Plains CO_2 Reduction (PCOR) Partnership
Energy & Environmental Research Center (EERC)

TECHNICAL APPROACHES TO STACKED STORAGE

Plains CO_2 Reduction (PCOR) Partnership
Task 2 – Deliverable D3.A

Prepared for:

Joshua Hull

National Energy Technology Laboratory
U.S. Department of Energy
626 Cochrans Mill Road
PO Box 10940
Pittsburgh, PA 15236-0940

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Prepared by:

Matthew L. Belobraydic
Lawrence J. Pekot
Ian K. Feole
Joshua G. Regorrah
Jake A. Meyer
Wesley D. Peck
Trevor L. Richards
Catherine R. Stevens
Michael P. Warmack
Shaughn A. Burnison
Ryan J. Klapperich
Nicholas W. Bosshart
Kevin C. Connors

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

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TECHNICAL APPROACHES TO STACKED STORAGE

EXECUTIVE SUMMARY

When two or more carbon dioxide (CO_2) storage targets are present in the subsurface at the same geographic location, a CO_2 storage project may pursue a stacked storage approach. A stacked storage approach may include a colocated combination of dedicated storage in saline aquifers and storage associated with enhanced oil recovery in hydrocarbon-bearing intervals. However, this investigation was predominantly focused on dedicated storage in stacked saline aquifers.

Advantages for using stacked storage include accessing more of the pore space available in a given area, which allows for a smaller project area and may result in a reduced area of review (AOR), which can minimize the number of legacy well penetrations needing review for containment assurance. The area requiring monitoring may also be reduced, which can result in significant cost reductions over the life of a project. A smaller project area may also reduce the number of landowners involved in the project and ease pore space leasing and unitization/amalgamation efforts. Using multiwell pads to access stacked storage can consolidate surface facilities and CO_2 distribution systems, which can minimize environmental risks and impacts.

Stacked storage also creates some unique design and operational considerations. Some of the most significant considerations include the following:

- Corrosion-resistant casing and cement across each of the storage intervals increases material costs.

- The use of multireservoir injection well completions is much more complex, more expensive, and increases operational risks.

- On-site equipment is necessary to support different injection pressures needed for each storage formation on a multiwell pad.

- Stacked storage reservoirs with little vertical separation may be difficult to image separately with seismic monitoring methods.

- Legacy wellbores within the AOR and unitized/amalgamated area for a stacked storage project will need to be assessed for compliance over each storage complex.

- The potential geomechanical effects of injection in multiple intervals on interburden and on the cap rock of the uppermost injection interval are not well understood.

Several sedimentary basins within the Plains CO_2 Reduction Partnership region contain multiple potential storage units that could be amenable for stacked CO_2 storage. A growing number of prospective CO_2 projects in the region are considering stacked storage scenarios. CarbonSAFE (Carbon Storage Assurance Facility Enterprise) projects focused in Wyoming and North Dakota are currently in development and are pursuing stacked storage approaches in the Powder River and Williston Basins, respectively. A Nebraska/Midcontinent CarbonSAFE project has concluded a stacked storage evaluation, combining dedicated and associated storage, in the Denver–Julesburg Basin. The Alberta Basin is estimated to have high storage resource potential in as many as ten deep saline aquifers.

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Plains CO_2 Reduction (PCOR) Partnership
Energy & Environmental Research Center (EERC)

TECHNICAL APPROACHES TO STACKED STORAGE

INTRODUCTION

The Plains CO_2 Reduction (PCOR) Partnership Initiative is one of four projects operating under the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) Regional Initiative to Accelerate CCUS (carbon capture, utilization, and storage). The PCOR Partnership region encompasses ten U.S. states and four Canadian provinces in the upper Great Plains and northwestern regions of North America. The PCOR Partnership Initiative is led by the Energy & Environmental Research Center (EERC) with support from the University of Wyoming and the University of Alaska Fairbanks and includes stakeholders from the public and private sectors. The goal of this joint government–industry effort is to identify and address regional capture, transport, use, and storage challenges facing commercial deployment of CCUS throughout the PCOR Partnership region.

To support the development of regional infrastructure for CCUS, DOE NETL created a network of seven Regional Carbon Sequestration Partnerships (RCSPs). The RCSP Program began in 2003, with characterization of each region's potential to store carbon dioxide (CO_2) in different geologic formations (i.e., storage units) (U.S. Department of Energy National Energy Technology Laboratory, 2021). Since 2007, DOE NETL has published several assessments of CO_2 storage resource potential in geologic formations and terrestrial sinks in the United States, with the following geologic reservoirs considered viable targets for CO_2 storage: saline formations, coal seams, conventional hydrocarbon reservoirs, basalt formations, and unconventional oil and gas formations, including shales and tight sands (U.S. Department of Energy National Energy Technology Laboratory, 2015). When two or more storage units are present within the stratigraphy at the same geographic location, a CO_2 storage project may use multiple reservoirs as part of the overall storage project. The use of multiple storage reservoirs with overlapping footprints in map view is referred to as stacked storage (Hovorka and others, 2006; Sorensen and others, 2009; Hovorka, 2013).

Using stacked storage for CO_2 injection has several advantages over the use of single-formation storage. A primary advantage of stacked storage is the reduction of the overall footprint of the storage project, leading to operational and monitoring advantages. The potential optimization of surface infrastructure and landowner access reduces capital and operating costs. In addition, the centralization of the CO_2 plume extents reduces numerous monitoring systems, all of which are critical for defining storage project boundaries. However, implementing stacked storage requires further technical considerations that have not been fully vetted in published literature. This document focuses on identifying and evaluating stacked storage technical challenges and opportunities within the PCOR Partnership region. Several basins within the PCOR Partnership region feature thick sedimentary packages containing multiple potential storage units that could be amenable for stacked storage. Figure 1 shows a PCOR Partnership region map and CCUS projects within the region.

Figure 1. PCOR Partnership region map showing active and developing CCUS projects and existing and planned CO_2 pipelines. GPSP stands for Great Plains Synfuels Plant. BEST stands for Brine Extraction and Storage Test. CCA stands for Cedar Creek Anticline. DGC stands for Dakota Gasification Company. MAG stands for Midwest AgEnergy Group.

This document reviews the definition of stacked storage with respect to commercial CO_2 injection projects and discusses several advantages and challenges for implementing commercially driven stacked storage. An overview of geomechanical concerns unique to stacked storage is discussed. An update is given to the unconventional reservoir (Bakken petroleum system) CO_2 storage approach of Sorensen and others (2018). A high-level review of commercial storage projects under DOE's CarbonSAFE (Carbon Storage Assurance Facility Enterprise) Initiative is presented, with plans to use stacked storage within the PCOR Partnership region: North Dakota CarbonSAFE, Wyoming CarbonSAFE, and Nebraska CarbonSAFE. Potential stacked storage in the Alberta Basin is also discussed.

DEFINITION OF STACKED STORAGE

This document also follows regulatory definitions for consistency in defining stacked storage. A *storage complex* is a subsurface geologic system comprising a storage unit and primary and, possibly, secondary seal(s), extending laterally to the defined limits of the CO_2 storage operation or operations. A *storage facility* is the reservoir, underground equipment, and surface facilities and equipment used or proposed to be used in a geologic storage operation, not including pipelines used to transport carbon dioxide (Canadian Standards Association, 2012; North Dakota Century Code, 2021). A *storage project* comprises both storage complex and storage facility.

Stacked storage occurs when CO_2 is stored in multiple storage complexes situated vertically in the stratigraphic column. This arrangement results in multilevel CO_2 plumes from a single storage facility (Figure 2). Sedimentary basins generally have multiple clastic and carbonate reservoirs isolated by confining layers (e.g., shale, evaporite) that could be available for stacked storage (Sorensen and others, 2009; Hovorka, 2013). Among the different types of geologic settings, most commercial CO_2 storage operations target deep saline formations with high permeability and porosity to store CO_2 rates in the millions of tonnes per year (Quillinan and others, 2020; Peck and others, 2020). These saline formations are deeper than 800 meters (m) (2625 feet [ft]), the depth at which pressure and temperature conditions are effective in keeping injected CO_2 in the supercritical state and with salinity greater than 10,000 milligrams per liter (mg/L) total dissolved solids (TDS), which is a key metric used to define underground sources of drinking water (USDWs) in the U.S. Code of Federal Regulations (CFR) Underground Injection Control (UIC) Program (Code of Federal Regulations, 2014a). Many formations meet these specifications for depth and salinity, with porosities and permeabilities great enough to accommodate CO_2 injection rates and desired stored CO_2 masses for a wide range of projects.

The potential for stacked storage expands when hydrocarbon production zones are considered. However, for this report, stacked storage will mainly explore deep saline formations capable of receiving CO_2 at rates useful for commercial storage projects.

ADVANTAGES FOR STACKED STORAGE

Many technical assessments are required for any CO_2 storage project to comply with regulatory requirements and ensure CO_2 storage permanence. These analyses begin with the CO_2 capture system and end with the storage reservoir(s). Throughout a project, from site screening to closure/postclosure, potential project risks and the economic, technical, and practical challenges must continually be assessed. This report does not discuss all technical assessments required for initiation of CO_2 storage projects, but the following sections detail technical aspects that may be advantaged by stacked storage approaches, including implicit benefits to geologic storage potential

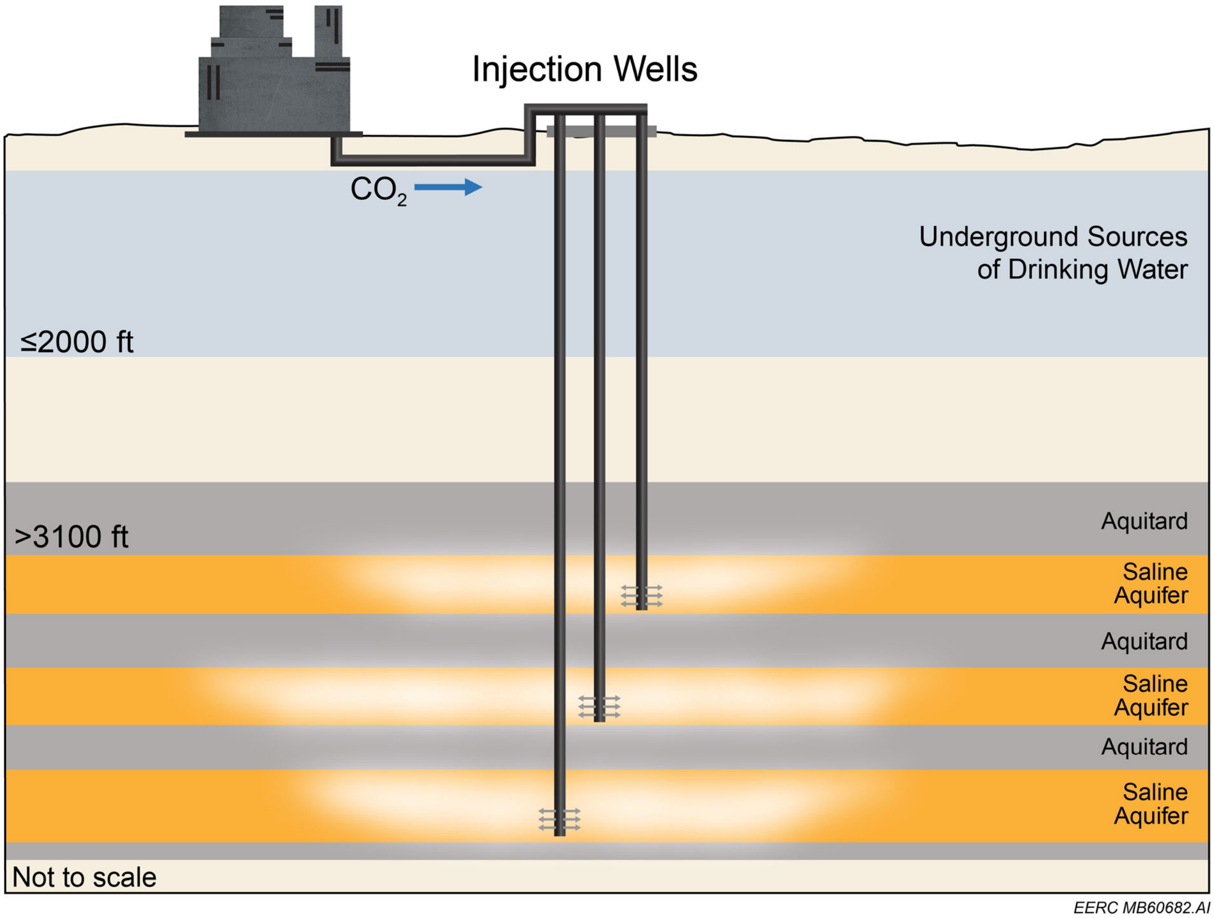

Figure 2. Stacked storage diagram illustrating three saline aquifer storage units separated by aquitard confining layers. One stacked storage well pad is depicted from a single capture facility. Distances and depth are not to scale.

per geographic area, minimizing the extent of injected CO_2 footprints, reducing the area of review (AOR), minimizing areas requiring monitoring, consolidating pore space leasing, and gaining efficiency in surface facility operation.

