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Integrated Geologic Storage Prefeasibility Study proximal to Dry Fork Power Station, Powder River Basin, Wyoming

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Abstract

The pre-feasibility study—funded by the Department of Energy CarbonSAFE program (DE-FE0029375)—is centred around Basin Electric's Dry Fork Station (DFS) in Wyoming's Powder River Basin. Dry Fork Station, completed in 2011, is a high efficient coal-fired power plant that emits 3.3 million tons of CO_2 per annum. The DFS site also host's the Wyoming Integrated Test Center (ITC) funded by a $15 million investment by the State of Wyoming. The ITC is a public-private partnership test bed for CCS technologies. Geologic storage sites are in immediate vicinity of the DFS providing significant opportunities for co-located source and saline storage.

The Powder River Basin (PRB) of Wyoming and Montana, was identified by NETL (2010) as having a "high potential" for commercial-scale carbon sequestration. The basin contains as much as 17,000 feet of sedimentary rock and covers an area of approximately 24,000 square miles. The PRB has a long history of hydrocarbon production and remaining undiscovered reserves. Accumulations and production of hydrocarbons in the basin indicate the presence of reservoir formations with significant pore volumes and impermeable sealing formations. This attribute alone suggests the reservoir and seal characteristics of the formations provide significant opportunities for CO_2 storage in saline reservoirs.

Four high quality potential reservoir and sealing complexes have been identified for geologic storage. These formations range in depth from 6,500-9,500 feet underneath DFS including: (1) the Pennsylvanian Minnelusa Formation reservoir and Permian Goose Egg Formation (Opeche Shale) seal; (2) the Jurassic Hulett and Canyon Springs Sandstones of the Sundance Formation sealed by the Late Jurassic Upper Sundance Member and Morrison Formation and (3) the Early Cretaceous Lakota and Dakota, and Muddy Formation reservoirs sealed by the Mowry Shale. The preliminary reservoir characterization results integrate data from petrophysical well logs, core measurements, faults/fractures analysis, artificial penetrations, and published literature to evaluate geologic storage capacity and potential risk, for the Powder River Basin. These reservoir and seal combinations reside within ideal depth constraints and show suitable reservoir and seal characteristics conducive to commercial-scale storage.

Specifically, this paper presents 1) high level description of the geologic storage complex 2) a first order risk analysis associated with pre-existing oil and gas wells, and 3) preliminary storage capacity and Area of Review estimates.

Keywords: Carbon Capture and Storage, Powder River Basin, CarbonSAFE.

1. Introduction

Announced in 2016, the U.S. Department of Energy's (DOE) Carbon Storage Assurance and Facility Enterprise (CarbonSAFE) program is intended to support the development of several large-scale integrated carbon capture and storage (CCS) projects by the 2025 timeframe. Each project is directed to investigate the geologic storage of CO_2 in one or more saline reservoirs that could contain a minimum of 50+ million metric tons (Mt) CO_2 (or approximately 2 million metric tons of CO_2/year over a 25-year project life).

Over the coming decade DOE intends to implement CarbonSAFE through four phases of competitive grant funding, with projects advancing from phase to phase through a down-select process: (1) Phase I (project pre-feasibility); (2) Phase II (storage complex feasibility); (3) Phase III (site characterization); and (4) Phase IV (permitting and construction). DOE is currently implementing Phases I and II. All future phases are dependent upon federal appropriations.

In late 2016, DOE awarded ten research institutions Phase I pre-feasibility awards (for a total of thirteen sites). Led by the University of Wyoming's (UW) Carbon Management Institute (CMI), one of the winning Phase I sites was Dry Fork Station (DFS) in the Powder River Basin (PRB) in Gillette, Wyoming. Teamed with CMI at this site are: Basin Electric Power Cooperative; Energy & Environmental Research Center; Wyoming Infrastructure Authority; UW's Enhanced Oil Recovery Institute; UW's College of Law; UW's College of Business; Advanced Resources International, Inc.; KKR; Carbon GeoCycle, Inc.; Schlumberger; Computer Modeling Group Inc.; and UW's School of Energy Resources.

Based in the PRB, the Nation's most prolific coal-producing region, the project benefits from a wealth of existing subsurface data based upon decades of regional mining and oil & gas production activities. The PRB saline storage complex under study is in the immediate vicinity of DFS, existing CO_2 pipeline infrastructure and CO_2-EOR operations that need CO_2. Prior studies estimate 180 million barrels of oil are recoverable via CO_2-EOR in the fields directly adjacent to the PRB storage complex, creating favorable project economics. The project also stands to benefit from synergies created by the DFS-based Wyoming Integrated Test Center (ITC), a new test facility for researchers studying the management and utilization of CO_2 emissions using a slipstream of DFS' flue gas. The ITC host's researchers from the coal-track of the NRG COSIA Carbon XPRIZE, an international competition to incentivize the conversion of CO_2 emissions into valuable products.

