A Viable Path Forward to Carbon Capture and Storage in Wyoming, USA

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Abstract

The State of Wyoming, USA, benefits from favorable geologic, regulatory, and infrastructure attributes that promote efficient and sustainable carbon capture and storage (CCS). Two research sites in Wyoming exhibit high potential for the underground geologic storage of greater than 50 million metric tons of carbon dioxide (CO_2) over 25 years. Funded by the U.S. Department of Energy's (DOE) Carbon Storage Assurance and Facility Enterprise (DOE CarbonSAFE) Phase I prefeasibility initiative, studies of both sites indicate promising capture, transport, utilization, and storage characteristics.

The Dry Fork site is located near Gillette, in northeast Wyoming. Four storage reservoir/seal pairs have been identified at the Dry Fork site that provide excellent prospects for stacked storage of CO_2. All four reservoirs lie at sufficient depths to maintain supercritical CO_2 and all four seals exhibit favorable characteristics for stratigraphic confinement. The reservoir with the highest expected significance is the Pennsylvanian/Permian Minnelusa Formation, which consists of near-shore dunes and shoreline sands, as well as shale and carbonate layers. The Minnelusa resides at a depth of ~2,900 m below the land surface and is ~45 m thick in the study area. Average porosity for samples from core within 10 km of the study area is 9%, with permeability values as high as 169 mD (n=6). The Permian Opeche Formation seals the Minnelusa and consists of redbed shales with minor fine-grained siltstones and evaporite deposits. Entry pressures as high as ~4700 psia were measured by mercury injection capillary pressure (MICP) analysis on core samples from the Opeche. A CarbonSAFE Phase II feasibility proposal at the Dry Fork site has recently been selected by DOE for negotiation leading to award.

The second proposed site is located at the Rock Springs Uplift (RSU) in southwest Wyoming. Four reservoir/seal pairs have been studied at the RSU, all of which present promising geologic attributes for the stacked storage of CO_2. The two deepest reservoirs (Mississippian Madison Limestone and Pennsylvanian/Permian Weber Formation) and their seals were studied previously under the auspices of the Wyoming Carbon Underground Storage Project (WY-CUSP), which was funded by DOE and the State of Wyoming. For the more recent CarbonSAFE initiative, two shallower reservoir/seal pairs were studied in detail. The highest priority of these reservoirs is the Triassic/Jurassic Nugget Formation, which consists of eolian sands and minor fluvial and interdune deposits. The Nugget lies at a depth of ~2,800 m and is ~140 m thick in the study area. Average measured porosity for samples from core within 40 km of the study site is 9%, with permeability values as high as 91 mD (n=10). The Nugget is sealed by the overlying Jurassic Gypsum Spring and Morrison Formations, as well as a thick (~1,700 m) regional Upper Cretaceous seal that includes shales from multiple geologic units. Entry pressures as high as 1120 psia were measured by MICP for shales within this regional confining unit.

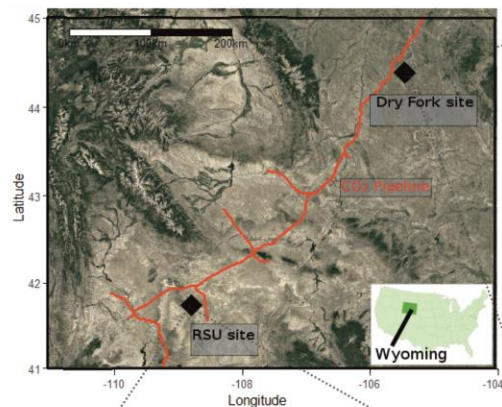
Overall, the State of Wyoming provides an advantageous climate to develop sustainable integrated CCS projects based on the following considerations: (1) well-characterized and favorable geology; (2) some of the largest deposits of economically recoverable coal in the USA; (3) an existing CO_2-enhanced oil recovery industry, including CO_2 pipeline infrastructure; (4) supportive commercial enterprises, including utilities and the oil and gas industry; (5) supportive policymakers; (6) a favorable legal and regulatory environment; (7) proximity to carbon-constrained markets such as the State of California; (8) large CO_2 emission sources, including coal-fired power plants; and (9)

backing for carbon capture, storage, and management related research and development, specifically implementation of the Integrated Test Center at Dry Fork Station, which is hosting the coal-track of the NRG/COSIA Carbon XPrize® competition.