Increased Pore Space Accessible for Storage

An advantage of stacked storage is access to more storage formations (more pore space) available in a given area. In comparison to a scenario targeting one storage formation and with multiple CO_2 injection wells dispersed throughout a region, a scenario using multiple CO_2 injection wells at a single surface location and completed in different storage complexes may enable a reduction in the lateral extents of both injected CO_2 footprints and pressure buildup.

Accessing multiple storage complexes within the same geographic location potentially allows CO_2 to occupy a smaller areal extent for a given CO_2 volume. For example, if one storage unit stored 50 MMt CO_2 within an areal extent of 35 km^2 (13.5 square miles), then two storage units with similar characteristics might store the same 50 MMt CO_2 within an areal extent of

17.5 km^2 (6.75 square miles). Discussed in the next section, stacked storage may reduce the extent of the AOR and active monitoring area. A stacked storage approach may also help consolidate pore space leasing and/or reduce acquisition requirements, which are important operational considerations. While maximizing the storage resource potential is not necessarily an operational consideration, the regulator may be interested in promoting orderly development of the pore space resource and encourage stacked storage as a means of increasing storage resource potential and number of storage projects per geographic area. An appropriate set of incentives could maximize resource potential while reducing the possibility for pressure interference between multiple competing projects.

AOR and Monitoring Extent Reduction

For geologic CO_2 storage the U.S. Environmental Protection Agency (EPA) requires an AOR delineation and a technical evaluation within the AOR to demonstrate storage reservoir integrity. The AOR is defined as the region surrounding the storage project where USDWs may be endangered by injection activity (Code of Federal Regulations, 2014c). The AOR is a function of whichever areal extent is greater, either 1) the pressure front (buildup) in the storage unit in response to CO_2 injection or 2) the injected CO_2 footprint in the storage unit. The disposition of each depends on storage unit petrophysical properties and injection design (e.g., number of injection wells, CO_2 injection rate). The AOR is delineated using computational modeling to predict lateral extent of the CO_2 plume and associated pressure from the start of injection to the end of the postinjection monitoring period. The AOR is then evaluated for any potential fluid migration pathways, including faults, fractures, and artificial penetrations. There are many site-specific factors that influence the delineated extent of the AOR (e.g., formation thickness, formation pressure, geologic heterogeneities, injection volumes, number of injection wells, etc.), in certain geologic settings the EPA Class VI injection well methods for delineating the AOR may result in an extensive AOR. Review processes can be compounded in regions of historic oil and gas activity when numerous legacy wells that penetrate the injection zone may fall within the AOR delineation. Stacked storage, where appropriate, has the potential to reduce the extent of the CO_2 plume and associated pressure front to reduce the risk of potential fluid migration pathways in AOR delineation.

The AOR is not synonymous with the area required for monitoring, although monitoring activities are expected to be focused inside the AOR, specifically above the expected CO_2 plume extent in the subsurface. Testing and monitoring for tracking the CO_2 plume and associated pressure front as required by the UIC Class VI injection well regulations can use direct and indirect methods (Code of Federal Regulations, 2014d). Direct monitoring is performed within the injection horizon using a dedicated monitoring well or injection well(s). In a stacked storage scenario, a deeper injection well can be used to monitor overlying injection horizons using external monitoring equipment (e.g., casing conveyed external fiber optic for temperature and pressure monitoring). A variety of technologies and techniques are used in indirect monitoring to detect CO_2 plumes in the subsurface. 2D and 3D seismic surveys are indirect monitoring methods further described in the section of this report discussing seismic monitoring of vertically stacked plumes.

Stacked storage can help minimize the footprint of injected CO_2 and, therefore, minimize the area in which monitoring activities are required. The active monitoring areas are expected to generally overlap for each storage interval in the subsurface. The reduction in areal extent of monitoring can reduce associated costs significantly over the operational and postoperational time frames of a storage project.

Consolidation of Pore Space Leasing

In the states of North Dakota and Wyoming, unitization or amalgamation of the storage reservoir pore space is required to operate the storage facility, and the extent of pore space that will be occupied by CO_2 is a major component of the storage facility permit (North Dakota Administrative Code, 2021; Wyoming Statutes, 2011). The use of multiple, smaller stacked CO_2 plumes reduces the overall subsurface CO_2 footprint and helps consolidate pore space leasing and/or acquisition requirements because the number of land parcels (i.e., land with an owner or lessee of record) encompassed by the CO_2 plume will be reduced. The state of North Dakota requires at least 60% of the pore space landowners to consent to the storage project; the North Dakota Industrial Commission may require pore space owned by nonconsenting owners be included in the storage facility and subject to geologic storage. The state of Wyoming requires 80% of pore space landowners to consent to the storage project, which places even greater incentive on minimizing the CO_2 plume extent. Therefore, a smaller CO_2 plume areal extent, or footprint, results in fewer landowners and a potentially greater chance of achieving consent from the required minimum percent of pore space landowners.

Surface Facility Efficiency Gains

Stacked storage of CO_2 provides several operational efficiency advantages over single-formation storage. A stacked storage operation can take advantage of multiwell pad designs (i.e., drilling two or more injection wells on the same well pad) to provide opportunities for integrating surface facilities to support the demands of pressure increases (i.e., booster pumps) or pressure reductions (i.e., control valves) for individual storage complexes. Multiwell pads can also reduce the span of the infield pipeline distribution systems by consolidating delivery points to connect the wells and pads throughout the storage project area. Surface monitoring equipment can also be consolidated compared with monitoring a larger footprint. All these benefits contribute to a reduction in capital and operating costs. The advantages of a multiwell pad design extend to configurations that can reduce land management by decreasing the footprint required for several injection facilities: well pads, earthworks, and roads. The multiwell pad design still allows for individual well maintenance and workovers, enabling the surface injection facility to continue injection operations and saving the facility from repetitive and costly shutdowns.

CONSIDERATIONS FOR STACKED STORAGE

While stacked storage may yield many potential advantages, this approach requires consideration of several aspects unique to multizone storage project design and operation. These considerations include multiwell pad design, multireservoir well completions, multiple well injection pressure modification, project area optimization, monitoring multiple injection formations, legacy well integrity analyses, and implications to satisfying regulatory requirements. Each of these aspects is discussed in the following sections.

Multiwell Pad Design

The UIC Class VI guidance, mandated under the Safe Drinking Water Act, is designed to protect USDWs. The UIC Class VI well construction requirements are, therefore, aimed at protecting USDWs from potential environmental impacts caused by the injected CO_2. The UIC Class VI specifications require CO_2-resistant materials for cementing and casing products across injection zones and extend into the confining layers (Figure 3). Therefore, every well on the pad is required to have a wellbore configuration with CO_2-resistant casing and cement properties across every zone of injection and corresponding confining layers for the entire pad. This requirement would stand for any new wells drilled within the active CO_2 plume area or area expected to experience CO_2 saturation in the future. This is expected to result in greater casing and cement costs; however, a multiwell pad approach is expected to yield more significant cost reductions in other aspects (e.g., monitoring costs) to offset increases in material costs for well construction.

Multireservoir Well Completions

Another possible, but not widely recommended, approach to stacked storage is multireservoir well completion methods enabling injection into multiple storage complexes using a single injection well. This approach applies to stacked storage scenarios where the desired injection intervals are separated enough (vertically) that different injection pressures are needed for each horizon to achieve effective injection in each. If injection intervals are close enough (vertically), such that a single injection pressure will result in effective injection in all storage intervals, this approach is not necessary. Multireservoir well completions require an array of considerations that mostly pose significant challenges for economic feasibility, construction, operation, and ability to satisfy regulatory requirements.

If a single well is constructed and open to multiple formations for injection without dedicated injection tubing strings for each storage interval, maximum injection pressure will be limited by 90% of the fracture pressure in the shallowest storage formation. This pressure may not be great enough to achieve effective injection in the deeper storage formation(s). Aside from injection pressure limitations in this approach, UIC Class VI guidance dictates strict zonal isolation requirements between the target injection horizons. This requires the design of a multireservoir completion injection well to include a long-string casing with an inner diameter large enough to enable the placement of multiple injection tubing strings and casing packers to isolate each zone. For commercial storage projects with high CO_2 flow rates, modeling of gas injection into the wellbore (e.g., nodal analysis) indicates the need for large tubing sizes (e.g., >4 inches), which requires larger production string casing diameters (e.g., 12 to 16 inches) to accommodate multiple tubing strings, much larger than standard production casing sizes (e.g., 7 to 9 inches). Corrosion-resistant casing, at present, is costly and somewhat difficult to procure even in standard sizes. The drilling costs for a large-diameter well for a multireservoir completion approach, combined with the increased costs for required oversized, corrosion-resistant casing, is likely to be significantly more expensive than a single completion CO_2 injection well.

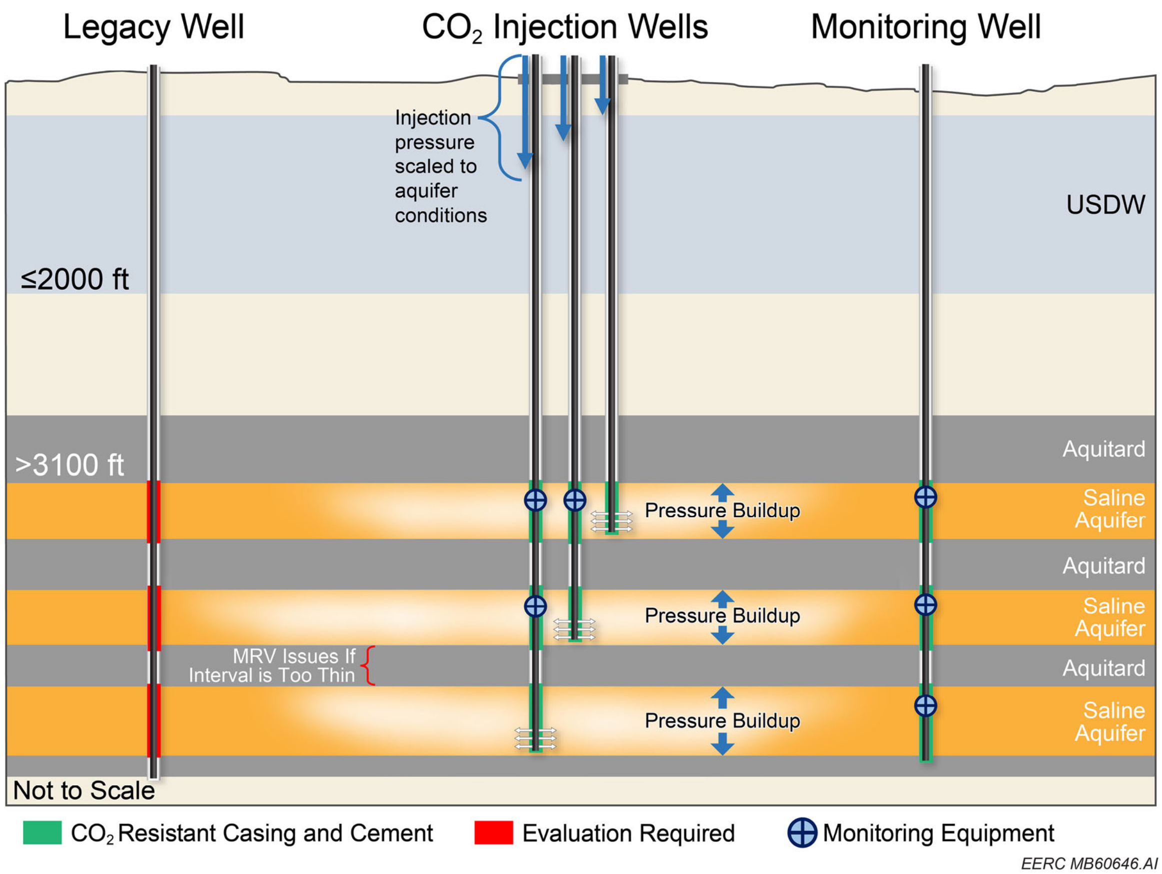

Figure 3. Multiwell pad schematic for three stacked saline aquifers separated by aquitard layers. Distances and depths are not to scale. The injection pressures for each well are scaled to the reservoir conditions with the highest pressure for the deepest saline aquifer. CO_2 injection wells and a monitoring well are constructed with CO_2-resistant casing and cement over saline aquifer zones, indicated in green. The legacy well is colored red where evaluation will be required because of potential exposure to CO_2 and pressure increases. Pressure buildup in the saline storage aquifers is indicated with blue arrows. Monitoring equipment sites are indicated in the blue ringed crosses. If the vertical distance between storage formations is too thin, seismic monitoring may be challenged because of relatively low imaging resolution.

Aside from increased material costs and difficulties in well construction, multireservoir completion injection wells have other technical challenges. Tubing movement calculations are also necessary to ensure that axial tubing forces exerted from the different injection rates and pressures will not prematurely unset the dual packer (Anthony and Kaushik, 2017). Well workover considerations (i.e., well maintenance) involve more complex zonal isolation methods for pressure control between the zones. Additionally, wireline tool obstructions are created with the packer assemblies in the wellbore. Because of the separate zonal isolation needed between injection intervals for this approach, requirements of successful annual mechanical integrity tests, to be completed along the length of the wellbore, are very difficult to achieve. When well workover or maintenance issues arise with any of the completion zones, cessation of CO_2 injection is likely to occur in all storage intervals until the well is back online, potentially extending shutdowns to facilities and infrastructure.