2. Storage Complex Characterization

Saline aquifers within the PRB have an estimated storage as high as 196 Gt of CO_2 according to NETL (2010). The U.S. Geological Survey (USGS) Powder River Basin Carbon Dioxide Assessment (Craddock et al., 2012) identified potential storage complexes within the PRB that were further investigated during the Phase I of the project (Fig. 1). These formations range in depth from 4,500-7,000 feet in the eastern part of the study area and from 6,500-9,500 feet underneath Dry Fork Station. In order of decreasing depth these are: (1) the Pennsylvanian Minnelusa Formation reservoir and Permian Goose Egg Formation (Opeche Shale) seal; (2) the Jurassic Hulett-Lak Sandstones of the Sundance Formation sealed by the Late Jurassic Upper Sundance Member and Morrison Formation and (3) the Early Cretaceous Lakota, Fall River (Dakota), and Muddy Formation reservoirs sealed by the Mowry Shale.

2.1. Storage Reservoirs

2.1.1. Minnelusa

The Minnelusa in the northern PRB was deposited as near-shore dunes and shoreline sands which graded westerly into a continental sabkha and easterly into a shallow evaporitic sea (Anna, 2009). It is divided into Lower, Middle and Upper Members bound by unconformities. In the northern PRB, the Lower and Middle Members consist of shale and carbonate layers. The Upper Member consists of sandstone with minor carbonate layers and is a prolific hydrocarbon reservoir with dispersed fields across the eastern margin of the PRB, having produced 600+ million barrels of oil (Anna, 2009). These fields commonly have a limited water drive, indicative of confinement.

The Upper Minnelusa in the project's study area is thick, porous, permeable and saline. Located at approximately 9,450 ft below land surface, the Minnelusa is approximately 150 ft thick (Figure 1). Porosity and permeability measured from core within 6.2 miles of DFS had an average porosity of 9% and permeability values as high as 169 milliDarcies (mD; n=6; Figure 3). Characterization of well logs surrounding the study area suggest that the Minnelusa and its overlying seal are laterally continuous. Data from the USGS Produced Waters database report a salinity of 33,500 parts per million (ppm) total dissolved solids (TDS) proximal to DFS.

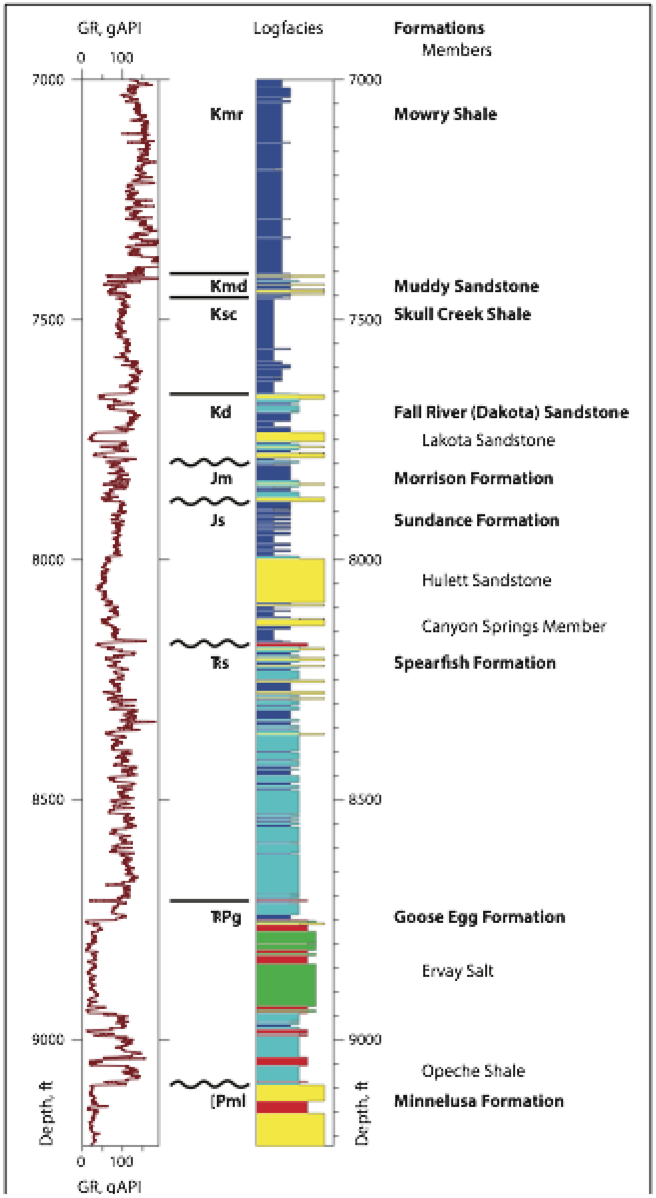

Figure 1. Wireline log (left) from Callaway 15-5 well (API 562532), approximately 4 miles from DFS, and color-coded logfacies profile (right) obtained from log cluster analysis. This analysis is able to discriminate sandstone reservoir units from non-reservoir shale-siltstone.