1. Introduction

Two research sites in Wyoming, Dry Fork and the Rock Springs Uplift (RSU), exhibit the potential for the underground geologic storage of greater than 50 million metric tons of carbon dioxide (CO_2) over 25 years. Funded by the U.S. Department of Energy's (DOE) Carbon Storage Assurance and Facility Enterprise (DOE CarbonSAFE) Phase I prefeasibility initiative, studies of both sites indicate promising capture, transport, and storage characteristics. The Dry Fork site is located in the Powder River Basin (PRB) in northeast Wyoming. The RSU site is located in the Greater Green River Basin (GGRB) in southwest Wyoming (Fig. 1).

Overall, the State of Wyoming provides an advantageous climate to develop sustainable integrated carbon capture and storage (CCS) projects based on its favorable geology and a multitude of policy, legal, and infrastructure aspects, which are summarized for both sites in the following manuscript.



Dry Fork

Geologic Period	Formation
Cretaceous	Lance Formation
	Fox Hills Sandstone
	Pierre (Lewis) Shale
	Niobrara Shale
	Carlile Shale
	Belle Fourche Shale
	Mowry Shale
	Muddy Sandstone
	Skull Creek Shale
	Fall River (Dakota) Formation
	Lakota Formation
Jurassic	Morrison Formation
	Upper Sundance Formation
	Lower Sundance Formation
	Gypsum Spring Formation
Triassic	Spearfish Formation
Permian	Minnekahta Limestone
	Opeche Shale (Goose Egg)
Pennsylvanian	Minnelusa Formation
Mississippian	Madison Limestone

Rock Springs Uplift

Geologic Period	Formation
Cretaceous	Mesaverde Group
	Baxter Shale
	Frontier Formation
	Mowry Shale
	Muddy Sandstone
	Thermopolis Formation
	Cloverly Formation
Jurassic	Morrison Formation
	Sundance Formation
	Entrada Sandstone
	Gypsum Spring Formation
Triassic	Nugget Sandstone
	Chugwater Formation
	Dinwoody Formation
Permian	Phosphoria Formation
Pennsylvanian	Weber Sandstone
	Amsden Formation
Mississippian	Madison Limestone

Figure 1: Map of Wyoming depicting the locations of the Dry Fork site and the RSU site, along with CO_2 pipeline infrastructure (upper left). Simplified stratigraphic sections for both sites are also shown, with potential reservoirs in yellow and potential seals in blue.

2. Dry Fork Site

2.1. Background and Geologic Setting

The first proposed site is located in the PRB in northeast Wyoming (Fig. 1), which is co-located with coal-based CO_2 sources. The PRB is a Laramide aged (~80-55 Ma) structural basin that extends approximately 350 km in a north-south trend. The PRB is the most prolific coal producing basin in the US, with subbituminous coal seams occurring in the Paleocene Fort Union Formation and the Eocene Wasatch Formation.

2.2. Reservoir characteristics

Four storage reservoirs have been identified at the Dry Fork site: the Minnelusa Formation, the Lower Sundance Formation, the Lakota/Fall River Group, and the Muddy Sandstone. Each formation lies at a depth sufficient to maintain supercritical CO_2 and collectively the stratigraphy at the Dry Fork site is favorable for the stacked storage of CO_2. The characteristics of each reservoir are discussed below and sealing units are discussed in section 2.3.

Minnelusa Formation: The Pennsylvanian/Permian Minnelusa in the northern PRB was deposited as near-shore dunes and shoreline sands that graded into continental sabkha settings to the west and into a shallow evaporitic sea to the east (Anna, 2009). The Minnelusa Formation is divided into Lower, Middle, and Upper Members, which are bound by unconformities. In the northern PRB, the Lower and Middle Members consist predominantly of shale and carbonate layers and the Upper Member consists of sandstone with minor carbonate and evaporite layers. The Upper Minnelusa is of primary interest as a reservoir; in the study area it is ~2900 m below the land surface and ~45 m thick. Porosity and permeability were measured on six samples from core within 10 km of the study site; porosity ranges from 2 to 17% with an average of 9% and permeability ranges from 0.001 to 169 mD with an average of 44 mD (Fig. 2). These values are in overall agreement with published porosity and permeability data for the Minnelusa (e.g., Anna, 2009).