While multireservoir completion injection wells are technically an option for CCUS, this technique is not being given much consideration because of a combination of increased costs and significant design, operational, and regulatory challenges. For these reasons, stacked storage projects in the PCOR Partnership region have been exclusively focused on scenarios using single completion wellbores, one for each injection horizon.

Multiple Well Injection Pressure

With multiple wells at one site individually injecting into different reservoirs, the economics for pressurization of CO_2 received by pipeline from the central delivery point (CDP) will need to be assessed to meet necessary pressures for each injection well. Two options are presented for consideration: pressurizing the CO_2 on-site or at the CDP.

CO_2 pressurization at a multiwell site involves assessing the volume of delivered CO_2 to pressurize, pipeline sizing, and distance from CDP. Assuming the CO_2 pressure is delivered in a supercritical phase for the pressure and temperature conditions, pressurization can be of the entire CO_2 stream (if CO_2 is received below necessary injection pressure for any well on-site), or a partial CO_2 stream dedicated to one or more of the injection wells (if delivered CO_2 pressure meets well requirements). On-site pressurization of the stream requires booster pumps designed to handle the maximum injection rate and pressure authorized for the injection wells. A consideration for on-site CO_2 pressurization is that transportation lines from the CDP to the multiwell site generally will be a larger design to limit the pressure reduction from the CDP.

A second option involves pressurizing the entire CO_2 stream at the CDP before transporting to multiwell site(s). This would require a higher horsepower load to pressurize the full CO_2 stream but offers the capability of reducing the size of the line for transporting the CO_2 between the CDP out to the multiwell sites and centralizing facilities to a single location. Any pressure reduction required at the multiwell sites can be accomplished through a system with control and shut-in valves to limit pressure and flow.

An overall cost analysis between investment and operational cost of pumps versus savings due to a reduction in line sizing from the CDP to the multiwell sites will ultimately direct the preferred method for a given storage project. Any system designed would need to accommodate changes in conditions (i.e., seasonal temperatures) of the delivered CO_2 and maintain requirements for all injection intervals.

Project Area Optimization

Site- and project-specific considerations (e.g., number and cost of wells) may dictate that an unbalanced injection approach between stacked storage formations is more suitable. However, if optimization of a storage project-monitoring footprint is desired, injected CO_2 volumes may be divided among storage units so that the stacked plumes are approximately the same size in areal extent (Figure 4). Nevertheless, variation in geologic characteristics among storage units such as

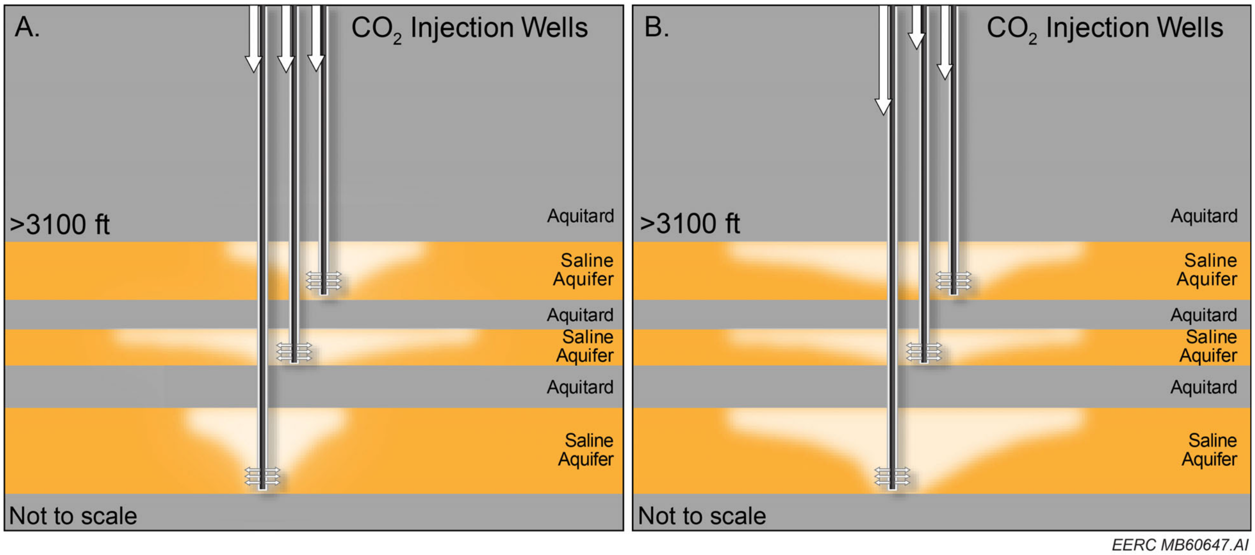

Figure 4. Project area optimization example: A) scenario injecting the same CO_2 volumes into three reservoirs with different pore space, resulting in each plume having a different areal extent and B) scenario using different CO_2 injection volumes for each saline aquifer to align areal extent for all the plumes. Both scenarios have roughly the same footprint, with Scenario B resulting in the larger volume injected.

anisotropic permeability, stratigraphic pinch-outs, or hydrodynamic conditions can create stacked plumes that are different in size or oriented in different directions. A large project may need to use a different number of wells, different well placements, or different well spacings for each storage unit to minimize the areal extent required for monitoring.

Similar considerations also apply if the objective of the project area optimization also includes an attempt to equalize the AOR among storage units. In most cases, the AOR for each storage unit will cover a larger area than the CO_2 plume. The defined AOR demands that all well penetrations within the area are reviewed and permanent structures are documented. Thus if the AOR for one storage unit is much larger than the other(s), considerable additional effort may be needed to make these reviews. A large AOR may also indirectly affect the area covered by the groundwater-monitoring plan, particularly if the largest AOR is associated with the shallowest storage unit, that is, closest to USDWs. Therefore, equalizing the size of the AORs may be desirable and could be considered a part of the overall optimization of the project area.

Optimized reduction of the project area for a stacked storage project has several advantages, as mentioned throughout this report. However, it is also apparent that such project area optimization requires thoughtful investigation and may require capital investment to achieve. The benefits of optimization must be weighed against these potential costs.

Seismic Monitoring of Vertically Stacked Plumes

Several considerations are necessary to monitor stacked storage reservoirs to ensure storage permanence under the UIC Class VI guidance and to evaluate operational effectiveness (i.e., areal extents of the pressure fronts and CO_2 plumes within the storage complex). Ultimately, the number of monitoring wells, sampling frequency, and monitoring technologies deployed in the monitoring, reporting, and verification (MRV) plan are site-specific, and multiple sets of monitoring devices may be required to determine that each storage unit is performing as expected (i.e., conformance). Geophysical techniques such as seismic surveys for monitoring plume extents are an important component of the overall MRV plan.

Seismic monitoring methods enable assessment of subsurface changes at periodic intervals during CO_2 injection to evaluate the lateral extent of CO_2 within the storage unit (i.e., CO_2 plume). In a stacked storage configuration, distinguishing between two or more layers of CO_2 within storage units must be anticipated and adequately accounted for to ensure accurate results (Figure 3).

Understanding the predicted seismic response resulting from site-specific stacked storage scenarios is necessary before committing to seismic as a monitoring method. Modeling the predicted seismic response will provide an estimation of the necessary vertical separation of layered CO_2 for resolving plume extents. This modeling requires well log data (i.e., dipole sonic and density well logs) and accurate fluid and pressure assumptions coupled with an understanding of seismic parameters (i.e., predicted or actual measurements of signal bandwidth and noise). Additionally, a time-lapse (4D) seismic program can improve detection of CO_2 plume extents in stacked storage scenarios when vertical separation allows for interpretation of plumes without interference of the waveform signal. Modeling operational scenarios and understanding repeatability of time-lapse response will provide an operator with feasibility for seismic monitoring methods to track plume extents in a stacked storage project (Johnston, 2013; Roach and others, 2015).

Conventional land 3D seismic modeling involves active surface seismic sourcing (e.g., vibroseis, dynamite) and recording with sensors capable of capturing reflected energy back to the surface from the seismic sources. These reflections are processed and summed into images resulting in cross sections from which structure, rock property, and fluid information can be derived. Assuming modeling shows that formations are adequately separated, traditional seismic methods can detect changing fluid responses (i.e., CO_2 saturations) based on interpretations of extracted amplitude and amplitude variation with offset response (Ivandic and others, 2018). When these "surface–surface" seismic data are collected at periodic time-lapse intervals and compared, the result is 4D seismic. 4D seismic analysis is the result of subtracting two successive seismic data sets, removing the unchanged parts of the imaged section, and leaving the changed reservoir.

The following describes two additional seismic methods to consider for improving vertical resolution in a stacked storage scenario and to complement the traditional surface–surface 3D and 4D monitoring methods:

- Vertical seismic profiles (VSPs), or borehole seismic data, are implemented by recording throughout the wellbore and actively sourcing on the surface. Surface–borehole methods can be collected in 2D and 3D. The recording instruments are placed in the borehole for lower noise levels, and seismic waves are generated from a series of surface sources that sequentially step away from the borehole. When a baseline VSP is collected followed by a VSP after a period of CO_2 injection, the resulting higher-resolution time-lapse image typically has a better vertical resolution. The radius used around the wellbore for the VSP is the approximate depth to the formations of interest. The high-frequency part of the recorded seismic reflections provides increased vertical sampling of rock layers, allowing for improved vertical resolution, and in some cases, improvement by a factor of two over surface–surface methods (Van Dok and others, 2016). While this improved resolution will allow for better monitoring in a stacked storage scenario, the area of monitoring is constrained by the location of the wellbore and depth to target injection formation.

- Crosswell (borehole–borehole) methods have been implemented in previous studies to understand the nature of fluid migration between wellbores. Application of this method for monitoring stacked CO_2 plumes within different storage units has been field-tested with some success, requiring proximal wellbores (i.e., 400 m [~1500 ft]), and results in a high-resolution profile of time-lapse changes (Li and others, 2001; Ajo-Franklin and others, 2013). This time-lapse method maps CO_2 saturations related to interwell velocity changes using tomographic analysis. The vertical resolution of this method can be 10 times higher than surface–surface seismic. This method is best implemented in early stages of injection for informing fluid migration and fluid conformance over short distances.

Legacy Well Integrity

A review of existing (legacy) wellbore integrity is required within a storage project AOR (Figure 3). Using multiple injection reservoirs increases the risks for containment control of the additional injection zones intersecting legacy wellbores requiring more extensive risk assessment over a greater portion of the wellbore. This requires greater scrutiny of cement and casing material integrity for all legacy wells within an AOR. Current wellbore completion requirements are more stringent, and previous procedures for plugging and abandoning wells rarely considered future field development to accommodate possible intrusion fluids, which can degrade cement or corrode casing. Using legacy wells as monitoring wells could still require additional corrective steps for existing casing and cement bonds upon reentry into the wellbore. Remediations to legacy wells may be costly and add to project risk, but also may be necessary to protect USDWs and ensure CO_2 remains contained within the intended injection intervals.

Regulatory Requirements

For permitting a UIC Class VI injection well or a storage facility in the state of North Dakota, there are no specific additional regulatory requirements for stacked storage beyond those that apply to any CCUS project. Similarly, for MRV plans under Subpart RR of the EPA greenhouse gas reporting rule, the specific monitoring requirements for stacked storage also apply to the monitoring of any CCUS project. Permitting is based on the single injection horizon; therefore, a permit is required for each individual storage complex in the stack.

As wide-scale CCUS deployment builds and additional projects target stacked storage, there may be efficiencies gained in the permitting process, if allowed by a regulatory permitting authority. When permitting a CCUS project, there are distinct portions of the permit that are specific to the geology and storage complex that need to be addressed as individual permits. There are also sections of the permit that encompass the entire CCUS project and are not influenced by the individual geologic horizons. For instance, the regulator must consider the geologic unit (injection zone and upper and lower confining zones) and pore space amalgamation for each individual horizon in a stacked storage CCUS project, but the geologic model and computational simulations can and should be evaluated for the stacked storage project as a whole. This project-centric regulatory evaluation of a stacked storage permit would also include an AOR and corrective action plan, risk assessment, testing and monitoring plan, postinjection site care and facility closure plan, emergency and remedial response plan, well casing and cementing program, plugging plan, and financial assurance demonstration. The regulatory permitting authority that has the flexibility to evaluate stacked storage projects by separating sections of a permit that are unique compared to other portions that encompass the CCUS project as whole will be able to efficiently review and evaluate multiple permits at once by eliminating redundant sections of the permit. For example, an applicant's financial assurance demonstration will not be based on a single geologic unit; rather, the applicant will provide a financial demonstration for the entire stacked storage CCUS project.

Permitting CCUS projects entails a public comment period and public hearing for each individual permit. A regulatory permitting authority that has the flexibility and latitude to consolidate portions of a stacked storage permit (e.g., financial assurance demonstration) for the purposes of the hearing will be able to eliminate redundancy and focus on the unique nature of the storage reservoir while ensuring all requirements are met.