2.1.2. Lower Sundance

The Hulett and Canyon Springs members are the two primary reservoirs located in the lower Sundance (Ahlbrandt and Fox, 1997). They were deposited in prograding shoreface and foreshore parasequences prior to inundation of the Jurassic Sundance Sea (Ahlbrandt and Fox, 1997). The Hulett and underlying Canyon Springs Members were deposited in a barrier island complex during regression of the Sundance seaway (Rautman, 1978; DeCelles, 2004). The Hulett is a trough-crossbedded, silty sandstone with shale interbeds (Rautman, 1978). The Canyon Springs Member consists of fine-grain sands of incised valley fill and eolian/sabkha sand deposits (Ahlbrandt and Fox, 1997). Sundance reservoirs are considered to be "exceptional reservoirs" with a high potential for confinement (Ahlbrandt and Fox, 1997), though they are not typically hydrocarbon-bearing.

In the project's study area, the basal sands of the Sundance lie at a depth of 8,410 to 8,550 ft below land surface and have a combined thickness of 110 ft. During the Prefeasibility study, log porosity (Figure 2) was used to estimate porosity ranges from 2-18% and permeability ranges from 0.1 to 1000 mD (with an average of 6.26 mD). To supplement these well log data, eight samples collected from outcrop from the Hulett and Canyon Springs members had measured porosity from 18 to 24% and permeability ranging from 38.86 to 1083 mD. Logfacies profiles indicate that the Sundance is characterized by good lateral continuity and is a promising reservoir in terms of thickness and uniformity (Figures 1 and 2). Because of variability between legacy data and Phase I findings, coupled with the possibility of a 30 ft-thick interval within the Hulett sandstone with superior reservoir properties, the Phase II feasibility study will investigate this reservoir(s) in detail. Water quality data for these intervals are also limited, including only one measurement of salinity (33,000 ppm) reported roughly 5 miles up-dip from the study area. Generally, formation salinity in the PRB increases with depth and distance from recharge (Quillinan and Frost, 2011); thus, the team assumes that in the study area the Sundance reservoirs are of equal or greater salinity than the up-dip measurement.

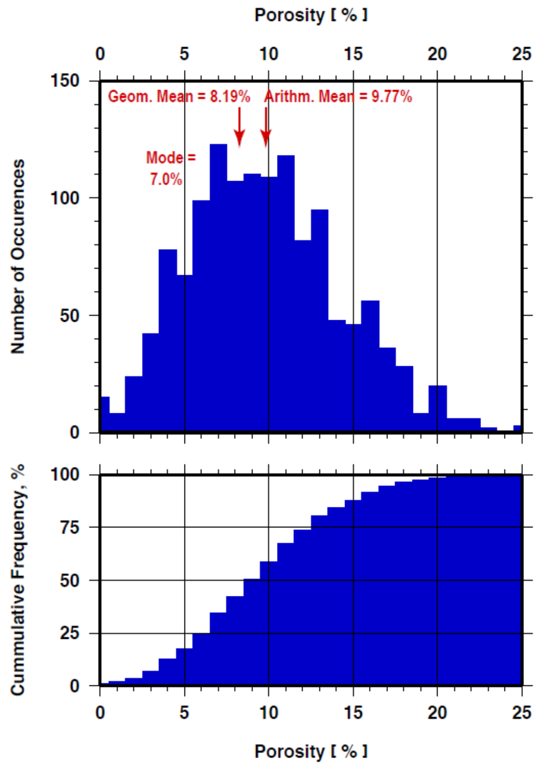

Figure 2. Ordinary (top panel) and cumulative (bottom panel) histograms of log-derived porosity interpreted for the Hulett-Canyon Spring Sandstones of the lower Sundance Formation based on log measurements in six wells in the project's study area.

2.1.3. Lakota/Fall River

The Lakota sandstones were deposited on an alluvial plain in a large, north-trending fluvial system in incised valleys across multiple, unconformable surfaces (Meyers et al., 1992). They include conglomerate, siltstone, mudstone and coarse sandstone. Across the region porosity measurements of up to 25% are reported by Dolton and Fox (1996), and permeability ranges from 0.1 to 450 mD (Craddock et al., 2012; Nehring and Associates, Inc, 2010). Proximal core samples were not available during Phase I for site-specific reservoir quality estimates; however, log porosities allow the team to predict an average porosity of 15%. The Fall River (also called Dakota) sandstones were deposited as a broad deltaic system that included valley and distributary fill, delta plain facies and delta front facies. Average reservoir porosity in the PRB ranges from 8 to 23% (Dolton and Fox, 1996), permeability ranges from a few hundred to several thousand mD, and total reservoir thickness varies from 50 to 80 ft (Bolyard and McGregor, 1966).

In the study area, Lakota/Fall River reservoirs represent roughly 60 ft of reservoir quality thickness that occur at depths 7,650 to 7,790 ft below land surface. Formation salinity is the largest unknown variable associated with these reservoirs. Water quality measurements for these reservoir intervals have not been reported in the public domain, and as such salinity measurements within these formations during the Phase II feasibility study will be a significant contribution to understanding the storage feasibility of Lakota/Fall River. Though water quality data are not available, salinity estimates from resistivity logs in the area suggest a salinity value greater than 20,000 ppm.