Lower Sundance Formation: The Hulett and Canyon Springs Members are the two primary reservoirs within the Jurassic Lower Sundance. The Hulett comprises shoreface to foreshore marine deposits and the Canyon Springs consists of fine-grained sands filling incised paleovalleys, primarily deposited by estuarine and eolian processes (Ahlbrandt and Fox, 1997). The Lower Sundance members lie at a depth of ~2580 m below the land surface and have a combined thickness of ~30 m. Log porosity based on six wells near the study site was used to estimate porosity ranging from 2 to 18% and permeability averaging 6 mD.

Lakota/Fall River Group: The early Cretaceous Lakota sandstones and associated lithologies were deposited on an alluvial plain within a fluvial system characterized by abundant incised valleys (Anna, 2009; Meyers et al., 1992). The Fall River (also called Dakota) sandstones were deposited within a deltaic system and include incised valley fill, delta plain facies, and delta front facies (Anna, 2009; Rasmussen et al., 1985). In the study area, the Lakota and Fall River reservoirs together represent ~18 m of reservoir quality thickness at depths of ~2350 m. Average porosity of 15% is predicted based on log porosity, in general agreement with literature data (e.g., Dolton and Fox, 1995). Permeability ranges from 0.1 to 450 mD (Craddock et al., 2012; Nehring Associates Inc., 2010).

Muddy Sandstone: The Muddy comprises marine and nonmarine lithologies including incised valley-fill fluvial and estuarine sandstones as well as nearshore marine sandstones (Anna, 2009). The Muddy varies widely in thickness and reservoir characteristics. The reservoir thickness of the Muddy ranges up to ~8 m in the eastern PRB, but in the Dry Fork study area may be as thin as ~1 m, at a depth of ~2270 m. In this study, porosity and permeability were measured on seven samples from core within 7 km of the study site; porosity ranges from 4 to 15% with an average of 9% and permeability ranges from 0.0002 to 0.21 mD with an average of 0.06 mD. Higher porosity and permeability have been measured in reservoir-quality sandstones in the eastern PRB; porosities greater than 20% and permeabilities greater than 1000 mD have been measured (Anna, 2009).

2.3. Seal characteristics

Opeche Formation: The Permian Opeche Shale, which includes redbed siliciclastics and bedded evaporites, directly overlies and seals the Minnelusa (Benison and Goldstein, 2000). The combined thickness of the Opeche and overlying Minnekahta, Goose Egg, and Spearfish Formations is over 250 m thick. Mercury injection capillary pressure (MICP) measurements of three Opeche samples from core within 12 km of the Dry Fork site show entry pressures of 691, 1596, and 4789 psia, with pore throat sizes indicative of effective seal characteristics (Fig. 3).

Upper Sundance/Morrison Formations: The Lower Sundance is sealed by thick shales of the Jurassic Upper Sundance and Morrison Formations, which together are ~35 m thick at the study area. The Redwater Shale Member, the primary sealing lithology, is continuous across much of Wyoming.

Skull Creek Shale/Upper Cretaceous seal: The Cretaceous Skull Creek is the primary seal for the Lakota/Fall River Group reservoir. Both the Lakota/Fall River and Muddy are overlain by a thick section of marine shales including the Mowry, Belle Fourche, Carlile, Niobrara, and Pierre (also called Lewis). In the study area, the total thickness of these regionally continuous seals is ~1210 m. Near the study site, the top of the Skull Creek/Upper Cretaceous seal is approximately 1800 m below land surface. MICP measurement of a Mowry sample from core ~6 km southwest of the study site yielded an entry pressure of 194 psia, with 80% of the pore throats falling in the nanopore range ($\leq$0.1 μm; Fig. 3). Legacy MICP analyses from elsewhere in the PRB indicate closure pressures as high as 11,461 psia (USGS Core Research Center wells #T322 and D636) for the Mowry, indicating promising seal qualities at the bottom the Upper Cretaceous sealing package. The thickness and continuity of the Skull Creek/Upper Cretaceous seal are desirable characteristics for stratigraphic confinement.

2.4. Policy, legal, and other considerations

The Dry Fork project site is aligned with Wyoming's policy of attracting Carbon Capture, Utilization, and Storage (CCUS) projects and investments. Wyoming's CCUS policy and incentives are rooted in State laws that: (1) specify who owns the pore space (*Wyo. Stat. § 34-1-152 (2017)*); (2) establish permitting procedures for CCS sites (*id. § 35-11-313*); (3) provide a mechanism for post-closure monitoring, verification and accounting (MVA) via a trust fund approach (*id. § 35-11-318*); (4) provide for unitization of storage interests (*id. § 35-11-315*); (5) specify that the injector, not the pore space owner, is generally liable -- a clarification that reduces project uncertainties (*id. § 34-11-513*); (6) clarify that vis-a-vis storage rights, production rights are dominant but cannot interfere with storage (*id. § 30-5-501*); and (7) provide a certification procedure for CO_2 incidentally stored during enhanced oil recovery (EOR) (*id. § 30-5-502*).

