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CO_2 storage resource potential of the Cambro-Ordovician Saline System in the we stern interior of North America

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Abstract

A 3-year binational effort between the United States and Canada was initiated to characterize the lowermost saline system in the northern Great Plains–Prairie region of North America and determine its CO_2 storage capacity. This saline system covers an area of 1.34 million km^2 from northern South Dakota in the United States to central Alberta and Saskatchewan in Canada. This basal system, overlain mostly by shales and comprising Middle Cambrian to Ordovician sandstones and carbonates that overlie the crystalline Precambrian basement, crops out in recharge areas in South Dakota and Montana and in discharge areas in Manitoba. Pressures in the system follow a gradient of 10.8 kPa/m. Temperatures vary from greater than 150°C in the deepest part of the system to less than 10°C in outcrop areas. Water salinity ranges from greater than 300,000 mg/L in central Alberta and in North Dakota to less than 10,000 mg/L in recharge and discharge areas. Porosity varies from less than 1% in very deep regions to more than 25% in shallower regions. The area of the basal saline system suitable for CO_2 storage was determined using the following criteria: a) CO_2 should be stored at a distance greater than 20 km from the 10,000 mg/L water salinity isoline, to protect groundwater resources; b) porosity should be greater than 4%, to ensure storage capacity and injectivity; and c) CO_2 should be always in dense phase. The storage capacity in the area of the saline system thus determined as suitable for CO_2 storage was estimated using thickness, porosity, and CO_2 density calculated at in situ conditions, and a storage efficiency coefficient of 2.4%, resulting in a storage capacity of 113 Gt CO_2 with P50 confidence.

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1. Introduction

A binational effort between the United States and Canada was initiated to characterize the lowermost saline formation in the Williston and Alberta Basins of the northern Great Plains–Prairie region of North America and determine its CO_2 storage resource. This saline system extends from northern South Dakota in the United States to central Alberta and Saskatchewan in Canada, covering an area of 1.34 million km^2 (Figure 1). The goal of this 3-year project is to determine the potential for, and effects of, geological storage of CO_2 in Cambrian-to-Ordovician rocks at the base of the sedimentary succession. To date, no other studies have attempted to characterize on a regional scale the storage potential of such large, deep saline systems across an international border. This multiprovince/multistate, multiorganizational, and multidisciplinary project is led on the U.S. side by the Plains CO_2 Reduction (PCOR) Partnership at the University of North Dakota Energy & Environmental Research Center (EERC) and on the Canadian side by Alberta Innovates–Technology Futures (AITF). The PCOR Partnership is one of seven regional partnerships under the U.S. Department of Energy (DOE) National Energy Technology Laboratory's (NETL's) Regional Carbon Sequestration Partnership (RCSP) Program. NETL and RCSP are part of DOE's Office of Fossil Energy.

The central interior portion of North America covered in this report encompasses the northern Great Plains–Prairie region of the United States and Canada. This region of North America is generally characterized by broad expanses of relatively flat land covered by prairie, steppe, and grassland and is bounded by the Canadian Shield to the northeast, the Rocky Mountains to the west, and the central lowlands of Minnesota and Iowa to the southeast. In addition to having a strong agricultural focus, this region is also home to a robust energy industry that includes coal, oil, and gas development. The abundant energy resources of this area have resulted in the establishment of many large-scale CO_2 sources such as coal-fired power plants and refineries. This region of North America is underlain by the deep, broad Alberta and Williston sedimentary basins that have accumulated a thick sequence of alternating layers of sandstone-, carbonate-, and shale-dominated formations. These configurations of rock form promising opportunities for the geologic storage of CO_2. Carbon capture and storage in geological media is a short-to-medium term technology that can significantly reduce atmospheric emission of anthropogenic CO_2. Compared with oil and gas reservoirs, deep saline systems are less well known and have received less attention in terms of their properties.

