled in the Copper Ridge member of the Knox Group, the whole Knox Group, and the deep Rome Formation.

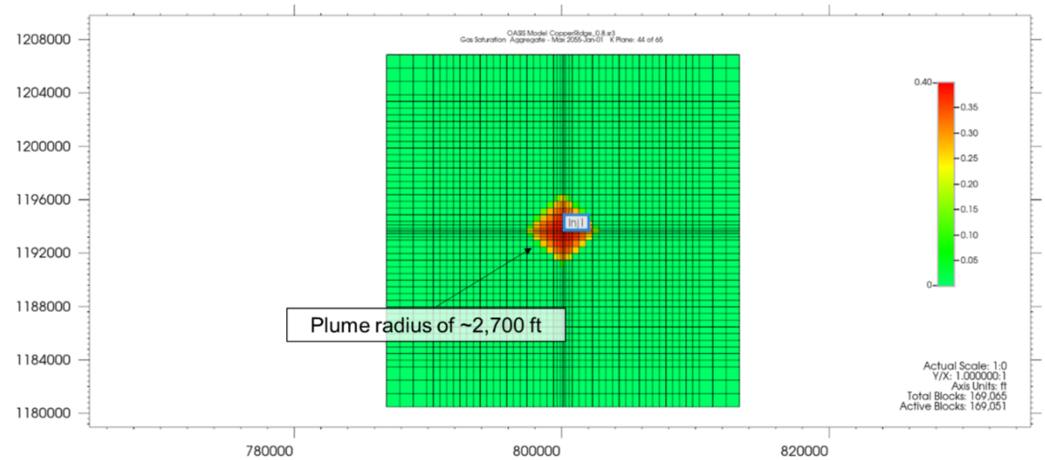

Figure 8. CO_2 Plume of Vertical Well Injection into the Copper Ridge. End of Injection.

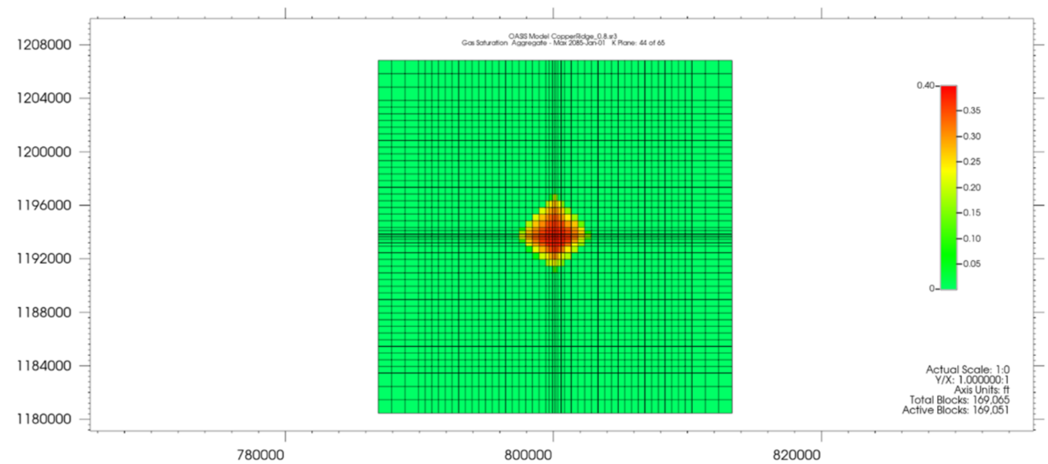

Figure 9. CO_2 Plume of Vertical Well Injection into the Copper Ridge. 30 Years Post-Injection.