GEOMECHANICAL CONCERNS OF STACKED STORAGE

Currently, storage projects in the PCOR Partnership region have mainly focused on single-formation storage. The implementation of stacked storage has not yet been attempted for a commercial project. Under a single-formation storage scenario, the geomechanical investigations are generally limited to the storage unit and the overlying confining zone (e.g., cap rock). However, under a stacked storage scenario with multiple storage reservoirs in play, there is potential for each storage complex to affect the others. Further investigations are needed to evaluate the resulting combined stresses and pore pressure changes associated with multiple formations containing significant volumes of CO_2 at the same time. The geomechanical impact and stresses on the interburden (i.e., rock layers between two storage units) between pressured storage units as well as the uppermost confining layer need to be investigated. For example, the unexpected failure of the upper cap rock at a stacked storage site may not necessarily compromise the storage integrity of deeper injection zones. Similarly, failure of an interburden cap rock may not necessarily lead to failure of the entire storage complex as the upper confining layer(s) may remain intact. Evaluating the geomechanical stresses from stacked storage generally requires mechanical earth models that combine mechanical properties for the rock layers in the storage complex and simulate the effect of CO_2 injection on the state of stress throughout multiple geologic layers.

The openness of reservoir boundary conditions (e.g., ability for fluids to be displaced laterally) largely dictates pore pressure response (i.e., pressure buildup) to CO_2 injection. Since the geomechanical response is largely attributable to the pore pressure (and resultant stress), the openness of reservoir boundary conditions also affects the geomechanical response. A more closed boundary system experiences significant increases in average reservoir pressure relatively quickly (i.e., within a few years), because the formation fluids are not displaced horizontally from the storage reservoir and, therefore, storage comes from rock compressibility (e.g., pore dilation), native brine compressibility, and the limit of acceptable pressure increase (e.g., maximum CO_2 density) in the system. The greater pressure response in a closed system increases the geomechanical stress. Mitigation measures for alleviating pressure buildup include brine production, where fluids are removed from the storage unit and reinjected into a different geologic formation (Bosshart and others, 2021). More open systems could experience only minimal pressure change, even without brine production, because in addition to the rock, brine, and CO_2 compressibility, the open system boundary allows formation fluids to easily displace away from an injection site. In geologic systems, where one or more storage units exhibit closed or semiclosed boundary conditions, distributing injection into multiple stacked reservoirs may reduce geomechanical stress, and potential risks from exceeding the geomechanical integrity of confining layers may be reduced, particularly for closed-system projects. The exploration of geomechanical changes due to injection into stacked reservoirs is the subject of future research under the PCOR Partnership and is beyond the scope of this report.

UNCONVENTIONAL RESOURCES AND STACKED STORAGE

Unconventional formations with high clay mineral and total organic carbon (TOC) content can adsorb significant CO_2 volumes along with storing CO_2 within available pore space. Sorensen and others (2018) demonstrated that the adsorbed CO_2 volume provided a 40% to 390% increase for different members of the Bakken and Three Forks Formations over the CO_2 volume stored in pore space alone. The estimates in Sorensen and others (2018) were also found to be conservative with respect to the CO_2 density used in the calculations. Originally calculated as 727 kg/m^3 using the reservoir pressures as an upper limit, the CO_2 density could be as high as 789 kg/m^3 and still be within a maximum injection pressure constraint of 90% of the fracture pressure in the intended storage formation (U.S. Environmental Protection Agency, 2018; Code of Federal Regulations, 2014b) for most potential injection sites. As shown in Table 1, this increases the estimated storage potential of each lithofacies from 1.6% to 5.9% in terms of the amount of CO_2 able to be stored in a cubic meter of rock (kg CO_2/m^3).

Table 1. Updated Summary of Most Likely CO_2 Storage Resource Estimates for Each Lithofacies Considered in the Bakken Petroleum System (modified from Sorensen and others [2018])

		Most Likely Estimate			
Input	**Units**	**Upper Bakken Shale**	**Middle Bakken Member**	**Lower Bakken Shale**	**Three Forks**
Porosity	L3/L3	0.031	0.038	0.056	0.074
Porosity Factor for Hydraulic Fracture	–	1.0	1.0	1.0	1.0
CO_2 Density	kg/m^3	789	789	789	789
Pore Space Storage	kg CO_2/m^3 rock	24.6	30.1	44.3	58.6
E_φ	–	0.17	0.19	0.17	0.19
Adjusted Pore Space Storage	kg CO_2/m^3 rock	4.2	5.7	7.5	11.1
Bulk Density	kg/m^3	2215	2576	2265	2547
TOC Content	wt%	13.6	0.2	11.6	0.2
TOC Content	kg TOC/kg rock	0.136	0.002	0.116	0.002
TOC Content	kg TOC	300	6	263	5
Clay Content	wt%	19.8	8.1	26.5	13.9
Clay Content	kg clay/kg rock	0.198	0.081	0.265	0.139
Clay Content	kg clay	438	207	600	353
C_S	kg CO_2/kg (TOC + clays)	0.045	0.025	0.045	0.025
Sorbed Storage	kg CO_2/m^3 rock	33.2	5.3	38.8	8.9
E_S	–	0.50	0.50	0.50	0.50
Adjusted Sorbed Storage	kg CO_2/m^3 rock	16.6	2.7	19.4	4.5
Total Storage (pore + sorbed)	kg CO_2/m^3 rock	57.9	35.4	83.1	67.6
Adjusted Total Storage (pore + sorbed)	kg CO_2/m^3 rock	20.8	8.4	26.9	15.6
Increase over Sorensen and Others (2018)	%	1.6	5.6	2.2	5.9

If a stacked storage project was attempting to manage a 35-km^2 area and the resource scenario from Sorensen and others (2018) is maintained, where thickness of the Upper Bakken Shale and Lower Bakken Shale Members are 7 and 15 m thick, respectively, and the Middle Bakken and Three Forks Members are 26 and 10 m thick, respectively, the CO_2 storage resource can be calculated using Equation 1 (modified from Sorensen and others [2018]) below:

$$G_{CO2,TOTAL} = G_{CO2,UBS} + G_{CO2,MB} + G_{CO2,LBS} + G_{CO2,TF} \quad \text{[Eq. 1]}$$

Where:

$G_{CO2,TOTAL}$ = Total mass CO_2 storage resource of the Bakken petroleum system
$G_{CO2,UBS}$ = Mass CO_2 storage resource of the Upper Bakken Shale
$G_{CO2,MB}$ = Mass CO_2 storage resource of the Middle Bakken Member
$G_{CO2,LBS}$ = Mass CO_2 storage resource of the Lower Bakken Shale
$G_{CO2,TF}$ = Mass CO_2 storage resource of the Three Forks Formation

Using the values and assumptions noted above, the storage resource potential of the hypothetical area is estimated below in Equation 2:

$$35km^2 \times \left(\left(7m \times \frac{20.8\ kg\ CO_2}{m^3\ rock}\right) + \left(26m \times \frac{8.4\ kg\ CO_2}{m^3\ rock}\right) + \left(15m \times \frac{26.9\ kg\ CO_2}{m^3\ rock}\right) + \left(10m \times \frac{15.6\ kg\ CO_2}{m^3\ rock}\right)\right) = 32.3Mt \quad \text{[Eq. 2]}$$

This results in an additional 32.3 MMt of CO_2 storage potential for the hypothetical stacked storage project with the inclusion of the Bakken petroleum system. There are other unconventional reservoirs in the PCOR Partnership region with CO_2 storage potential that can be investigated further in the future, including the Mowry Shale of the Powder River Basin in Wyoming, the Niobrara Shale of the Denver–Julesberg and Powder River Basins, the Colorado Group of the Alberta/Western Canadian Basin, and other more minor unconventional plays. The approach of Sorensen and others (2018), used in the estimation above, can be tailored for application in storage estimates within such other unconventional reservoirs if the required variables are known: specifically, area, thickness, temperature, pressure, CO_2 density (at reservoir temperature and anticipated maximum injection pressure), porosity (matrix and fractures), bulk density of the rock, mass of TOC and clay, and adsorption potential measured from laboratory analyses.

Clay- and organic-rich formations are not ideal for dedicated, solo CO_2 storage, but where present, these types of formations could be considered to extend the life of a stacked storage complex. Hydrocarbon presence introduces additional complications, with competing goals for the resource between mineral rights, hydrocarbon leases, enhanced oil recovery (EOR), and permanent CO_2 storage projects. For these reasons, dedicated storage in hydrocarbon-producing unconventional reservoirs may be unlikely to occur in the future. However, as production in such unconventional reservoirs continues to mature, associated CO_2 storage through EOR is a likely eventuality. In that respect, unconventional reservoirs may represent widespread targets to augment the storage resource available in saline aquifers as part of stacked storage operations. An associated storage approach is likely to decrease the storage efficiency from estimates achieved assuming dedicated storage, such as the method above, as production is likely to lower operating pressures. This would result in a relatively lower CO_2 density and decreased sorptive capacity. Different methods would need to be applied to yield better estimates of associated CO_2 storage potential, but this is outside the scope of this report.

STACKED STORAGE OPPORTUNITIES IN THE PCOR PARTNERSHIP REGION

The PCOR Partnership region has many opportunities for stacked storage in deep saline storage complexes, with additional EOR options in hydrocarbon-bearing formations. The data displayed in Figure 5 show the number of identified reservoirs and the total potential CO_2 volume in million tonnes estimated to be stored per 100 km^2. The estimates for Figure 5 use a volumetric equation of thickness, porosity, CO_2 density (from depth, pressure, and salinity), and efficiency factor to calculate potential CO_2 volumes for each formation below 800 m (2625 ft), resulting in a sum of all stacked formations for each 10,000 by 10,000 m (32,800 by 32,800 ft) grid cell (U.S. Department of Energy National Energy Technology Laboratory, 2010). For any location being considered for CO_2 storage, local characterization is necessary to verify storage complex reservoir quality and confining layer competency. Areas with fewer legacy wells, because of well density or less sampled formations, may offer favorable storage opportunities, but the lack of wells also increases the uncertainty for characterization.

The following sections discuss local characterization and stacked storage potential for the Wyoming CarbonSAFE project in the Powder River Basin, the North Dakota CarbonSAFE project in the Williston Basin, and the Nebraska/Midcontinent CarbonSAFE project in the Denver–Julesburg Basin. Assessment of the Alberta Basin is also discussed.

Wyoming CarbonSAFE – Powder River Basin

The Powder River Basin in northeast Wyoming hosts multiple candidate formations for CO_2 storage that can potentially be used in stacked storage scenarios. Craddock and others (2012) identified 13 potential stacked reservoirs within the Powder River Basin separated by regional seals, of which the Lakota, Lower Sundance (Hulett Sandstone Member), and Minnelusa Formations were selected for additional study in the Wyoming CarbonSAFE project (Figure 6). The Wyoming CarbonSAFE project goal is to support the capture and storage of 50+ MMt of CO_2 from the Dry Fork Station near Gillette, Wyoming (Quillinan and others, 2020). The project team is characterizing and testing the Minnelusa Formation and Hulett Sandstone Member of the Sundance Formation for stacked storage using multiple injection sites over the 25-year project life cycle. This plan also allows the Lakota to remain free for later brine disposal or as a pressure dissipation zone. Phase III for the Wyoming CarbonSAFE project (ending in 2023) is anticipated to finalize the assessment to increase the accuracy of the injection predictions (Quillinan and others, 2020).