At the base of the sedimentary succession in the Williston and Alberta basins of the northern Great Plains–Prairie region of North America there is a saline system, referred to as the Cambro-Ordovician Saline System (COSS), composed of variable lithology that includes a variety of clastic and carbonate facies deposited across a range of environments. This system lies directly on top of igneous and metamorphic basement rocks and is largely contained beneath sealing formations that include shales and tight carbonates. These Middle Cambrian- to Lower Silurian-aged rocks extend from west-central Alberta into Saskatchewan, southwestern Manitoba, and then south into Montana, North Dakota, and South Dakota and form an extensive saline system generally devoid of hydrocarbon resources. In the 1.34 million km^2 area underlain by the COSS there are 42 large CO_2 sources that each emit more than 0.75 Mt CO_2/year (Figure 1), for a total of ~144 Mt CO_2/year. Assuming that all of these emissions from each of these sources will be stored in the COSS, the main questions to be addressed by this study are 1) what is the CO_2 storage resource of the system? 2) how many years of CO_2 emissions will it be capable of storing? and 3) what will be the fate and effects of the stored CO_2?

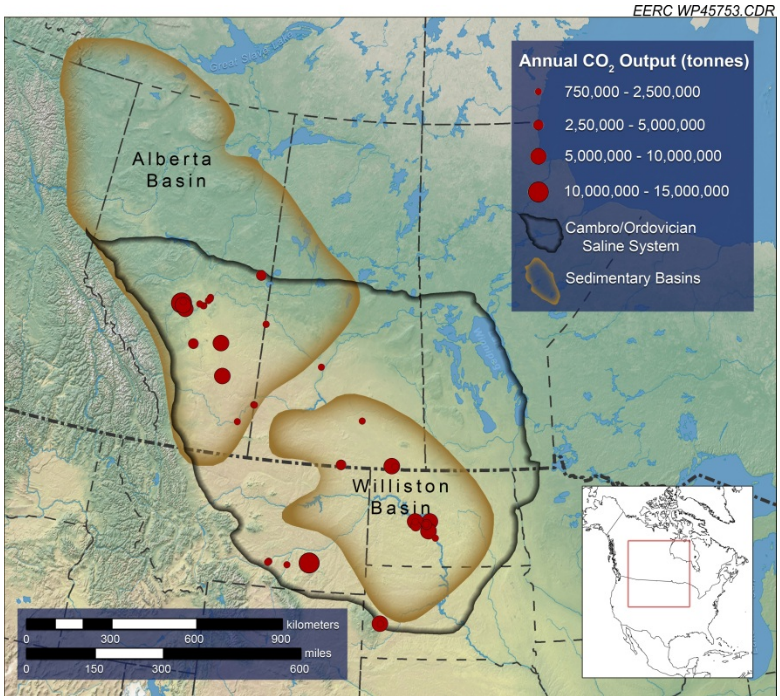


Fig. 1. Location and areal extent of the Cambro-Ordovician Saline System (COSS) in the northern Great Plains–Prairie region of North America, and location and size of major CO_2 sources

2. Geological setting

The COSS comprises several diachronous rock units of variable lithology: the Middle Cambrian Basal Sandstone in the Alberta Basin adjacent to the Middle Cambrian Flathead Formation in Montana, and the Late Cambrian Deadwood and Middle Ordovician Black Island Formation in Saskatchewan, Manitoba, and the Dakotas. These strata are overlain by Upper Ordovician and Lower Silurian carbonates (Figure 2). The COSS is overlain by Cambrian shales in the Alberta Basin and by Ordovician shales or Middle Devonian tight shaley carbonates in the Williston Basin. The COSS reaches depths of more than 5000 m near the Rocky Mountain Thrust and Fold belt in the Alberta Basin and nearly 4900 m at the depocenter of the Williston Basin. The rock sequence crops out in recharge areas in South Dakota and Montana and in discharge areas in south-central to southeastern Manitoba where it is a source of fresh groundwater [1].

Most of the geologic characteristics of the COSS can be attributed to major changes in sea level, subsidence of the Williston and Alberta Basins, and intermittent reactivation of Precambrian basement structural features. Two major transgressions and regressions occurred within the study area from the Cambrian through the Devonian, correlating to two major unconformities and depositional sequences. Subsidence of the Williston and Alberta Basins and intermittent reactivation of Precambrian basement features have affected the thicknesses, porosity, and facies distribution of sediments from all three sequences throughout the study area.