2.1.4. Muddy sandstone

The Muddy lies at a depth of 7,400 to 7,450 ft and consists of fluvial and marine lithologies. These include channel and bar sands, over-bank deposits, splays, deltas, incised valleys, and nearshore sands. This prolific hydrocarbon reservoir is found across the Rocky Mountains. In the PRB, most of the Muddy production comes from thickened sands associated with incised valley and transgressive channel fill deposits. As such, the Muddy can locally vary in thickness and reservoir characteristics. Porosity of reservoir lithologies can range from 4 to over 20% with permeability ranging from <0.01 to over 1000 mD (Anna, 2009). From core collected within 4 miles of DFS, the permeability ranges from 0.0002-0.21 mD and porosity averages 9.4% (n=8; Figure 3). The Muddy's reservoir thickness in the eastern PRB averages between 10 and 25 feet (Anna, 2009), and in the immediate area of DFS is as thin as 0 to 4 ft in total reservoir thickness. The non-reservoir lithologies have significantly lower porosity and permeability, and can be 50 ft thick in the study area. TDS of Muddy brines exceeds 67,000 ppm in the study area. The Muddy is sealed above by thick and regionally continuous Upper Cretaceous marine deposits of the Mowry Shale, and below by the Skull Creek Shale (Figure 1).

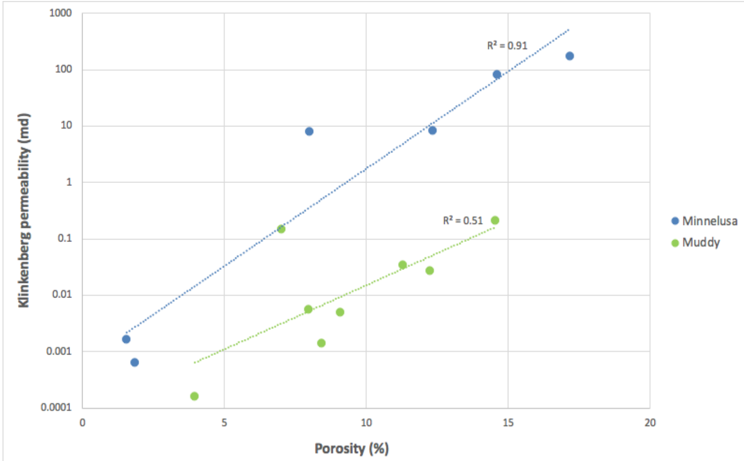

Figure 3. Semi-log plot of porosity versus Klinkenberg permeability at reservoir pressures for the Minnelusa (USGS CRC #B070(4), D379, B649) and Muddy (USGS CRC #T123(4), A606, D780, A110, A650) for samples analyzed by routine core analysis in this feasibility study. Exponential trend lines are shown for each geologic unit.

2.2. Confining Systems

2.2.1. Opeche Formation

The Opeche seals the Minnelusa. In the eastern PRB and within the study area, the Opeche and Minnekahta become formations distinct from the overlying Goose Egg Formation. The Opeche is a redbed shale with some fine-grained siltstones and minor evaporite deposits occurring throughout the shale section. The Opeche is overlain by the Minnekahta, which in turn is overlain by the Goose Egg and then Spearfish Formations with a combined thickness of 950 ft (Figure 1). This confining system of Opeche through Spearfish is a proven seal in Minnelusa hydrocarbon fields (Anna, 2009). Mercury injection capillary pressure (MICP) measurements of three Opeche samples from core within 7 miles of DFS show entry pressures of 691, 4789 and 1596 psia, with pore throat sizes indicative of excellent seal characteristics (Figure 4).

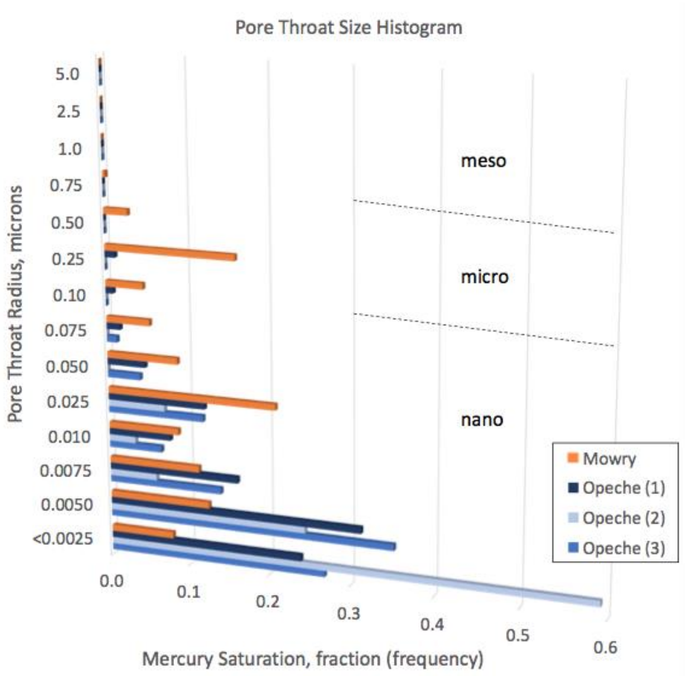

Figure 4. Pore throat size histogram for three Opeche samples (USGS CRC #D106(2) and B070) and one Mowry sample (USGS CRC #B200) from MICP analysis.