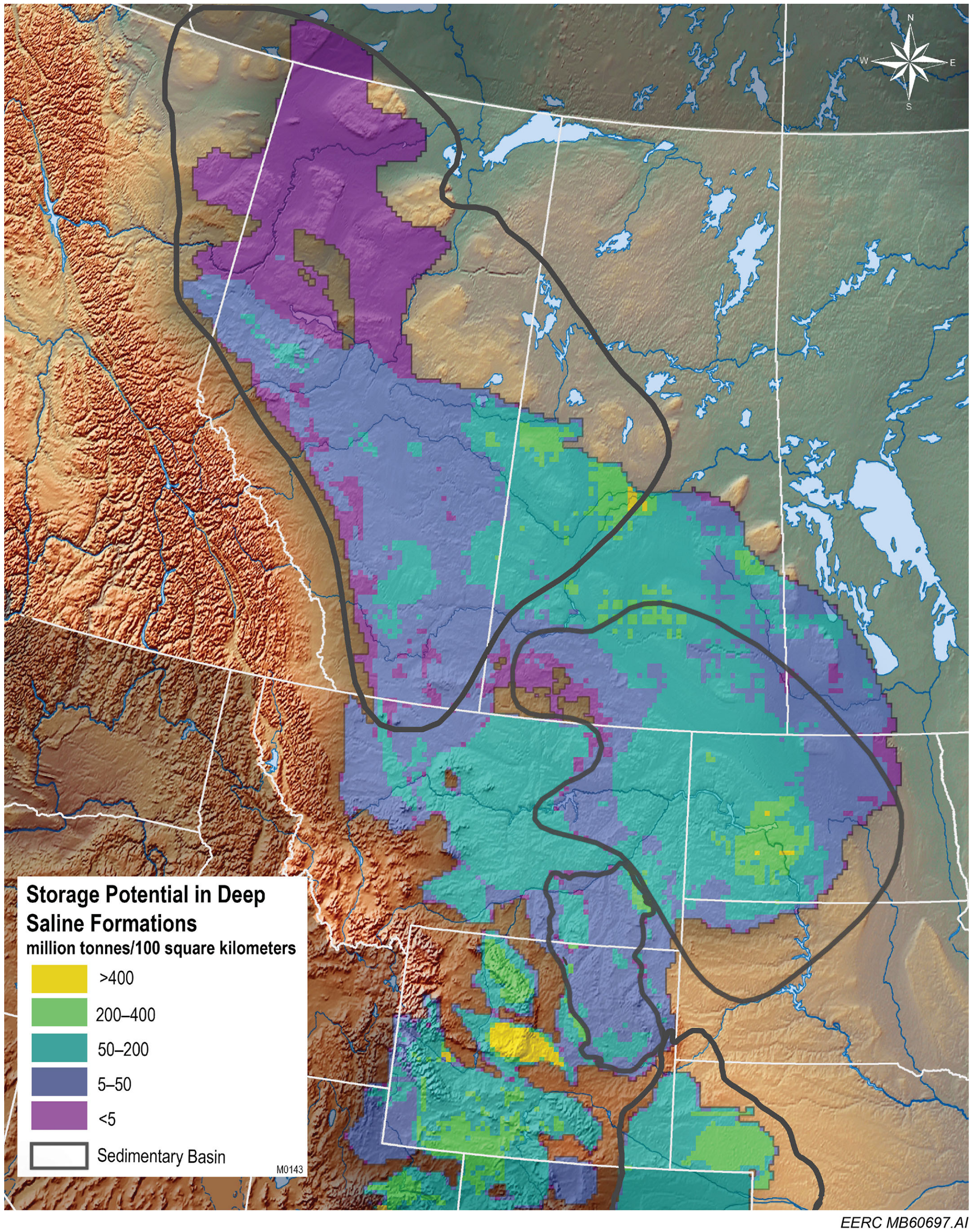

Figure 5. Saline storage potential map of the PCOR Partnership region. Map of estimated CO_2 storage volumes measured in MMt/100 km^2 (based on data contained in the National Carbon Sequestration Database [Bauer and others, 2018]).

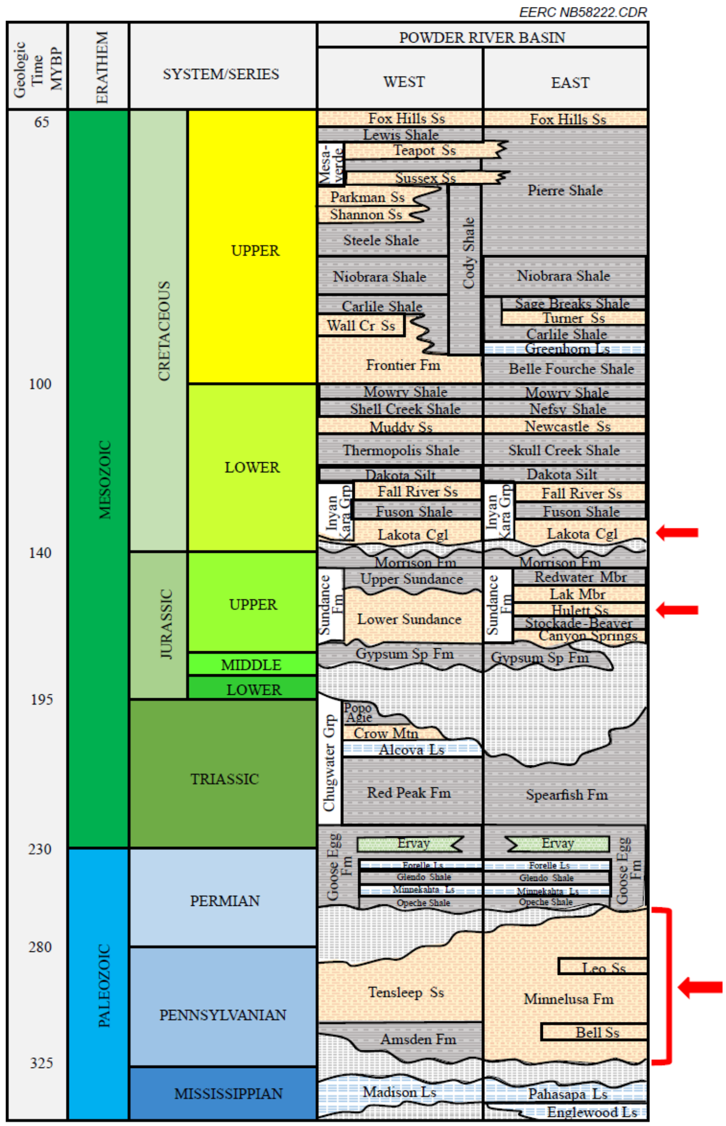

Figure 6. Stratigraphic column of the Powder River Basin. Intervals investigated in Wyoming CarbonSAFE Phase II are shown with red arrows, including the Lakota Member, Hulett Member, and Minnelusa Formations (modified from Quillinan and others, 2020).

The stacked formations selected for CO_2 injection contain suitable porosity and permeability for injection and are nonproductive for hydrocarbons in the area around the Dry Fork Station. The Lakota Formation includes conglomerate, siltstone, mudstone, and coarse sandstone. The Hulett Member is one of two primary reservoirs within the Lower Sundance (Ahlbrandt and Fox, 1997) and is a trough-crossbedded, silty sandstone with shale interbeds (Rautman, 1978) with a high potential for confinement (Ahlbrandt and Fox, 1997). The Minnelusa is divided into lower, middle, and upper units bound by unconformities: the Upper Minnelusa consists of dolostones and sandstones; and in the northern Powder River Basin, the Lower and Middle Minnelusa consist of shale and carbonate layers (Quillinan and others, 2020).

The regional confining layers for the selected reservoirs ensure good isolation from the lowest USDW in the Fox Hills Formation and from each other. The thick Cretaceous shale package consisting of the Pierre, Cody, Niobrara, Carlile, Greenhorn, Belle Fourche, and Mowry Formations is the secondary confining zone for the planned injections above the Muddy Formation. The Fuson Shale and Skull Creek Formation are the upper confining layers for the Lakota. The shales of the Morrison and Upper Sundance Formation isolate the Hulett Member of the Lower Sundance Formation from the Lakota Formation. The Goose Egg and Spearfish Formations isolate the Upper Minnelusa from the Hulett (Quillinan and others, 2020).

Estimations from simulations conducted by Quillinan and others (2020) showed that no single reservoir on its own could accept the CO_2 injection target of 50+ MMt over a 25-year period, even at up to seven injection sites for Wyoming CarbonSAFE (Table 2). Simulations of stacked storage scenarios showed that at least two reservoirs, Minnelusa and Sundance, could be used to reach the target injection volumes in the 25-year period. This use of stacked storage to reach the target CO_2 injection volume also eliminated the need for considering seven well pads to reach storage goals with cumulative volumes being achievable with five (Figure 7; Quillinan and others, 2020). Decreases in the required number of well pads reduced the distance for pipelines needed to reach those two well pad locations. This strategy allows for the possibility for two remaining well pad locations to be used later if more CO_2 storage resource is required.

A challenge with using stacked storage in the Powder River Basin is accommodating the oil and gas reservoir development that has occurred around any planned CO_2 injection site(s). The Muddy Formation is a prolific hydrocarbon reservoir and is found across multiple Rocky Mountain basins. As this formation lies above planned storage formations, likely a high count of legacy oil and gas wells in any proposed AOR could require monitoring or mitigation depending on site selection. Since the Muddy Formation would also be considered a pressure dissipation zone, these wells may be an issue for monitoring. The Upper Minnelusa is also a prolific hydrocarbon reservoir with dispersed fields across the eastern margin of the Powder River Basin, having produced 600+ million barrels of oil (Anna, 2009). This issue of legacy well density provides an opportunity

Table 2. Simulation Results from Wyoming CarbonSAFE Using Stacked Storage to Meet Total Injection Goals of 50+ MMt over a 25-year Project Life Cycle (modified from Quillinan and others, 2020)

Formation	Scenario	Cumulative Gas Mass, MMt
Lakota	Seven sites	4.4
	Five sites (1, 2, 3, 5, 6)	3.3
Sundance	Seven sites	26.4
	Five sites (1, 2, 3, 5, 6)	18.1
Minnelusa	Seven sites	42.7
	Five sites (1, 2, 3, 5, 6)	35.6
Sundance – Minnelusa Stacked	Seven sites	69.1
	Five sites (1, 2, 3, 5, 6)	53.7
Lakota – Sundance – Minnelusa Stacked	Seven sites	73.5
	Five sites (1, 2, 3, 5, 6)	57.0

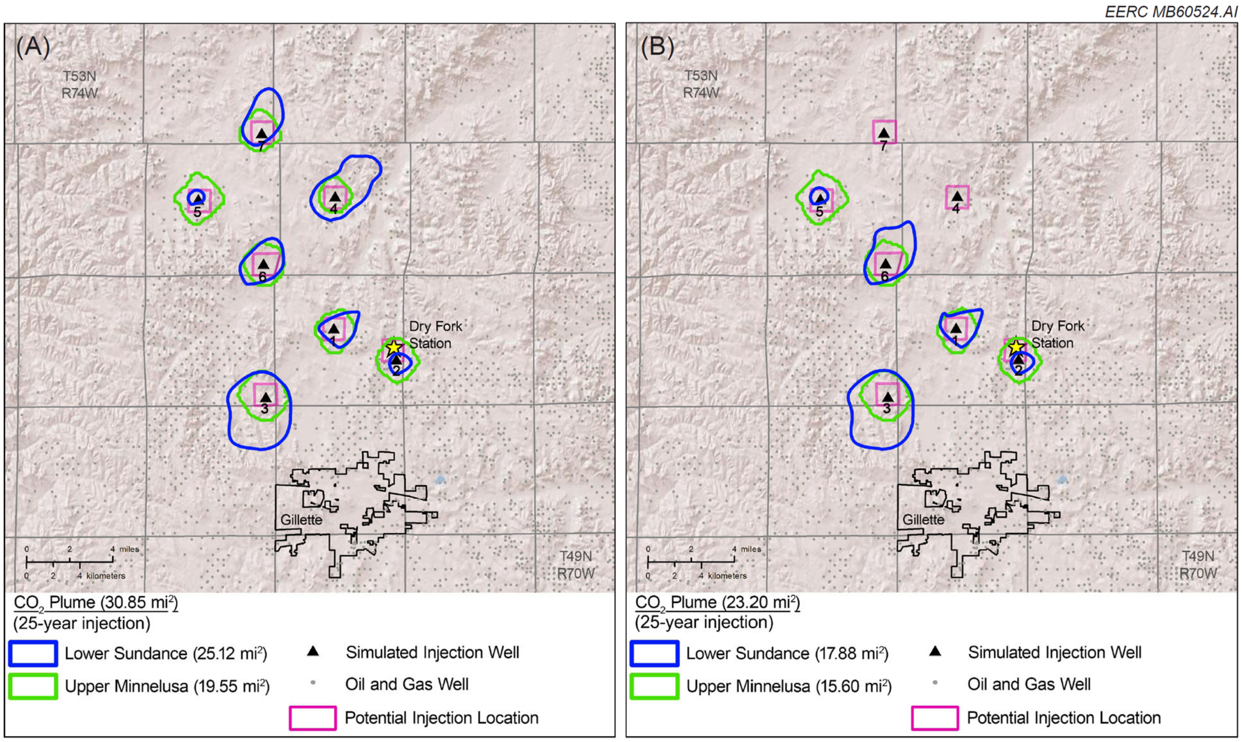

Figure 7. Wyoming CarbonSAFE simulated CO_2 injection plume maps. The results show CO_2 footprints resulting from a stacked storage approach considering injection within the Lower Sundance and Upper Minnelusa storage complexes for A) all seven injection sites, resulting in total simulated storage of 69.1 MMt, and B) five selected locations, resulting in simulated total storage of 53.7 MMt (modified from Quillinan and others, 2020).

for better characterization of formations by leveraging the collected well correlations, well logs, and petrophysical data. Any potential interference of oil in pore space in the Minnelusa that could affect mineral rights owners would need to be addressed before initiation of CO_2 injection.

North Dakota CarbonSAFE – Williston Basin

The Williston Basin of western North Dakota, eastern Montana, and southern Saskatchewan and Manitoba hosts multiple candidates for CO_2 storage that could be used in a stacked storage scenario. The most promising deep saline storage formations that have emerged through study are the Inyan Kara, Broom Creek, Black Island, and Deadwood Formations (Figure 8).