The Dry Fork site also primarily consists of privately owned lands, which suggests that the acquisition of pore space rights at this location should be relatively straight forward because Wyoming law related to pore space rights would apply.

In another positive development for this site, on January 31, 2018, the Wyoming Department of Environmental Quality (WYDEQ) filed for Class VI primacy with the U.S. Environmental Protection Agency (EPA). This is potentially important because it could ultimately bear on permitting and related requirements.

The Dry Fork site's economic model, structure, and financing do not depend upon the outcome of ongoing deliberations over the fate of the federal Clean Power Plan or other shifting federal carbon management policies. This is by design to immunize the project from future shifting political winds, and is also because of the project's location in Wyoming, which creates immediate economic opportunities through, for example, sales of CO_2 for CO_2-EOR and low-carbon electricity to nearby states.

3. Rock Springs Uplift

3.1. Background and Geologic Setting

The second proposed site is located at the RSU in southwest Wyoming (Fig. 1). As with the Dry Fork site, the RSU is co-located with coal-based CO_2 sources. The RSU is an asymmetric doubly-plunging anticline located in the GGRB of southwest Wyoming. The RSU is the youngest Laramide uplift (~45 Ma) within the GGRB, with active faulting occurring through the late Eocene (Roehler, 1992). Neogene extension produced high-angle normal faults in the area (Bader, 2008). Laramide uplift and later denudation resulted in the removal of much of the Cenozoic section. The Paleozoic and Mesozoic rocks at the study site comprise terrestrial and marine deposits, with marine sediments predominating (Love et al., 1993).

3.2. Reservoir characteristics

Four storage reservoirs have been examined in detail at the RSU: the Madison Limestone, the Weber Sandstone, the Nugget Sandstone, and the Entrada Sandstone. The Madison and Weber and their seals were studied previously under the auspices of the Wyoming Carbon Underground Storage Project (WY-CUSP; Surdam, 2013), which was funded by DOE and the State of Wyoming. For the more recent DOE Phase I CarbonSAFE initiative, the Nugget and Entrada reservoirs and their sealing formations have been investigated. The characteristics of each reservoir are discussed below and sealing units are discussed in section 3.3.

Madison Limestone: The Mississippian Madison consists of two units: an upper limestone and a basal dolomitic reservoir, which is the primary CO_2 injection target (Surdam, 2013). At the RSU, the Madison Limestone is ~120 m thick and occurs at depths greater than 3700 m. The dolomitic unit contains ~75 m of total reservoir thickness. Within the thickest dolomitic reservoir interval, the average porosity is 13.1% and the average permeability is 22.7 mD. Porosity and permeability, however, vary by pore type; permeability in vuggy or moldic pore types ranges to higher values than in intergranular pore types (McLaughlin and Garcia-Gonzalez, 2013).

Weber Sandstone: The Pennsylvanian/Permian Weber comprises a basal shallow marine unit that includes carbonate, clastic carbonate, and shale and an upper unit that includes cross-bedded sandstone and siltstone deposited in near-shore dune and interdune zones (McLaughlin and Garcia-Gonzalez, 2013). The Weber is ~3410 m below the land surface in the study area, with an overall thickness of ~200 m. The ~70 m thick upper unit is the primary CO_2 injection target and has heterogeneous reservoir properties. Within this unit, porosity measurements from core samples range from 1.7 to 8.8%, with an average of 6.3% and permeability ranges from 0.001 to 13.8 mD, with an average 2.7 mD (McLaughlin and Garcia-Gonzalez, 2013).

Nugget Sandstone: The Triassic/Jurassic Nugget in southwestern Wyoming is primarily made up of eolian sands, with some interdune deposits (Johnson, 2005). At the study site, the Nugget is ~140 m thick and lies ~2800 m below the land surface. Measured porosity for samples from core within 40 km of the study site ranges from 4 to 15% with an average of 9%. Permeability ranges from 0.02 to 91 mD with an average of 26 mD (Fig. 2). These data, combined with literature data, allow the development of a heterogeneous permeability property model for the Nugget, which indicates permeabilities within the tens of millidarcy near the study site, but also the possible presence of zones of higher permeability, in the hundreds of millidarcy (Fig. 4).