2.2.2. UpperSundance/Morrison Formations (Sundance/Morrison)

The sandstone units of the lower Sundance are sealed by thick shales of the upper Sundance and the overlying Morrison (Figure 1). The Redwater Shale Member of the Sundance/Morrison is the primary seal of the basal sands. This seal was deposited in a westerly transgressing sea, and is continuous across much of Wyoming (Ahlbrandt and Fox, 1997). In the study area, the sealing lithology of the Sundance/Morrison is approximately 125 ft thick (Figure 1).

2.2.3. Skull Creek Shale/Upper Cretaceous (Skull Creek/Cretaceous)

The Skull Creek is the primary seal of the Lakota/Fall River. Both Lakota/Fall River and Muddy are capped with a thick section of marine shales including the Mowry, Belle Fourche, Carlisle, Niobrara and Pierre (also called Lewis). In the study area, the total stratigraphic section of these regionally continuous seals is 3,990 ft in total thickness. This makes the Skull Creek/Cretaceous the ultimate seal for all reservoirs below. Near DFS, the top of the Skull Creek/Cretaceous ultimate seal is slightly more than 6,000 ft below land surface. MICP measurement of a Mowry sample from core ~4 miles southwest of DFS yielded an entry pressure of 194 psia and a median pore throat radius of 0.0140 mm (Figure 4). Legacy MICP analyses from elsewhere in the PRB indicate closure pressures as high as 11,461 psia (USGS CRC well #T322 and D636) for the Mowry, indicating superior seal qualities at the bottom of the ultimate seal. This high closure pressure combined with the Skull Creek/Cretaceous seal's thickness offer exceptional stratigraphic confinement.

3. Wellbore Analysis

Existing wells in the study area have been inventoried and evaluated in preparation of further risk assessment. The wellbore analysis used the approach of Nelson (2013) to assess pre-existing wells within a 10-mile radius centred on DFS. A six-mile radius is also shown for a spatial reference. This method considers many factors of risk independently, including seal penetration, well density, well age, permanent plug and abandonment (P&A) date and surface topography.

3.1.1. Wellbore Density

The legacy well density in the study area is highest in the shallowest confining layer, the Lewis shale. The density analysis found 69% of the sections have less than four wells penetrating the Lewis; however, three sections exist with 10-25 wells penetrating the Lewis (Figure 5). Two of these sections are outside the 6-mile buffer around DFS. Each subsequent seal has a lower density of well penetration per section, indicating less risk with increased depth (Figure 5). Only one section contains more than ten wells that penetrate the Opeche. This section is located on the border of the 10-mile buffer to the east. For each seal, the

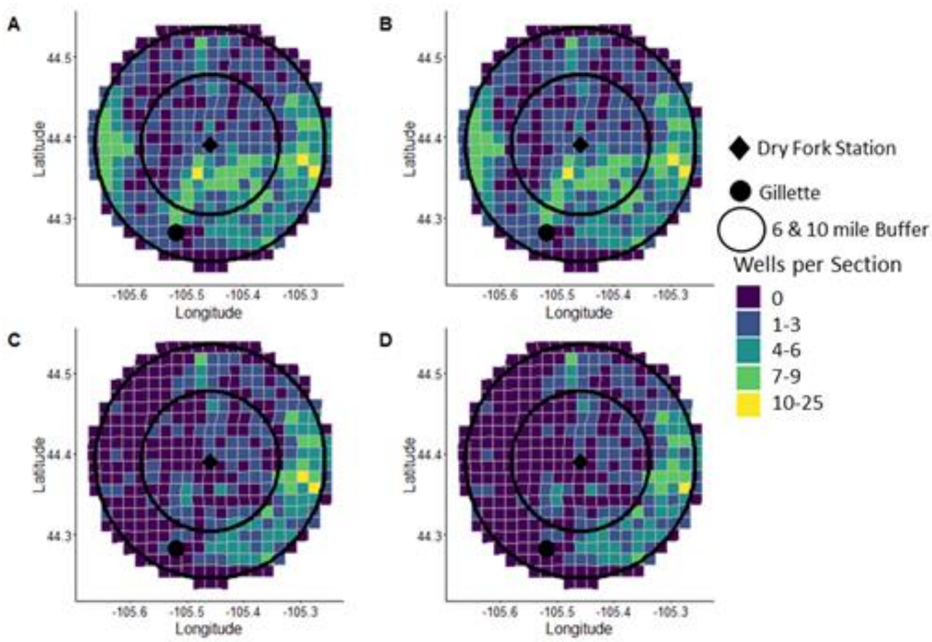

Figure 5. Density of wells per township section (1 mile x 1 mile) that penetrate the: (A) Lewis (top of the Upper Cretaceous Seal); (B) Mowry (Bottom of the Upper Cretaceous); (C) Morrison; and (D) Opeche confining layers surrounding DFS.

highest concentrations of wells exist outside of the 6-mile buffer surrounding DFS.