The Inyan Kara is a clastic formation that includes coarse to fine sandstones, siltstones, and shales (Bader, 2017). The Broom Creek Formation comprises mostly clastic sandstones and dolomitic sandstones with some interbeds of dolostones and anhydrite (Ziebarth, 1972; Rygh, 1990). The Black Island and Deadwood Formations are the deepest formations in the Williston Basin and range from clastic arenite sandstones and shales of the Black Island Formation to the interbedded sandstones, siltstones, and shales and carbonate beds of the Deadwood Formation

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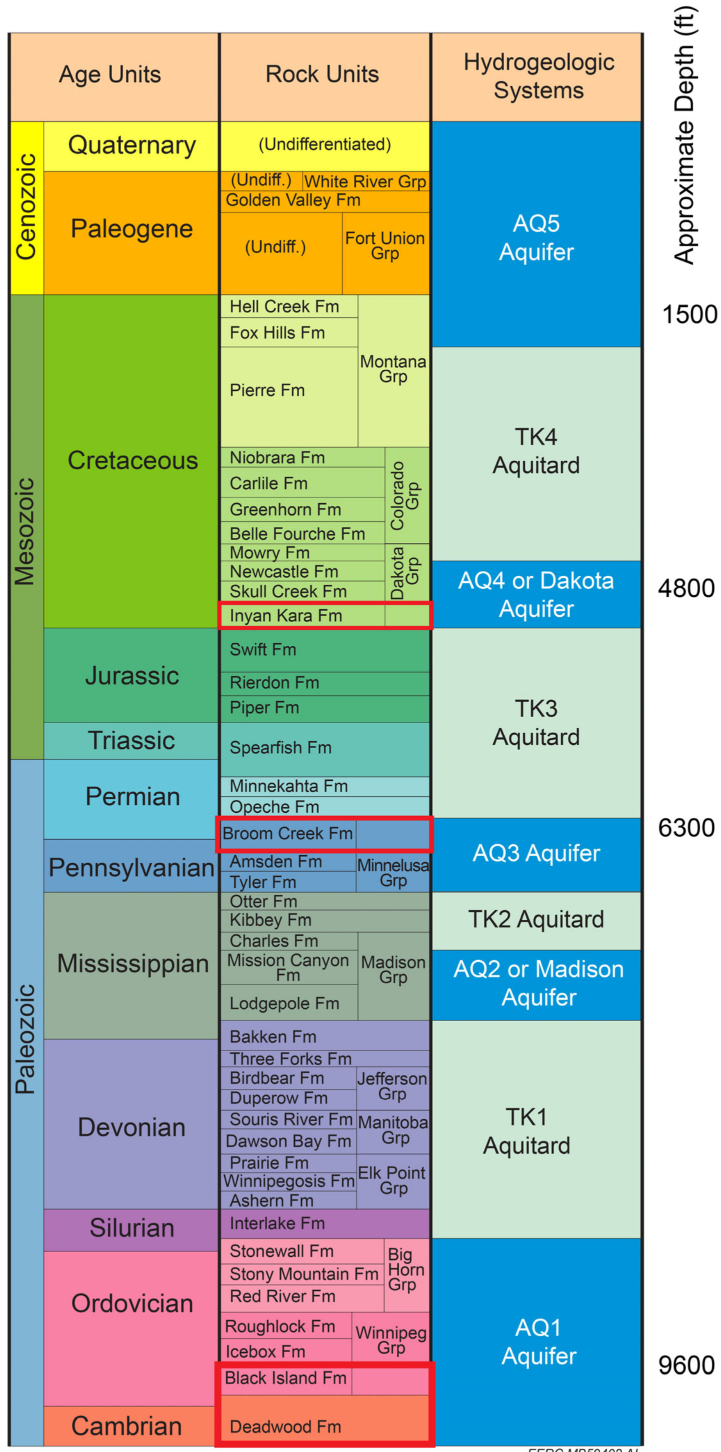

Figure 8. Williston Basin stratigraphic column with major aquifers and aquitards indicated. Red boxes indicate the targets assessed in North Dakota CarbonSAFE Phase II. Modified from Peck and others (2020) and Sorensen and others (2009).

(LeFever and others, 1987; Ellingson and LeFever, 1995). The Skull Creek Formation (shale) is the upper confining layer for the Inyan Kara. The shales of the Opeche and Spearfish Formations are the upper confining layer for the Broom Creek Formation. The Icebox Formation (shale) is the upper confining layer of the Black Island/Deadwood (Peck and others, 2020). A thick shale interval (~1000 feet) consisting of the Pierre, Greenhorn, and Mowry Formations is the secondary confining zone above the Inyan Kara. These confining formations ensure that any injected CO_2 will be isolated from the lowermost USDW in the Fox Hills Formation.

Under the DOE CarbonSAFE Program, the EERC performed a 2-year storage complex feasibility study that looked at CO_2 stacked storage in the above-mentioned formations. The planned source of captured CO_2 (3.5 MMT/yr) in this study is the Milton R. Young Station (MRYS) as part of Minnkota Power Cooperative's (Minnkota's) Project Tundra carbon capture and storage project. Well log and core data collected as part of the feasibility study indicated that together and in a stacked arrangement, the Broom Creek and Deadwood Formations beneath the vicinity of the MRYS could store 25 years of the planned CO_2 capture rate in two injection locations. For North Dakota CarbonSAFE/Project Tundra, stacked storage was investigated via reservoir simulation to reduce the number of acres required for pore space leasing and to leverage as much as possible acreage owned by Project Tundra partners.

Table 3 contains the summary of numerical simulation results of two scenarios modeled as part of the feasibility study. The results suggest the Broom Creek storage complex alone is adequate for storing the required volumes using four wells (Figure 9). For Scenario A, two of the four plumes for were shown to be mostly outside of partner-owned land to inject the required ~80 Mt CO_2. Scenario B incorporated the stacked storage concept and was investigated in an effort to reduce the surface acreage of the resulting plumes and to leverage the use of the partner-owned land, and still inject the required targeted mass of CO_2 (Peck and others, 2020). The Inyan Kara Formation was excluded from the CO_2 storage scenarios because it is being considered as the target horizon for a new wastewater injection well needed as part of the planned CO_2 capture facility.

Table 3. Summary of North Dakota CarbonSAFE Phase II Simulation Results (modified from Peck and others [2020])

Scenario	Formation	No. Wells and Configuration	CO_2 Stored, Mt	Total CO_2 Plume Area, mi^2
A	Broom Creek	Four verticals	101	19.9
B	Broom Creek	Two verticals	50	16.2
	Deadwood	Two horizontals	50	

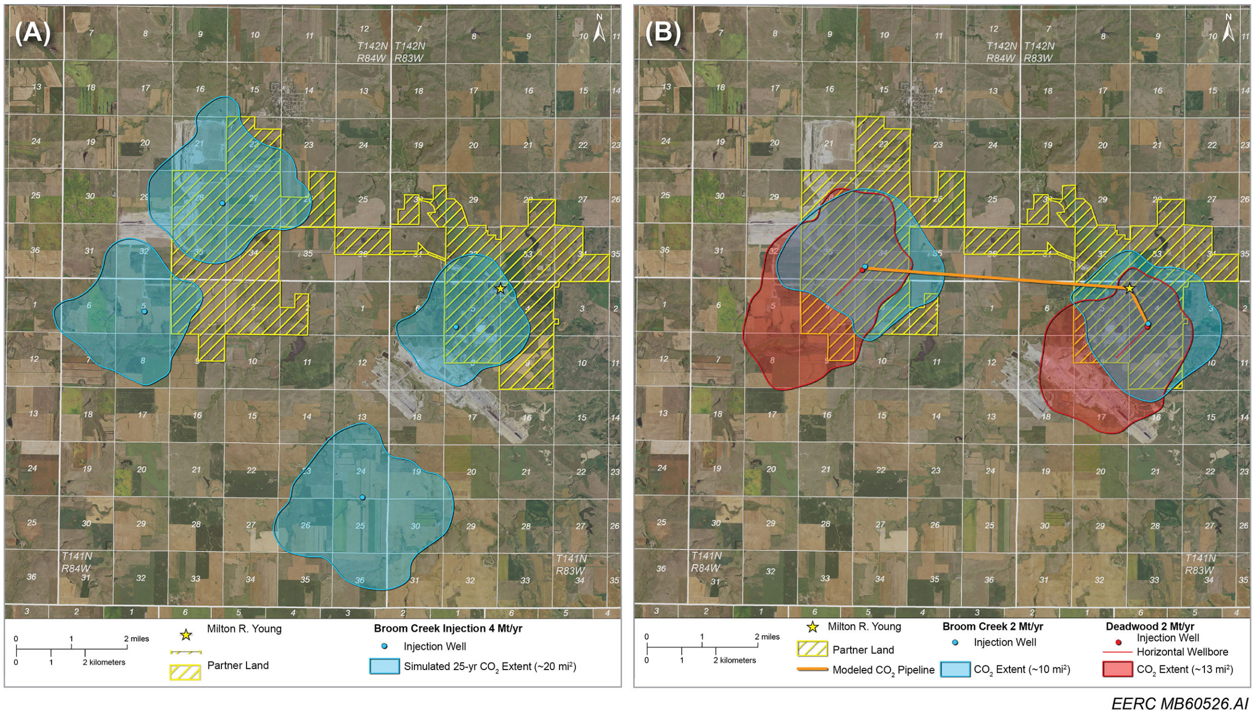

Figure 9. North Dakota CarbonSAFE simulated CO_2 footprint maps for two scenarios using different storage strategies. A) 101 Mt CO_2 injected with four vertical wells in the Broom Creek 4.0 km (2.5 mi) to 8.8 km (5.5 mi) apart. B) 100 Mt CO_2 injected with two multiwell pads into the Broom Creek and Deadwood 8 km (5 mi) apart (modified from Peck and others, 2020).

New site-specific geologic data gathered in 2020 as part of the Site Characterization and Capture Assessment phase of the CarbonSAFE Program provided greater insight into the geologic storage potential near MRYS. New core data from the Black Island/Deadwood interval and results of brine injection tests in the Broom Creek and Deadwood Formations were integrated into the geologic model and the resulting reservoir simulations suggest that the Broom Creek Formation alone may be able to accept the target rate of CO_2 injection via twin vertical wells from a single well pad adjected to MRYS. To account for uncertainty in the Broom Creek storage potential, the Black Island/Deadwood interval would also be permitted (Minnkota and others, 2021). Injection into this deeper horizon would be via a third well developed on the same pad. Thus stacked storage remains a vital CO_2 storage management plan for Minnkota's Project Tundra (Figure 10).

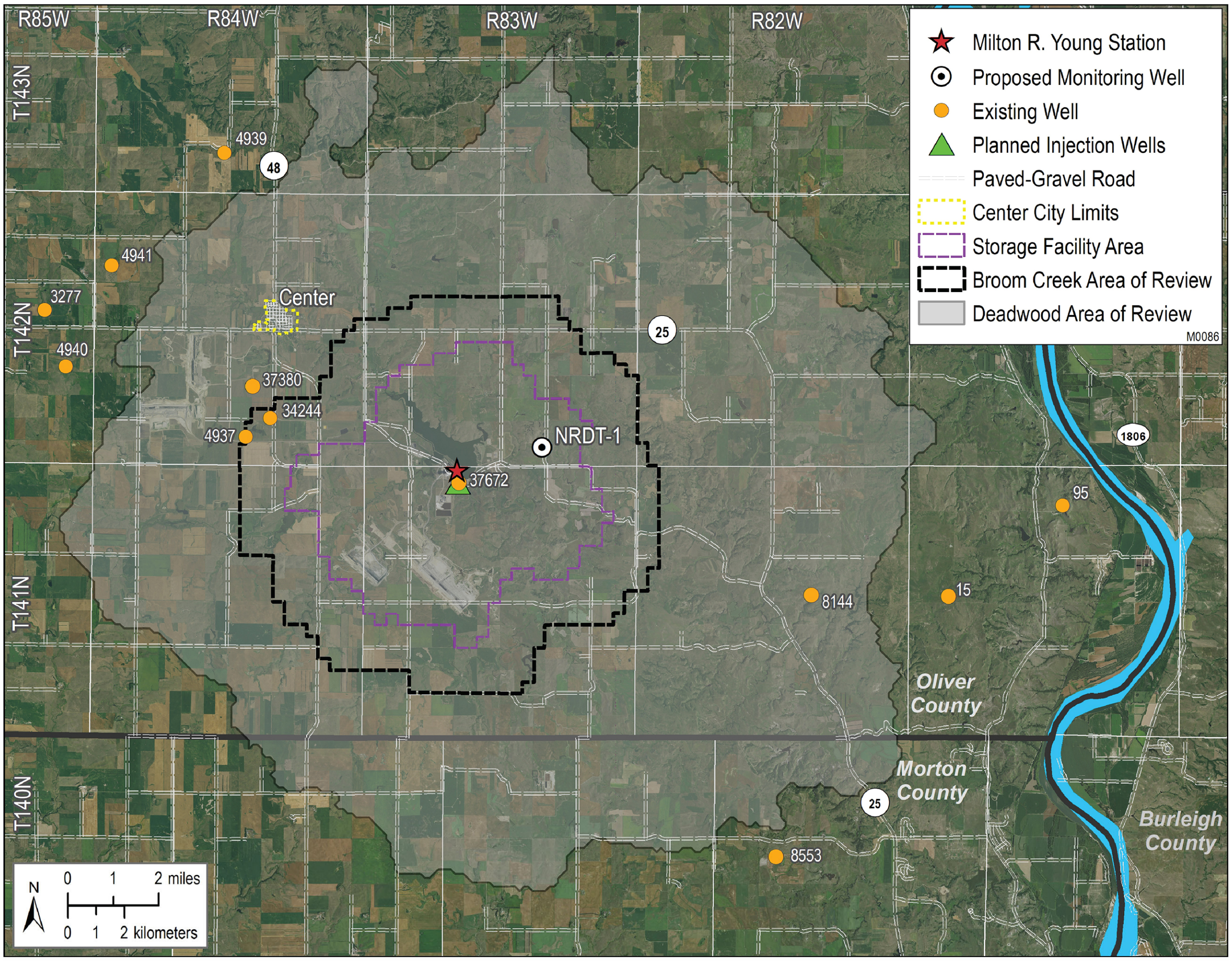

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Figure 10. The final proposed storage facility area for Project Tundra contains the extents of CO_2 plumes in both the Broom Creek and Deadwood Formations.