Entrada Sandstone: The Jurassic Entrada consists of a lower unit of primarily moderately- to well-sorted, fine- to medium-grained dune and interdune sands and an upper unit of well-sorted, very fine-grained sands (Brock and Nicolaysen, 1975; Johnson, 2005). The Entrada resides at ~2740 m below the land surface and is ~17 m thick, with ~9 m of high-quality reservoir thickness. Reported porosity for the Entrada is approximately 11 to 17%, with permeability of approximately 20 mD (Johnson, 2005 and references therein).

3.3. Seal characteristics

Upper Madison Limestone and Amsden Formation: At the RSU study site, the dolomitic reservoir intervals of the Madison are sealed by the Upper Madison and the Amsden. The Upper Madison, which is composed of ~36 m of micritic limestone, has porosity <0.5%, permeability <0.001 mD, and pore throat radii between 0.05 and 0.25 μm (McLaughlin and Garcia-Gonzalez, 2013; McLaughlin et al., 2014). The Pennsylvanian Amsden is ~125 m thick and is primarily composed of marine shales with thin interbedded carbonate. The Amsden has porosity <5%, permeability ≤0.005 mD, and pore throat radii between 0.008 and 2.5 μm (McLaughlin and Garcia-Gonzalez, 2013; McLaughlin et al., 2014).

Dinwoody and Chugwater Formations: This Triassic confining unit overlies and seals the Weber and has a total thickness of ~300 to 400 m. The Dinwoody and Chugwater package is a laterally extensive section of siltstones and shales with minor interbedded sandstones and carbonates (McLaughlin and Garcia-Gonzalez, 2013). At the study site, these formations have porosities of <1.5%, permeability of <0.001 mD, and pore throat radii ranging from 0.001 to 1.6 μm (McLaughlin and Garcia- Gonzalez, 2013; McLaughlin et al., 2014).

Gypsum Spring Formation: The Jurassic Gypsum Spring Formation seals the Nugget Sandstone reservoir and is ~32 m thick in the study area. The Gypsum Spring includes massive gypsum, gypsum-bearing limestone, shale, and sandstone (Johnson, 2005). This unit may not be continuous throughout the study site (Love et al, 1993), so a hydrogeological connection could exist with the overlying Entrada reservoir, potentially yielding a Nugget-Entrada reservoir complex sealed by the Morrison/Cretaceous seal.

Morrison Formation/Cretaceous Seal: The Jurassic Morrison Formation is ~87 m thick near the study site and is a nonmarine unit deposited in an alluvial plain setting, composed of shales, sandstones, and limestones (Johnson, 2005). Overlying the Morrison is a thick, laterally extensive Cretaceous seal that includes shales of the Cloverly, Thermopolis, Mowry, Frontier, and Baxter Formations. Near the RSU, this confining unit is as thick as 2000 m (Clarey and Thompson, 2010). MICP analysis was performed on two Morrison Formation samples and three Mowry Formation samples from core within 32 km of the RSU study site. Entry pressures for the Morrison samples are 528 and 979 psia and entry pressures for the Mowry samples are 1007, 1016, and 1120 psia. For all samples, over 98% of the pore throats by volume were shown to be nanopores (≤0.1μm; Fig. 3).

3.4. Policy, legal, and other considerations

The policy, legal, and other considerations for the RSU site are identical to those for the Dry Fork site, discussed above, with one important exception: federal lands are in the vicinity of the RSU location, which means that separate federal government approvals related to storage may be necessary. There is no existing mechanism, for example, for the acquisition of pore space/storage rights on federal lands.