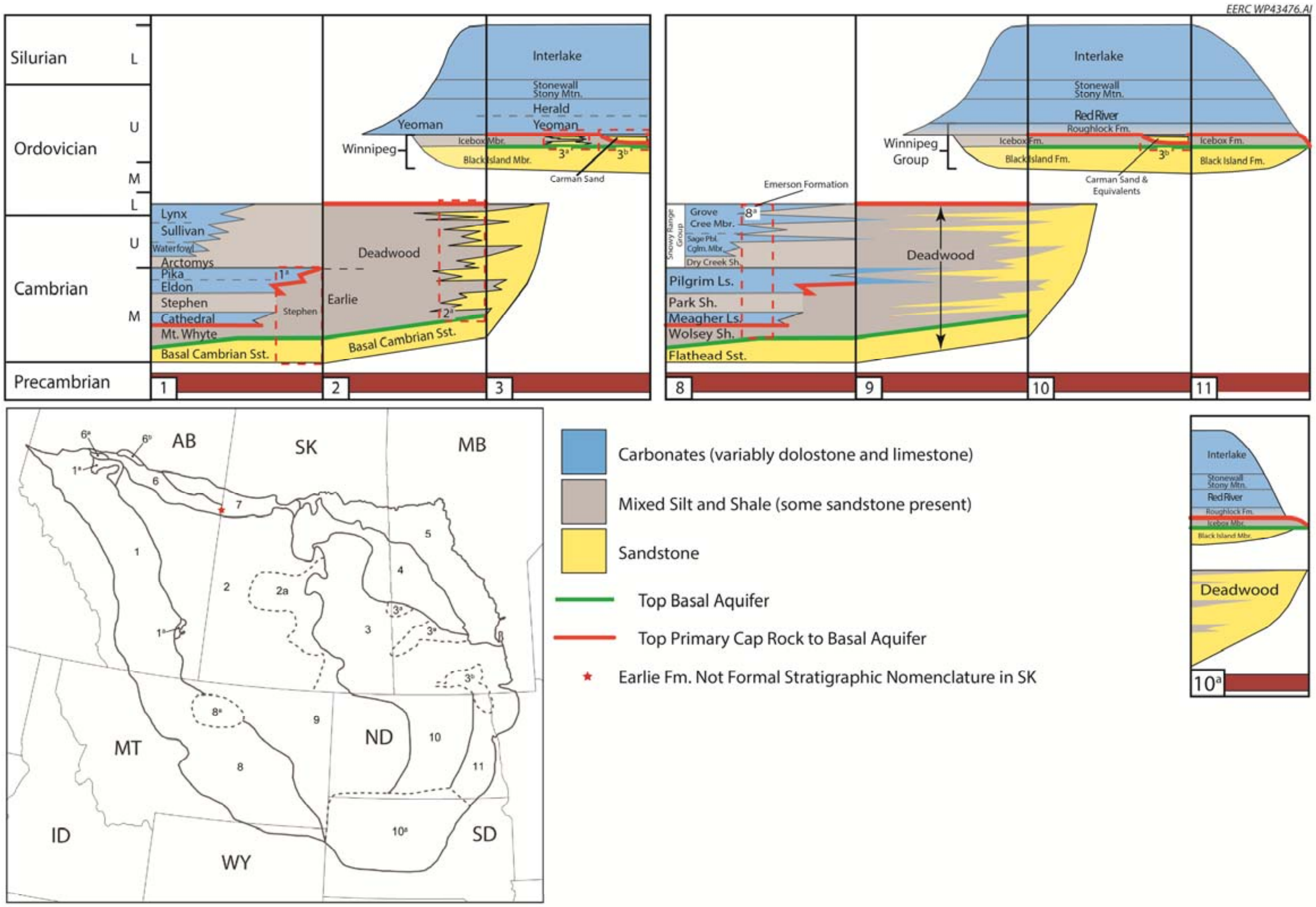
3. Methodology

A primary product of this research project to date is the creation of a CO_2 storage resource distribution map of the COSS. To create this map, a 2-D geologic model of the COSS was developed through integration of data derived from deep wells drilled as part of hydrocarbon exploration and production activities. The 2-D geologic model for the Canadian side of the COSS study region was completed by AITF independently and prior to the EERC effort. AITF had finalized raster GIS maps for the CO_2 storage resource distribution and each of the variables needed to calculate CO_2 storage resource of the COSS. This meant that the effort to seamlessly combine the two sides required generating the maps of property distribution on the U.S. side with a strong influence by the Canadian data along the U.S.–Canada border. This approach ensured that the spatial propagation of the values for parameters such as thickness, porosity, and CO_2 density on the U.S. side near the Canadian border would honor the existing data distribution on the Canadian side and create seamless maps of properties and CO_2 storage distributions.