Nebraska/Midcontinent CarbonSAFE – Denver–Julesburg Basin

The Nebraska/Midcontinent CarbonSAFE project included assessing the capacity for CO_2 storage in southwestern Nebraska. The Cloverly and Cedar Hills Formations were assessed in the Nebraska Integrated Carbon Capture and Storage Pre-Feasibility Study (Figure 11) (Wildgust and others, 2018). The Madrid, Perkins County, Nebraska, study area and the Sleepy Hollow Field located in Red Willow County, Nebraska, were assessed for CO_2 storage as part of the Integrated Midcontinent Stacked Carbon Storage Hub (IMSCS-HUB) project Phase II for storage in the Permian and Pennsylvanian Formations (Figure 12; Walker, 2020; Dalkhaa and others, 2021).

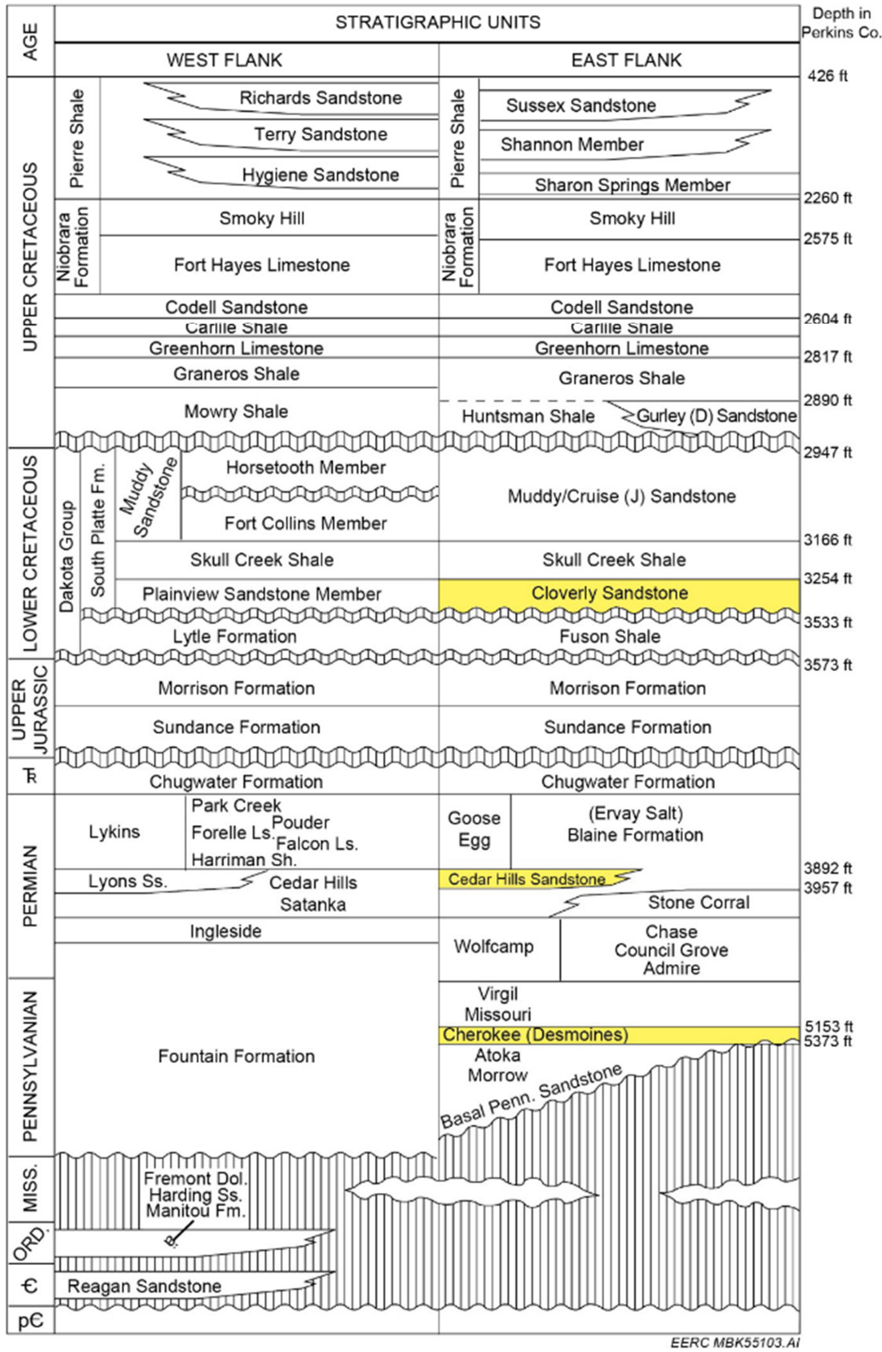

Figure 11. Stratigraphic column of the Denver–Julesburg Basin (modified from Higley and others, 1995). Colored intervals represent prospective CO_2 storage reservoirs discussed in Wildgust and others (2018). Depths are approximate for Madrid, Perkins County, Nebraska.

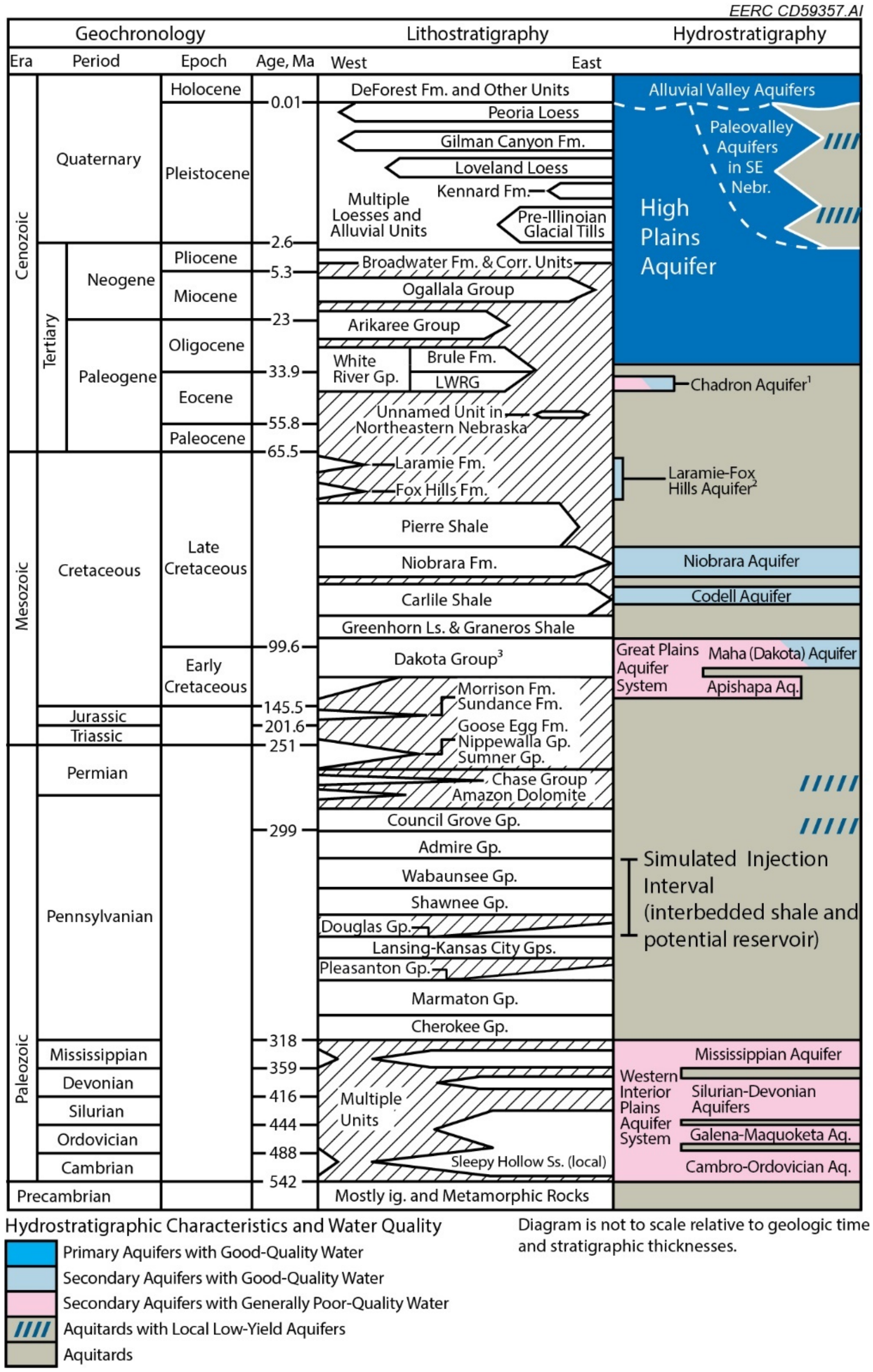

Figure 12. Generalized stratigraphic and hydrologic column of Nebraska (modified from Korus and Joeckel, 2011). Simulated injection intervals for the Sleepy Hollow Field located in Red Willow County, Nebraska, and the focus of the Nebraska/Midcontinent CarbonSAFE investigation are indicated in the hydrostratigraphy column.

This area of the Denver–Julesburg Basin is challenging for CO_2 storage because of the hydraulic connection of many of the Pennsylvanian formations. While stacked storage is possible, the Sleepy Hollow Field was found to be more attractive for CO_2 EOR, and saline formation CO_2 storage would likely result in less than 25 MMt without brine production (Walker, 2020; Dalkhaa and others, 2021). Numerical simulation predictions indicated the Madrid study area had potential to store an estimated 51 MMt of CO_2 over a 30-year period in the Cedar Hills Formation and the Cherokee and Lansing–Kansas City groups (Walker, 2020). Additional work in the future is suggested to determine the optimal methods to use stacked storage in this part of the basin.

Stacked Storage – Alberta Basin

Several formations have potential for use in CO_2 storage operations within the Alberta Basin. Bachu and others (2014) assessed Devonian saline formations in east-central Alberta for CO_2 storage potential (Figure 13). Because of a prominent geologic unconformity in the region, much of the Cretaceous-to-Devonian strata are not present. The area has 13 saline aquifers for potential stacked CO_2 storage, including the Wabamun, Blueridge, Nisku, Grosmont, Leduc, Cooking Lake, Moberly, Calumet, Slave Point, Swan Hills, Gilwood, Keg River, and Granite Wash aquifers. Bachu and others (2014) assessed the storage resource potential for these aquifers. The CO_2 storage resource potential assessment was made with screening criteria, including areas with aquifer depths greater than 1000 m (3280 ft), standoff from hydrocarbon resources, 4% porosity minimum cutoff, and temperature and pressure conditions keeping injected CO_2 in a supercritical state, with ten saline aquifers meeting all criteria (Table 4).