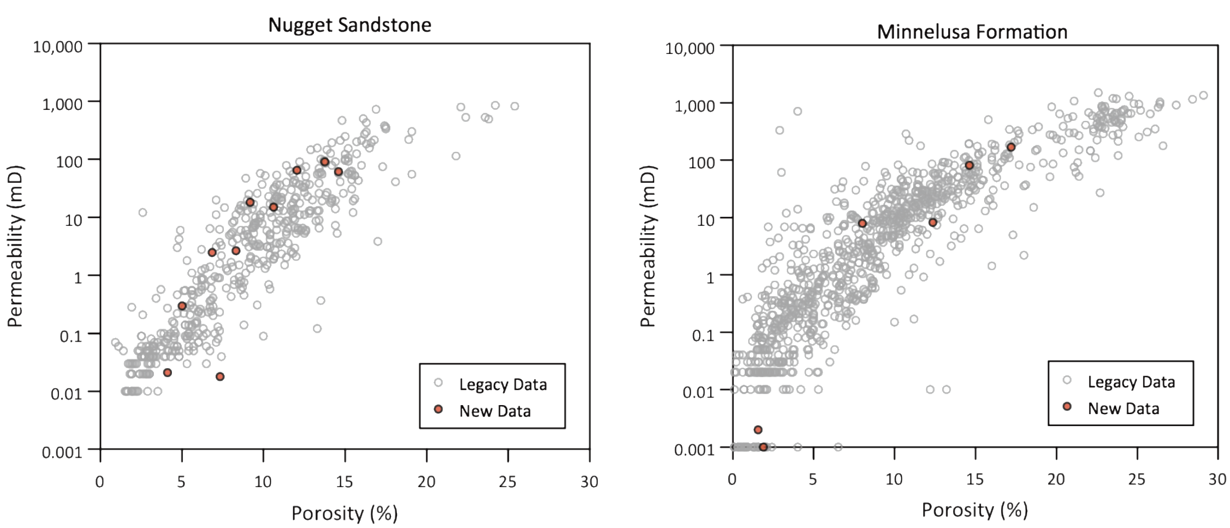


Figure 2: Semi-log plots of porosity versus permeability for the Nugget Sandstone (left) and the Minnelusa Formation (right). Legacy data were obtained from Wyoming Oil and Gas Conservation Commission reports. Legacy Nugget data are from wells within the RSU. Legacy Minnelusa data are from wells within the PRB; permeability values reported as <0.01 mD are plotted as 0.001 mD. New data from core samples near each study site were analyzed at CoreLab

for Phase I investigations; data reported at reservoir pressures; Klinkenberg permeability is reported.

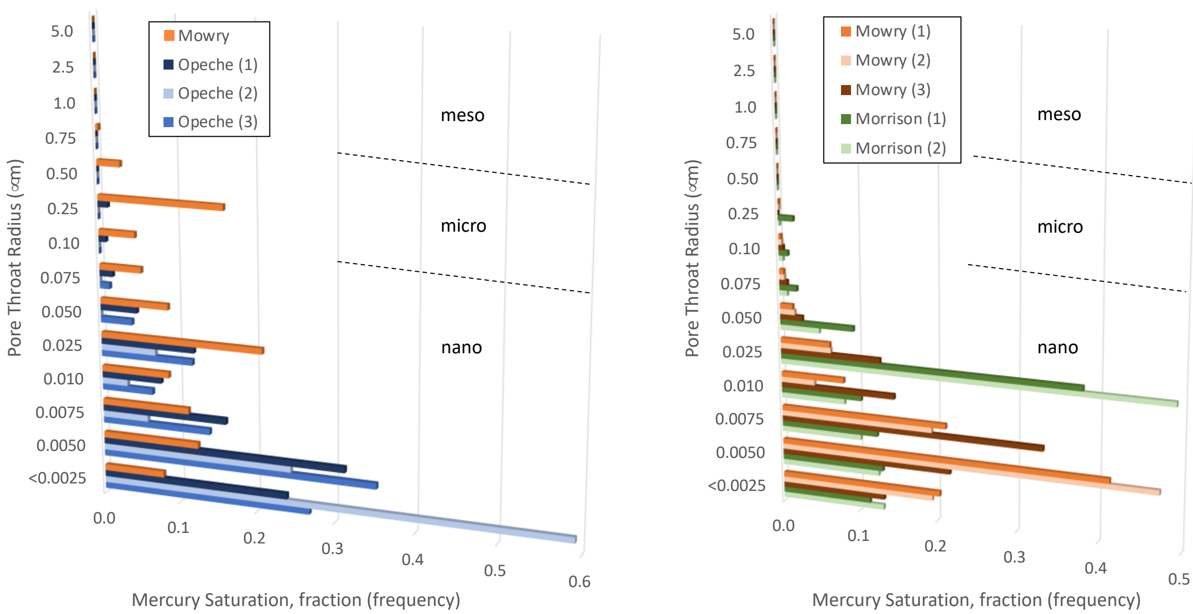


Figure 3: Pore throat size histograms for Mowry and Opeche samples from the Dry Fork site (left) and Mowry and Morrison samples from the RSU site (right).