The methodology used in this study to calculate the volumetric CO_2 storage resource capacity follows the approach described in the third edition of the *Carbon Sequestration Atlas of North America* [2], which builds on earlier CO_2 storage resource calculation work [3, 4]. Discussion of details involved in calculating the storage resource potential of saline formations is covered well in several publications [2–6]. The volumetric equation to calculate the CO_2 storage resource mass estimate for geologic storage in saline formations is:

$$MCO_2e = A \times h \times \phi \times \rho CO_2 \times E$$

The total area (A), gross formation thickness (h), and total porosity (ϕ) terms account for the total bulk volume of pore space available. The value for CO_2 density (ρ) at in situ conditions converts the reservoir volume of CO_2 to mass. The storage efficiency factor (E) reflects the fraction of the total pore volume that will be occupied by the injected CO_2. For saline formations, the CO_2 storage efficiency factor is a function of geologic parameters, such as area, gross thickness, and total porosity that reflect the percentage of volume amenable to CO_2 storage, and displacement efficiency components that reflect different physical barriers inhibiting CO_2 from contacting 100% of the pore volume of a storage unit. Volumetric methods are applied when it is generally assumed that the formation is open, as in the case of the COSS [7–9] and that formation fluids are displaced from the formation or managed via water production.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Silurian
L
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Precambrian
Interlake
Stonewall
Stony Mtn.
Herald
Yeoman
Yeoman
Winnipeg
Icebox Mbr.
Black Island Mbr.
Carman Sand
Lynx
Sullivan
Waterfowl
Arctomys
Pika
Eldon
Stephen
Cathedral
Mt. Whyte
Basal Cambrian Sst.
Stephen
Earlie
Deadwood
Basal Cambrian Sst.
1
2
3
Emerson Formation
Snowy Range Group
Grove
Cree Mbr.
Sage Pbl. Cglm. Mbr.
Dry Creek Sh.
Pilgrim Ls.
Park Sh.
Meagher Ls.
Wolsey Sh.
Flathead Sst.
Deadwood
Winnipeg Group
Red River
Roughlock Fm.
Icebox Fm.
Black Island Fm.
Carman Sand & Equivalents
8
9
10
11
AB
SK
MB
MT
ND
ID
WY
SD
Carbonates (variably dolostone and limestone)
Mixed Silt and Shale (some sandstone present)
Sandstone
Top Basal Aquifer
Top Primary Cap Rock to Basal Aquifer
Earlie Fm. Not Formal Stratigraphic Nomenclature in SK
Interlake
Stonewall
Stony Mtn.
Red River
Roughlock Fm.
Icebox Mbr.
Black Island Mbr.
Deadwood
10a

Fig. 2. Stratigraphic correlation and nomenclature chart for the Cambrian-Silurian sedimentary succession across various regions of the northern Great Plains–Prairie region of North America. The numbers on each stratigraphic column correlate to a region on the map

The storage efficiency factors used in this study were taken from Goodman et al. [6], where a range of efficiency factors for a variety of lithologies for the P10, P50, and P90 probability categories was established. The 2.4% value represents the P50 value for siliciclastics, which constitute the dominant lithology of the COSS. The methodology used in this project produced high-level, basin/regional-scale, CO_2 resource estimates of potential geologic storage. This would be considered the effective storage resource [6]. The degree of uncertainty associated with this approach means that these estimates should not be used as a substitute for site-specific characterization and assessments.

The area of the COSS suitable for CO_2 storage was determined based on water salinity >10,000 mg/L to protect groundwater resources [10], vertically averaged porosity >4%, and a requirement that CO_2 be in dense phase. The "open" system methodology used in this study for the CO_2 storage efficiency coefficient E uses total porosity (ϕ). With some minor exceptions, total porosity was derived from density logs. Well file data containing core porosity and core grain density were obtained from state and provincial regulatory agencies. A total of 222 wells (128 in Canada and in 94 the United States) with core analyses, LAS file, or both, were used in the determination of total porosity, which was vertically averaged. Well-averaged porosity in the COSS varies from 1% in deep regions to 25% in shallower regions. Areas with average density of <4% were considered as not suitable for CO_2 storage.