3.1.2. Well Age and Plug Date

Well development surrounding DFS began in circa 1937, but rapidly developed in the 1970's. Many wells drilled at this time (n=909) penetrate the Lewis shale. There are twenty wells with unknown ages, which pose an unknown risk. These twenty wells are treated as pre-1933 wells -- the highest risk group -- as a precaution. Well development penetrating the Morrison and Mowry seals began later than the Lewis, peaking in the 1980's.

P&A regulations have become more stringent over time. Many wells (n=767) have been plugged and abandoned in the study area. Four wells were plugged between 1883 and 1933 when there was no regulatory oversight. However, 98% of wells (n=748) were plugged and abandoned after 1962 when cement was widely used, suggesting greater plug integrity and safety. Wells with older plugs present higher risk and will be prioritized in future assessments.

3.1.3. Wellbore Location and Surface Depressions

The surface topography of each well location is important because CO_2 is heavier than air and if leaked to the surface can collect in surface depressions (defined by a low point with a 10° slope on two or more sides). About half (n=472) of the wells are not located near depressions, and were assigned the lowest risk value of "1". The remainder of the wells (n=381) are within a 328 ft (100 meter) radius of a depression, and fifty-six wells are directly in a depression. These wells were determined to be of higher risk with respect to surface topography and will be prioritized in future assessments.

3.1.4. Combining Risk Factors

To summarize, Figure 6 displays the location of P&A wells and their associated risk ascribed to topography and date of P&A. The single well with the highest topographic risk of "6" was plugged in 1976, has a Regulatory Risk of "4", and is approximately eight miles northeast of DFS. Nine wells with a topographic risk of "5" were plugged between 1962 and 1976; the closest is located one mile northeast of DFS. Four wells were plugged between 1933 and 1962, and were assigned a topographic risk of "4". One is located approximately seven miles west of DFS, and the other three are nine miles west of DFS. These wells are located in the down-dip direction of the expected CO_2 plume and thus should pose minimal risk. Nonetheless, the team will continue to investigate risk from these wellbores as the project proceeds.

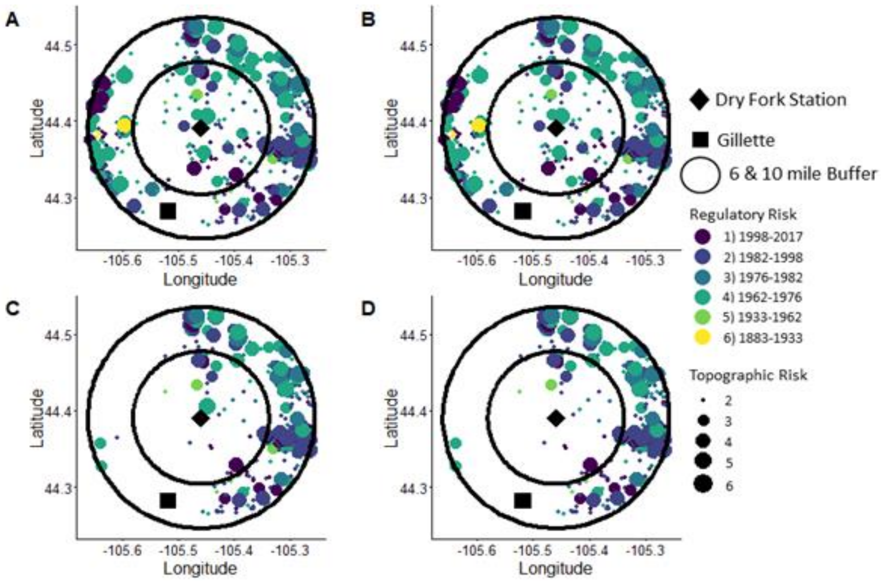

Figure 6. The risk associated with each P&A'd well within ten miles of DFS. The size of the point indicates the risk associated with topographic depressions, "6" being the riskiest. The color indicates the plug regulations of the time period, with yellow having the highest risk: (A) Lewis; (B) Mowry; (C) Morrison; and (D) Opeche confining layers surrounding DFS.

4. Prospective Storage Resources

4.1.1. Storage Capacity Estimates

The study area has adequate pore volume for storage as summarized in Table 1. These storage potential estimates are based upon average porosity and average thickness in three cases: P10, P50, and P90, each reflecting the ability of CO_2 to replace 10%, 50%, or 90% (respectively) of the brine currently in the pore space. This analysis suggests that the Minnelusa has the highest storage capacity of CO_2 per square mile, followed by the Lower Sundance, Lakota, and Muddy, in descending order.

Target Formation	Φ_{avg} (%)	k_{avg} (mD)	Average Thickness (ft)	Storage Volume (Mt/mi^2)		
				P10	P50	P90
Minnelusa	13%	44	150	0.84	1.6	2.7
Lwr. Sundance	10%	220	110	0.47	0.89	1.5
Lakota/Fall River	15%	100	70	0.45	0.85	1.5
Muddy	9%	0.05	10	0.04	0.07	0.1
Total				**1.8**	**3.4**	**5.8**

Table 1. Summary of storage reservoirs based on measured values, literature data and storage capacity estimates.