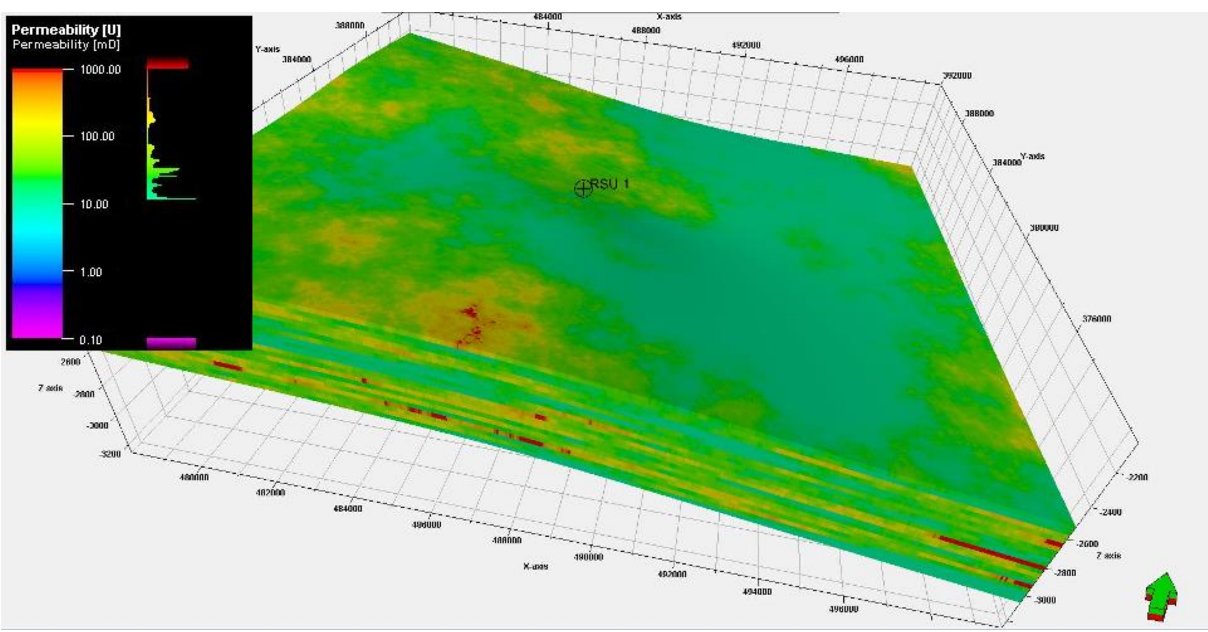


Figure 4: Permeability distribution of the Nugget Sandstone within the RSU study area. Permeability is relatively consistent and generally >10 mD, with zones of higher permeability. Plot is shown at 5x vertical exaggeration with coordinates in feet; each square on the horizontal

x- and y-axes is 305 m wide; each square on the vertical z-axis is 61 m tall. In ongoing studies seismic attributes will also be used to refine permeability models.

4. Discussion and Conclusions

The data and background in the previous sections provide information that allows us to estimate the storage capacity of reservoirs at both sites. At the Dry Fork site, it is estimated that the Minnelusa could store 31 million metric tons of CO_2 in a 25-year time frame with four injector wells (P50 confidence level). Stacked storage scenarios, which would likely result in higher overall storage capacity and reduction in the area of review, will be given consideration in future studies at the Dry Fork site.

At the RSU, it is estimated that one injector well with one water extraction well and the use of stacked storage utilizing the Madison, Weber, Nugget, and Entrada would result in the total CO_2 injection of 39 million metric tons over 25 years. The Nugget is the most promising reservoir and alone is estimated to have storage capacity of 15 million metric tons of CO_2 over 25 years. These results indicate that two injector wells, with one water extraction well and stacked storage, would accommodate in excess of 50 million metric tons of CO_2 over 25 years at the RSU, with total CO_2 plume areas ranging from 10.4 to 17.1 km^2.

Phase I investigations have shown the viability of commercial scale storage of CO_2 at both the Dry Fork and RSU sites. Plans for Phase II feasibility studies at the Dry Fork site include drilling a new stratigraphic test well and acquisition of new 3-D seismic data, both of which will serve to reduce uncertainties in our understanding of the subsurface and help to refine geologic models.

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