Water salinity in this system increases with depth, ranging from values <10,000 mg/L in recharge and discharge areas to values >350,000 mg/L in the Alberta and Williston Basins [7–9]. The delineation of the 10,000 mg/L salinity isoline is based on drillstem tests from several wells in Montana, North Dakota, and South Dakota and on earlier work by the U.S. Geological Survey [9]. Mapped areas outside the 10,000 mg/L isoline were clipped out of the preliminary modeling results, removing from consideration a significant portion of the COSS in east-central Montana, southeastern North Dakota, and central Manitoba. Figure 3a shows the distribution of water salinity (total dissolved solids) in the COSS.

Pressures, with an initial gradient of 10.8 kPa/m (Figure 3b), were assumed to increase to 11.5 kPa/m as a result of CO_2 storage, and temperatures at the top of COSS were determined from drillstem tests and bottomhole temperature measurements. The distribution of CO_2 density at the top of the COSS was calculated on the basis of these pressures and temperatures using the equation of state from Span and Wagner [11]. Shallower areas, where CO_2 at the top of the COSS would be in gaseous phase, were also considered as not suitable for CO_2 storage. This reduced the area of the COSS suitable for CO_2 storage from the 1.34 million km^2 extent of the COSS to 700,000 km^2 (Figure 4).

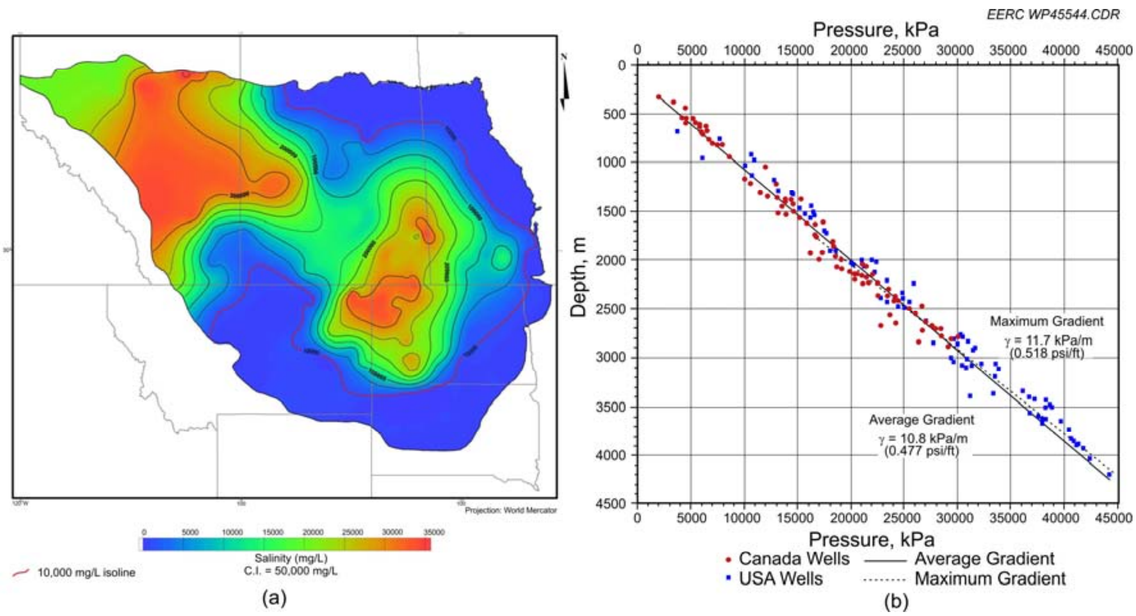

Fig. 3. Hydrogeological characteristics of the COSS in the northern Great Plains–Prairie region of North America: a) areal variation of water salinity (total dissolved solids), and b) pressure variation with depth. The red line in Figure 3a indicates the 10,000 mg/L isoline