5. Geologic Modeling

Geologic models for the highest priority storage unit -- the Minnelusa Formation -- were built using Schlumberger's Petrel E&P software. These models help image CO_2 injection simulations and evaluate dynamic storage potential. Also, these models provide an initial assessment of data quality and availability in the DFS region that guide key data acquisition during the Phase II feasibility study.

A large geographic extent (766 mi^2) was selected for the initial geologic model domain and was built using formation tops interpreted from geophysical well logs (Figure 7). The large geographic extent of the models allowed for the creation of regional isopach and structural maps necessary to identify structural and facies trends and ultimately to inform Phase II site selection. Numerical simulations refined the modeling domain to focus on a 444 mi^2 area within the larger model extent (Figure 7). Phase II feasibility efforts will again refine the modeling domain as updated with new 3-D seismic data and measurements from the new stratigraphic test well.

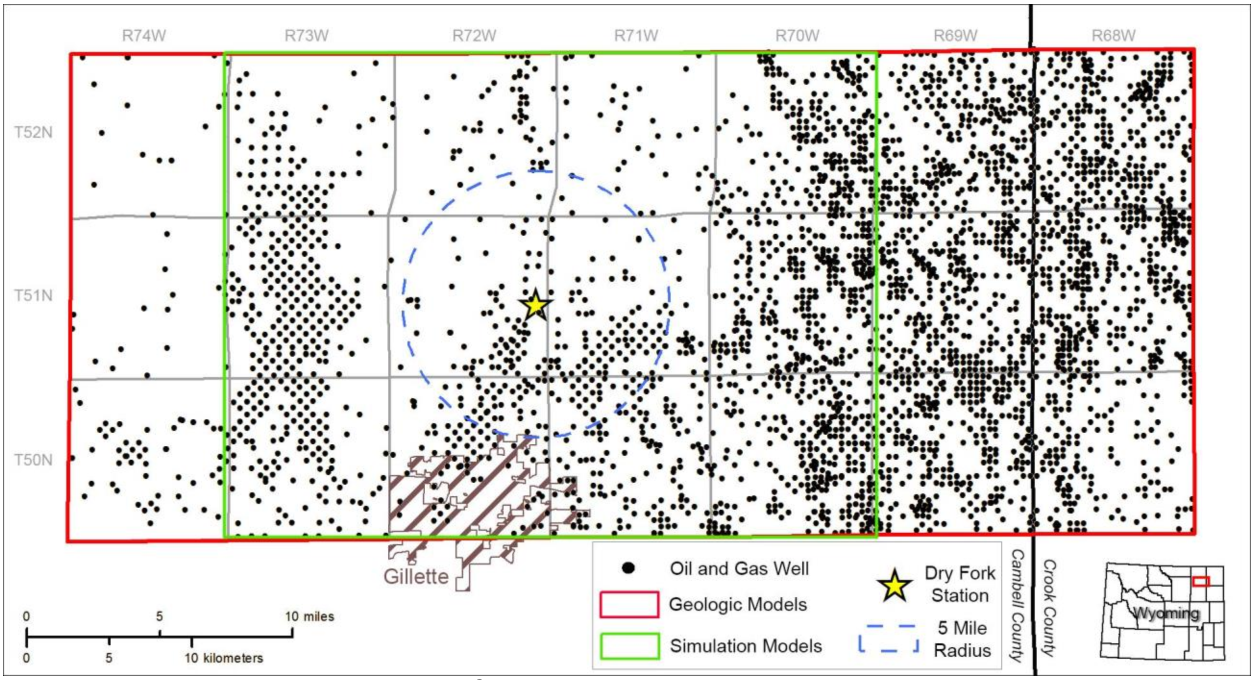

Figure 7. Map showing the larger extent (766 mi^2) of the geologic models along with the smaller simulation model extent (444 mi^2).

Facies distributions were defined for each formation on the basis of core sample, well log characteristics and previous work (Ahlbrandt and Fox, 1997; Geodigital, LLC, 2000a; Geodigital LLC, 2000b). Pressure and temperature estimates for each formation were based on legacy drill stem tests and bottom-hole temperature measurements, ranging from approximately 2400 psi and 145 ºF in the Muddy Formation to 3700 psi and 194 ºF in the Minnelusa Formation. Variograms based on these estimates, as well as facies models, were used to predict petrophysical properties.

Preliminary numerical simulations, using Computer Modeling Group's GEM compositional simulation module, provide estimates of CO_2 plume pressure and geometry. These estimates will inform field design, such as the number of injection wells required to meet the 50+ Mt storage goal, and assist in estimating the scenario's AoR. Initial assessments used a 2 Mt/year injection rate to meet the 50+ Mt storage goal. Initial simulation results suggest that if only the Minnelusa Formation were used, four wells would be needed to inject 50 Mt of CO_2 over 25 years. The Minnelusa simulation results determined an average CO_2 plume area of 3.6 mi^2 at each injection well and an estimated AoR of 157 mi^2 based on the pressure response within the formation using the methods described by EPA (2013) (Figure 8). No attempt to pack wells to optimize AoR was made during Phase I. Phase I simulation results suggest adequate storage and injectivity to implement CO_2 storage within the Minnelusa in the study area. Ongoing modeling efforts are now focusing on the other storage units.