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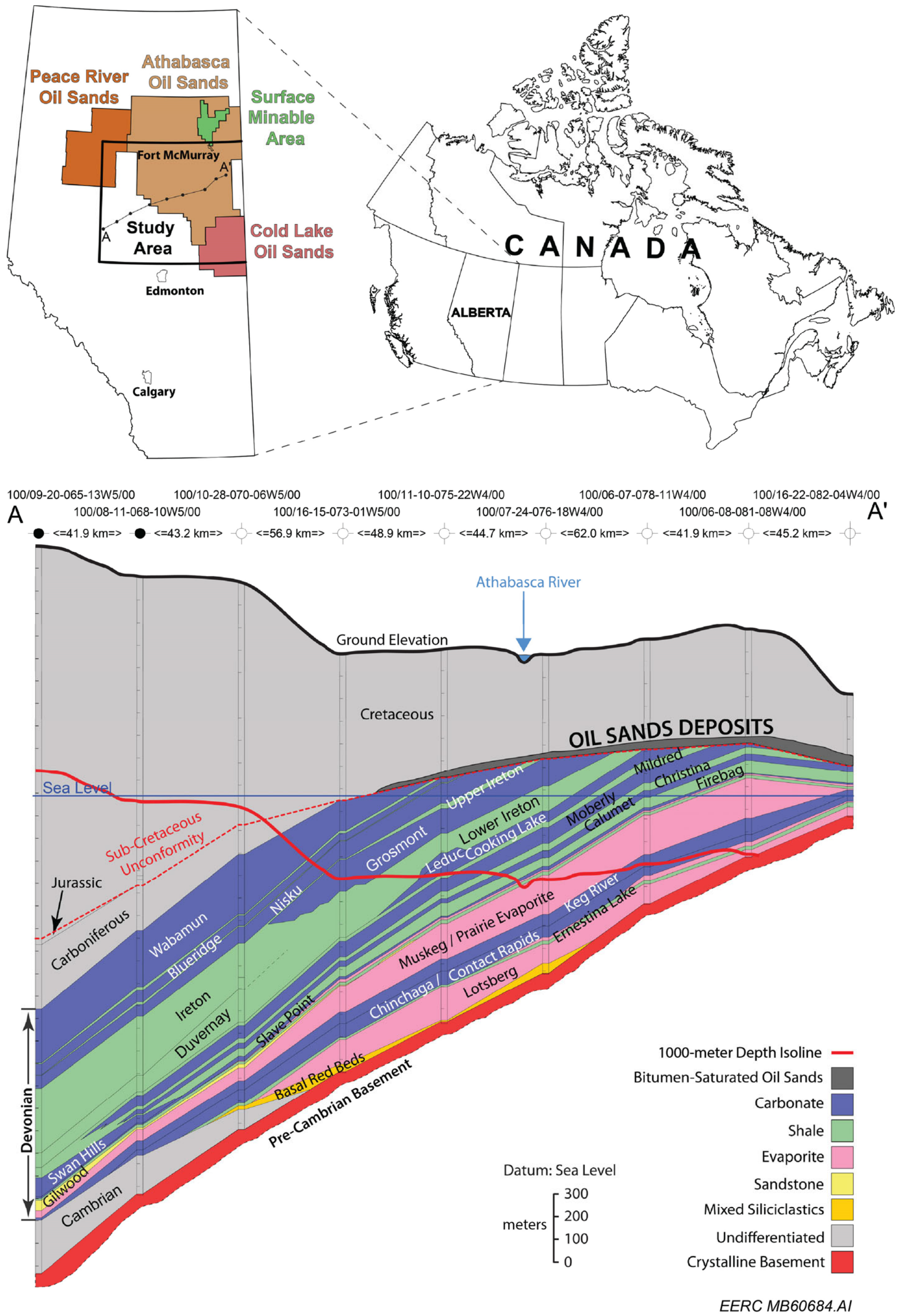

Figure 13. Location map and cross section of an area north of Edmonton, Alberta, Canada (modified from Bachu and others, 2014). The cross section runs generally west to east across the Alberta Basin. The carbonate and clastic reservoirs of the Devonian section provide potential stacked storage.

Table 4. CO_2 Storage Resource for the Devonian Saline Aquifers for the Study Area Used in Bachu and others (2014)

		CO₂ Storage Capacity, MMt					
Aquifer	**Area, km²**	**Whole Aquifer**	**At Depth >1000 m**	**After Resource Protection**	**After Porosity Cutoff**	**After CO_2 Phase Cutoff**	**In Prospective Areas**
Wabamun	64,832	4330.9	2601.6	2500.0	1851.4	1747.1	499.7
Blueridge	69,533	1657.1	1260.7	1260.7	1064.4	1040.3	397.2
Nisku	75,460	3130.9	2275.1	2274.8	2217.3	2115.6	200.5
Grosmont	48,102	1721.1	366.2	366.2	352.0	303.4	115.2
Leduc	5115	434.0	299.7	287.6	287.6	277.8	263.4
Cooking Lake	12,903	579.7	488.2	487.3	487.3	475.8	406.0
Moberly	105,510	4629.3	3279.6	3279.6	3197.7	3197.7	0.0
Calumet	101,524	1946.1	1431.0	1431.0	1379.4	1364.3	0.0
Slave Point	10,693	159.4	159.4	145.4	92.6	92.6	13.3
Swan Hills	7006	51.8	51.8	34.1	8.5	8.5	0.0
Gilwood	23,438	488.0	488.0	449.0	448.9	448.9	100.1
Keg River	114,963	10,734.9	7691.3	7674.4	7620.5	7620.5	1587.1
Granite Wash	16,368	533.3	533.3	512.3	504.3	504.3	150.4
Total		**30,396.5**	**20,925.8**	**20,702.4**	**19,511.9**	**19,196.1**	**3732.9**

A CO_2 storage potential of 3700 MMt was calculated for the area, and potential storage targets were mapped (Figure 14). Five areas provided a potential for stacked storage in the Devonian formations with the Basal Cambrian as another potential target below all prospective areas (Peck and others, 2014).

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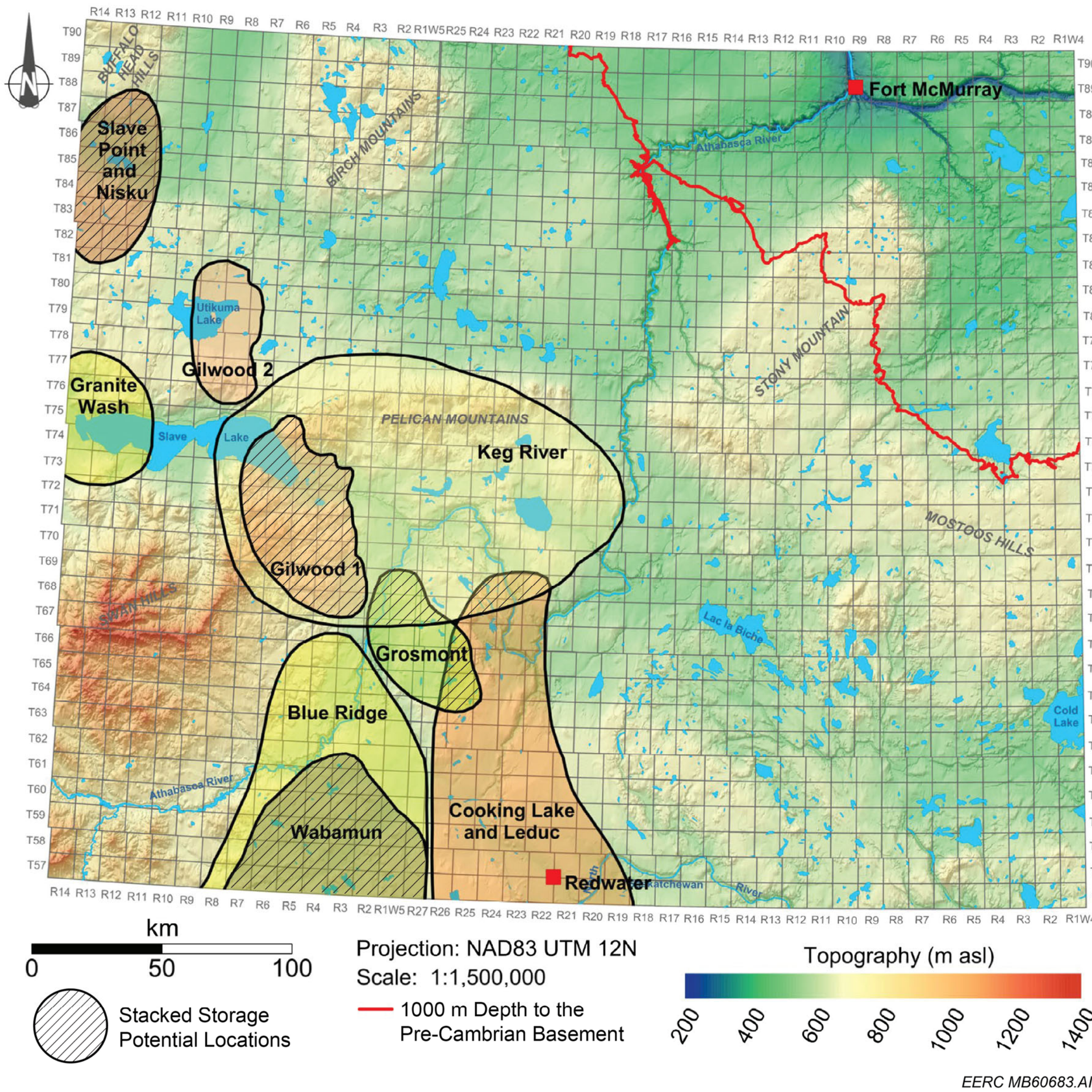

Figure 14. Map of study area from Bachu and others (2014) indicating areas of different potential saline storage formations. The formations depicted were screened for CO_2 storage criteria: regulatory, hydrocarbon protection, and geologic. Areas shown in blue hatched patterns are locations of more than one storage complex for potential stacked storage application in Devonian saline formations (modified from Bachu and others, 2014).

SUMMARY

Stacked storage is the storage of CO_2 using multiple storage complexes situated vertically in a stratigraphic column, potentially creating multilevel CO_2 plumes for a single storage facility. This report has reviewed many of the advantages and considerations associated with stacked storage and has summarized current projects within the PCOR Partnership region, applying the practice to meet storage project goals.

Advantages for Stacked Storage

- *Increased Pore Space Accessible for Storage*: Stacked storage allows for more effective use of available pore space, in comparison to scenarios where a single injection horizon is targeted, by enabling access to more of the total storage resource under a geographic area for a storage project. This can maximize storage resource potential while reducing the possibility and severity of impacts associated with injection from competing projects.

- *AOR and Monitoring Extent Reduction*: Stacked storage can reduce injected CO_2 footprints and the AOR extent for a storage project, potentially limiting the necessary monitoring and legacy well risk to comply with the EPA UIC Program Class VI (dedicated CO_2) injection well regulations.

- *Consolidation of Pore Space Leasing*: Stacked storage can result in a potentially smaller CO_2 footprint(s) and relatively fewer impacted landowners, which has the potential to increase likelihood of achieving required pore space consent and may help maintain plumes within a specific geographic area.

- *Surface Facilities Efficiency Gains*: Surface infrastructure to inject CO_2 into multiple reservoirs can be consolidated to multiwell pads (i.e., a single pad location that contains multiple wells) to save capital and operational expenses through consolidated on-site CO_2-handling facilities, reduced distributary pipeline spans, and a decreased land use footprint.

Considerations for Stacked Storage

- *Multiwell Pad Design*: For a stacked storage multiwell pad, each well is required to have corrosion-resistant materials for cementing and casing products across every zone of injection and the corresponding confining layers. This is expected to increase costs for well construction for each additional storage complex accessed.

- *Multireservoir Well Completions*: Injection wells with multizone completions (i.e., a single well completed in a manner that it can access multiple zones) are not recommended given difficulties and risks associated with complex injection operations, well maintenance, and required injection well mechanical integrity demonstration under the UIC Class VI regulations.

- *Multiple Well Injection Pressure*: Differences in injection zone depths in stacked storage scenarios will likely require each well to have different wellhead pressures. Multiwell pads need the necessary equipment on-site to adjust CO_2 pipeline delivery pressure to accommodate the requirements for each storage formation injection well.

- *Project Area Optimization*: Equalizing AOR and/or injected CO_2 footprints between stacked storage intervals can help optimize a project area and alleviate challenges associated with permitting, monitoring, landowner consent, and other important project considerations. Adjusting operational parameters (e.g., injection rates) may be required to ensure pressure fronts and injected CO_2 plumes within each storage unit remain consistent in areal extent.

- *Seismic Monitoring of Vertically Stacked Plumes*: Seismic monitoring is one approach to ensure compliance with UIC Class VI regulations, with proven potential in monitoring injected CO_2 within a geologic storage complex. Stacked storage adds a complexity with multiple plumes, and adequate vertical separation between reservoirs is necessary to minimize interference of the waveform signal. Multiple geophysical technologies have been identified to differentiate CO_2 saturations in stacked reservoirs, but modeling will be necessary to alleviate the uncertainties associated with close plumes for time-lapse monitoring and allow for a better understanding of the vertical and lateral changes expected.

- *Legacy Well Integrity*: Legacy wellbores intersecting injected CO_2 plumes and associated areas experiencing pressure buildup from injection represent containment control risks. These risks are compounded with multiple reservoirs receiving CO_2 injection during stacked storage and will require greater inspection of legacy wellbores for compliance with UIC Class VI AOR regulation.

- *Regulatory Requirements*: No specific additional regulatory requirements for stacked storage beyond those that apply to any CCUS project. The regulatory permitting authority that has the flexibility to evaluate stacked storage projects by separating out sections of a permit that are unique compared to other portions that encompass the CCUS project as whole will be able efficiently review and evaluate multiple permits at once by eliminating redundant sections of the permit.

To this date, stacked storage projects have yet to start operating in the PCOR Partnership region. Multiple projects are in various stages of development with several considering stacked storage scenarios. The Wyoming CarbonSAFE and North Dakota CarbonSAFE projects are currently in development and are expected to take advantage of available stacked storage in the Powder River and Williston Basins, respectively. The Nebraska CarbonSAFE project is still evaluating Denver–Julesburg Basin potential. The Alberta Basin is estimated to have a large, stacked capacity for the ten deep saline aquifers. As these projects come online and begin injecting into multiple reservoirs, the advantages and concerns discussed within this report will be tested and assessed. Lessons learned from these projects will provide additional guidance for future stacked storage projects.

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