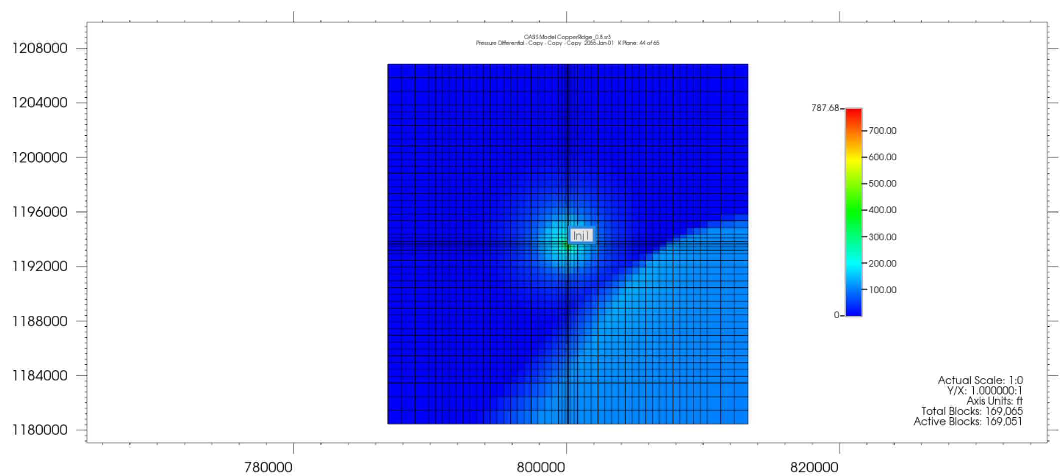

Figure 10. Pressure Differential in the Copper Ridge. End of Injection.

The aerial extent of the elevated pressure front and the 0.55 Mt CO_2 plume help establish the Area of Review and the design of the monitoring system for Project OASIS. This first scenario was also run with a horizontal well with a 5,400 ft lateral section. This increased injection to 0.144 Mt of CO_2 (144K tonnes/year per well) injected over a 30 year period (4.31 Mt in total, see Figure 11).

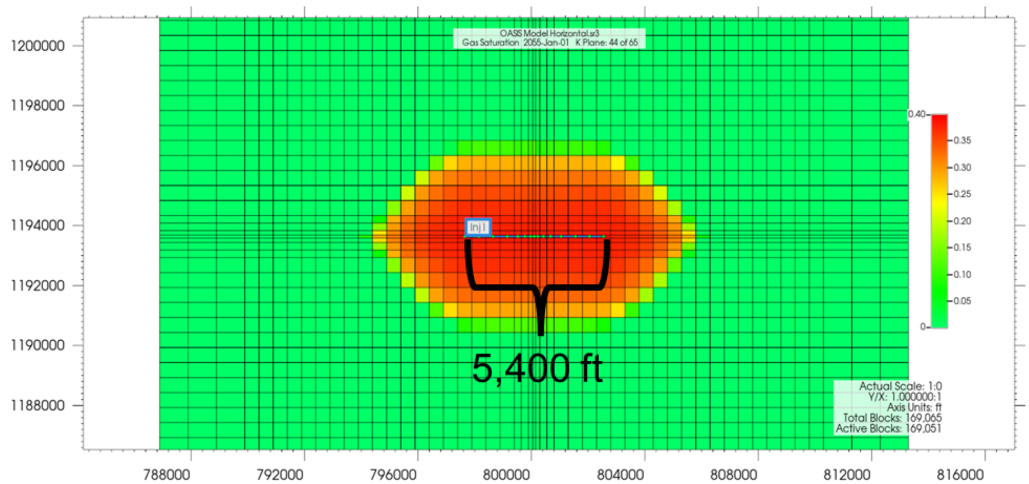

Figure 11. CO_2 Plume of Horizontal Well Injection in the Copper Ridge. End of Injection.

The second model represents injection into the full Knox Group interval, as opposed to the initial model which only injected into the Copper Ridge. This model was able to store 0.84 Mt CO_2 after 30 years with a plume within the confines of Westervelt-owned acreage.

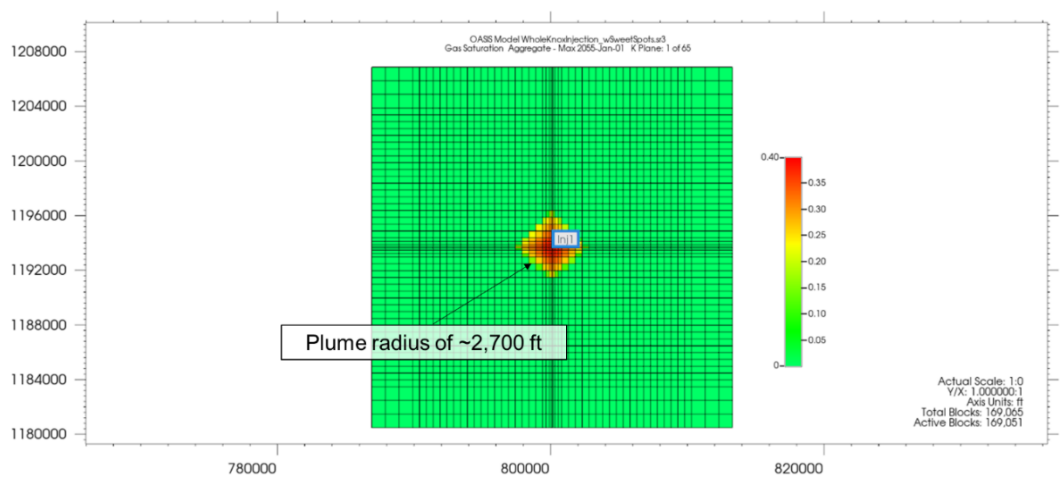

Figure 12. CO_2 Plume of Vertical Well Injection in the Whole Knox Interval. End of Injection.