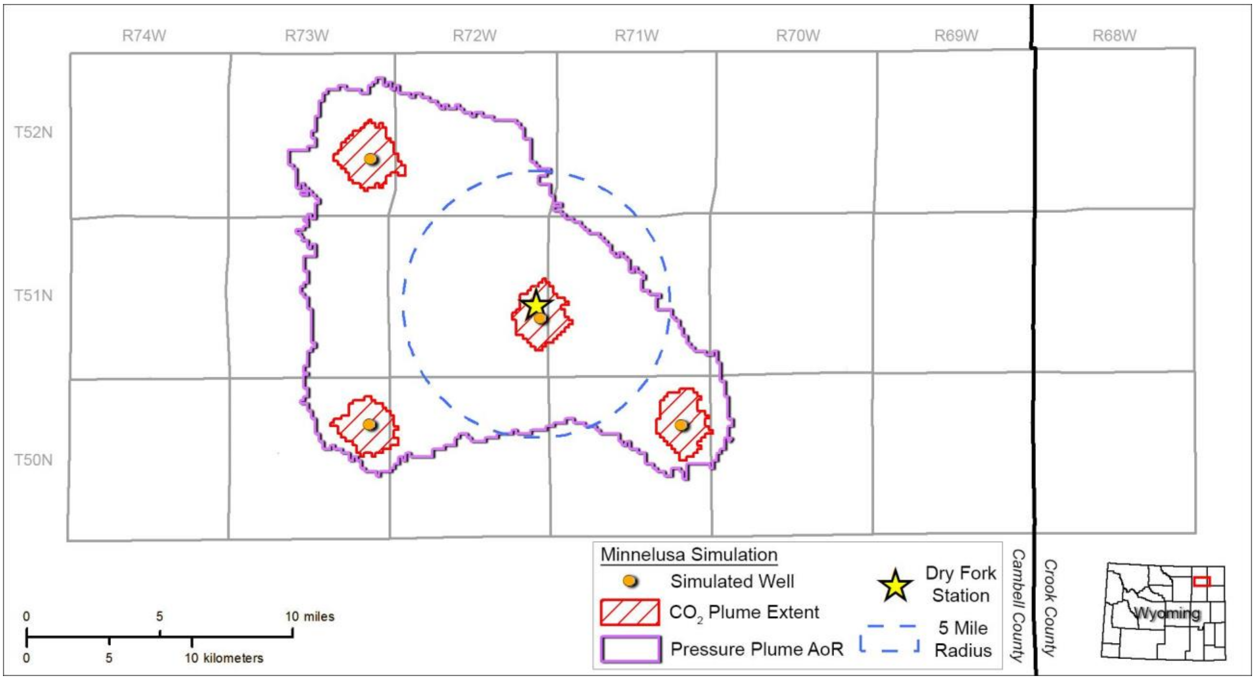

Figure 8. Simulated CO_2 plumes (red) and pressure AoR (purple) in the Minnelusa Formation after injection of 51 Mt of CO_2 across four wells over a 25-year timeframe. No attempt to optimize AoR was made during Phase I. Further refinement will occur in the Phase II feasibility study.

6. Summary

This pre-feasibility study—funded by the Department of Energy CarbonSAFE program (DE-FE0029375)—is centred around Basin Electric's Dry Fork Station (DFS) in Wyoming's Powder River Basin. Dry Fork Station, completed in 2011, is a highly efficient coal-fired power plant that emits 3.3 million tons of CO_2 per annum. The DFS site also host's the Wyoming Integrated Test Center (ITC) funded by a $15 million investment by the State of Wyoming. The ITC is a public-private partnership test bed for CCS technologies.

Four high quality potential reservoir and sealing complexes have been identified for geologic storage. These formations range in depth from 6,500-9,500 feet underneath DFS and contain pore space capable of supporting a commercial scale project (i.e. 50Mt of CO2 over 25 years).

Existing wells in the study area have been inventoried and evaluated in preparation of further risk assessment. The wellbore analysis used the approach of Nelson (2013) to assess pre-existing wells within a 10-mile radius centred on DFS. The analysis considers many factors of risk independently, including seal penetration, well density, well age, permanent plug and abandonment (P&A) date and surface topography.

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Preliminary numerical simulations, using Computer Modeling Group's GEM compositional simulation module, provide estimates of CO_2 plume pressure and geometry. These estimates will inform field design, such as the number of injection wells required to meet the 50+ Mt. Initial simulation results suggest that if only the Minnelusa Formation were used, four wells would be needed to inject 50 Mt of CO_2 over 25 years. The Minnelusa simulation results determined an average CO_2 plume area of 3.6 mi^2 at each injection well and an estimated AoR of 157 mi^2

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Acknowledgements

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