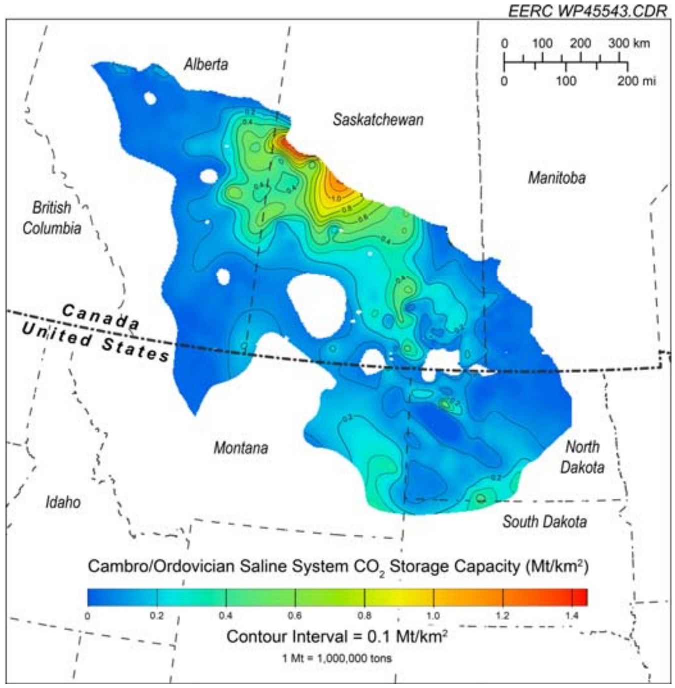

Fig. 4. Area suitable for CO_2 storage and distribution of the CO_2 storage resource at P50 probability in the COSS in the northern Great Plains–Prairie region of North America

4. Results and next steps

Previous efforts in this region and elsewhere in the world to map the distribution of various geological entities and parameters, and resource distributions, across international or even provincial or state boundaries have resulted in artificial "fault lines" (discontinuities) at the border. Evaluating the CO_2 storage resource and effects of CO_2 storage in a basin straddling a border should not be done in isolation, but through collaboration of organizations and agencies on both sides of the respective border.

To ensure that an international "fault line" was not part of the final product in the case of the Cambro-Ordovician Saline System of the northern Great Plains–Prairie region of North America, significant effort was expended to match the work done on the U.S. side of the study region with the data sets generated on the Canadian side. A diffusive aggregation method was successfully employed near the U.S.–Canadian border to form a seamless 2-D geologic model and CO_2 storage distribution map for the entire COSS international study region.

The integration of the various datasets of spatially distributed geologic properties of the COSS results in a CO_2 storage resource value of 113 Gt CO_2 (28 Gt and 85 Gt for the U.S. and Canadian sides of the COSS, respectively). This value represents the P50 confidence level as indicated by the 2.4% efficiency factor used in the calculation. The spatial distribution of this CO_2 storage resource is represented in Figure 4. This final map illustrates the seamless spatial distribution and variability of the geologic storage resource of the COSS across the northern Great Plains–Prairie region of North America. The distribution of CO_2 storage resource estimates for the U.S. and Canadian portions of the COSS based on the P10, P50, and P90 probability levels [8] is shown in Table 1. Assuming no increase in CO_2 emissions from the large stationary sources in the region and a capture efficiency of 90% [12], the P50 storage resource identified in this study will suffice to store CO_2 from these sources for 784 years.

The groundwork and success of this effort serve as the foundation of the next step in this project. Work now continues toward a comprehensive, seamless 3-D model of the COSS that will take into account the internal heterogeneity of complex facies relationships that exist vertically and laterally through the COSS. It is expected that much of the porosity for many of the individual sand bodies that was lost or diminished through the process of creating well-averaged values for the 2-D model will contribute significantly to the CO_2 storage resource in the 3-D model.

Table 1. Range of CO_2 storage resource estimates for the portion of the COSS suitable for CO_2 storage at the P10, P50, and P90 probability levels

Probability		P10	P50	P90
Saline formation efficiency factor		1.2%	2.4%	4.1%
CO_2 storage resource	United States	14 Gt	28 Gt	48 Gt
	Canada	43 Gt	85 Gt	145 Gt
	Total	57 Gt	113 Gt	193 Gt

In regard to the effects of injecting CO_2 in this deep saline system, geochemical modeling for several potential storage sites on the Canadian side [12] has shown that the amount of CO_2 that can ultimately be fixed by geochemical reactions is reduced because of the low reactivity of the rocks and high water salinity in the system. The amount of CO_2 that will be trapped through dissolution and mineralization during the early phases of a storage project (CO_2 injection and the following closure period) will be negligible. This allows decoupling of flow and geochemical processes in modeling the effects of injecting CO_2 in the Cambro-Ordovician Saline System of the northern Great Plains–Prairie region of North America. Modeling the flow effects of storing CO_2 in this deep saline system will be undertaken next.

Acknowledgements

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Disclaimer

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