The third and final model explores a scenario where a deep well targets the Rome Formation and is based on well logs from the ARCO-Anschutz Well (approximately ten miles from the OASIS site). This model was able to store 48.02 Mt CO_2 after 30 years of injection. Injection scenarios are summarized in Table 2 and indicate the need for multiple injector wells to reach CarbonSAFE thresholds for all scenarios.

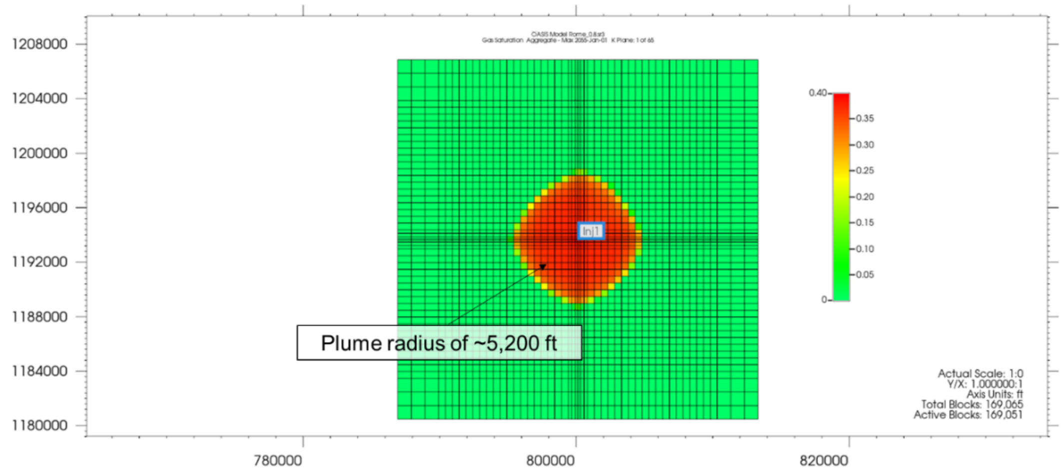

Figure 13. CO_2 Plume of Vertical Well Injection into the Rome Formation. End of Injection.

Table 2. Summary of Modeled Injection Scenarios, Assumptions, and Cumulative and Average Injection.

Model Scenario	Injection Gradient	Cumulative Injection, 30 Years (million tonnes)	Average Injection per Year (million tonnes/year)
Copper Ridge Sweet Spot ONLY	90% of 0.8 psi/ft Gradient	0.55	0.02
Rome Injection Only		48.02	1.60
5,400 ft Horizontal in Copper Ridge		4.31	0.14
Whole Knox Injection		0.84	0.03

Sections of the whole core collected at Westover #2 have been cut and cored by the Alabama Geological Survey and NETL. Two of the core samples will be used to calculate triaxial geomechanical measurements that will help refine the fracture pressure gradients of the Knox Group in situ. Models will be updated to reflect these pressure gradients once these data are available.

Next Steps

Regionally, the Southeastern US has abundant CO_2 emissions associated with industrial activities and power generation. In many instances, these CO_2 emitting facilities are not necessarily co-located with areas that have been identified as prospective for CO_2 storage, such as the Gulf South. As a result, facilities located outside of these regions must either (1) invest in costly pipeline infrastructure, or (2) invest in exploring CO_2 storage opportunities near these facilities. Project OASIS represents a critical transition of CCS appraisal projects into regions with limited data. Here, the Valley and Ridge Province of north-central Alabama is assessed for CO_2 storage opportunity in the region's Cambro-Ordovician carbonates. While this work illustrates the limited opportunity for CO_2 storage based on available data, Project OASIS has created invaluable information for the broader community, particularly those interested in evaluating CO_2 storage opportunities in the Valley and Ridge Province of Appalachia, where numerous CO_2 emitting facilities are in the eastern US. Moving forward, continued characterization of the OASIS location should include the collection of addition 2D or 3D seismic to ascertain the geometry of the fault bend fold and thrust structure in space. Further, addition stratigraphic test wells should be drilled to collect data from the Cambrian Rome Formation at the OASIS location such that critical parameters such as porosity, permeability, and thickness are not inferred from legacy wells located several miles from the project area.