# GEOLOGICAL CHARACTERIZATION OF THE BASAL CAMBRIAN SYSTEM IN THE WILLISTON BASIN

**Plains $CO_2$ Reduction (PCOR) Partnership Phase III**
**Task 16 – Deliverable D91**

*Prepared for:*

Andrea T. McNemar

National Energy Technology Laboratory
U.S. Department of Energy
3610 Collins Ferry Road
PO Box 880
Morgantown, WV 26507-0880

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*Prepared by:*

Wesley D. Peck
Chad M. Crotty
Damion J. Knudsen
James A. Sorensen
Charles D. Gorecki
Edward N. Steadman

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

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PCOR Partnership
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Energy & Environmental Research Center (EERC)

# GEOLOGICAL CHARACTERIZATION OF THE BASAL CAMBRIAN SYSTEM IN THE WILLISTON BASIN

## EXECUTIVE SUMMARY

A binational effort between the United States and Canada is under way to characterize the lowermost saline system in the Williston and Alberta Basins of the northern Great Plains–Prairie region of North America in the United States and Canada. This 3-year project is being conducted with the goal of determining the potential for geologic storage of $CO_2$ in rock formations of the 1.34-million-km$^2$ Cambro-Ordovician Saline System (COSS). To our knowledge, no other studies have attempted to characterize the storage potential of large, deep saline systems that span the U.S.–Canada international border. This multiprovince/multistate, multiorganizational, and multidisciplinary project is led on the U.S. side by the Energy & Environmental Research Center (EERC) through the Plains $CO_2$ Reduction (PCOR) Partnership and on the Canadian side by Alberta Innovates Technology Futures (AITF). The project objectives are to characterize this basal system in the northern Great Plains–Prairie region of North America and to evaluate its potential for, and effects of, $CO_2$ storage in this system.

At the base of the sedimentary succession in the Williston and Alberta Basins of the northern Great Plains–Prairie region of North America is a saline system composed of variable lithology which 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 area underlain by the COSS, there are 43 large $CO_2$ sources that each emit more than 0.75 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 storage resource of the system?, 2) how many years of $CO_2$ emissions will it be capable of storing?, and 3) what will the fate and effects of the stored $CO_2$ be?

The project started on October 1, 2010, and is structured in three 1-year phases. Phase I focused on delineating and characterizing separately the Canadian and U.S. portions of the COSS. These were subsequently brought together into a single model during Phase II. The completed 2-D model incorporates the geologic data collected in the baseline characterization effort and distributes the various rock properties throughout the study region through geostatistical methods. Data on depth, thickness, and porosity were distilled to produce components needed to compute the $CO_2$ storage resource of this saline system following the $E_{saline}$ formula detailed by the U.S. Department of Energy (DOE) methodology. A significant part of the effort was to match the work done on the U.S. side of the study region with the data sets generated by AITF for the Canadian side. All necessary gridded interpolations on the U.S. side were combined with the Canadian grids by a diffusive aggregation method near the U.S.–Canadian border to form a seamless $CO_2$ storage volume for the entire COSS international study region. This aggregation method involved feathering the Canadian data near the border and joining it to the data on the U.S. side, thus allowing the geostatistical processing functions to interpolate across the border and avoid the development of edge effect at the border. Once the calculation on the U.S. side was completed, it was clipped out and joined to the existing Canadian portion to form a seamless map. This novel approach worked well for joining the two data sets, and the resulting 2-D model indicated a storage resource of 113 Gt. This work also provides the groundwork for the development of a massive 3-D geologic model encompassing the entire study area.

In addition to the leading organizations of the EERC and AITF, other partners in the project are DOE, Lawrence Berkeley National Laboratory, and Princeton University in the United States and Saskatchewan Industry and Resources, Manitoba Water Stewardship, Manitoba Innovation – Energy and Mines, CanmetENERGY, Natural Resources Canada, TOTAL E&P Ltd., and the University of Regina Petroleum Technology Research Centre in Canada.

# GEOLOGICAL CHARACTERIZATION OF THE BASAL CAMBRIAN SYSTEM IN THE WILLISTON BASIN

## INTRODUCTION

Carbon capture and storage (CCS) in geologic media have been identified as important means for reducing anthropogenic greenhouse gas emissions into the atmosphere (Bradshaw and others, 2007). Several categories of geologic media for the storage of carbon dioxide ($CO_2$) are available, including depleted oil and gas reservoirs, deep brine-saturated formations, $CO_2$ flood enhanced oil recovery (EOR) operations, and enhanced coalbed methane recovery. The U.S. Department of Energy (DOE) is pursuing a vigorous program for demonstration of CCS technology through its Regional Carbon Sequestration Partnership (RCSP) Program, which entered its third phase (Phase III) in October 2007. This phase is planned for a duration of ten U.S. federal fiscal years (October 2007 to September 2017). One of the principal elements of the DOE effort is Core R&D which includes a significant effort to identify geologic formations that can safely and efficiently store $CO_2$ over long periods of time.

As one of the seven RCSPs, the Plains $CO_2$ Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), is assessing the technical and economic feasibility of capturing and storing $CO_2$ emissions from stationary sources in the central interior of North America (Figure 1). Through a major regional characterization activity, the EERC is working with Alberta Innovates Technology Futures (AITF) in a binational effort to characterize the lowermost saline system in the Williston and Alberta Basins of the northern Great Plains–Prairie region of North America. The goal of this characterization effort is to determine the potential and effect of large-scale injection of $CO_2$ into this deep saline reservoir.

The storage of captured $CO_2$ in geologic media is a technology that is immediately applicable as a result of the experience gained mainly in oil and gas exploration and production and deep waste disposal. Studies have also shown that geologic media has a large potential for $CO_2$ storage, with retention times of centuries to millions of years (Intergovernmental Panel on Climate Change [IPCC], 2005). Geologic storage of $CO_2$ is being actively investigated and pursued at several locations across the United States, Canada, and the globe, including several sites in the PCOR Partnership region.

Three geologic media have been identified as suitable for $CO_2$ storage: uneconomic coal beds, depleted oil and gas reservoirs, and deep (<800 meters) saline formations (also referred to as deep saline aquifers). Storage of $CO_2$ in coal beds has the smallest potential in terms of storage resource and is an immature technology that has not been proven yet (Bachu and others, 2011). Depleted hydrocarbon reservoirs have the advantage of demonstrating storage and


Figure 1. Map of the PCOR Partnership region.

confinement properties by having previously stored oil and/or gas resources for millions of years. The quest to discover and extract hydrocarbon resources has provided a broad base of understanding about the subsurface in oil- and gas-producing areas. The potential downside is that the numerous wells that have been drilled in those areas may diminish storage security (Bachu and others, 2011). Deep saline formations have the advantage of being much more widespread and, theoretically, have correspondingly larger storage capacities than the other geologic media.

In the United States and Canada, various studies have been initiated for more than a decade to estimate the $CO_2$ storage resource at the country or regional level. Regional characterization efforts of the PCOR Partnership project have conducted several regional and local investigations to evaluate the $CO_2$ storage resource potential of deep saline formations in the Denver–Julesburg and Williston Basins. The formations investigated in these evaluations include the carbonates of the Madison and Red River Formations and the siliciclastics of the Deadwood, Black Island, Broom Creek, Newcastle, and Inyan Kara Formations in the Williston Basin. In the Denver–Julesburg Basin, the sandstones of the Maha Formation were evaluated for $CO_2$ storage resource potential. Bachu and Adams (2003) have estimated the storage resource for the carbonate Keg River and siliciclastic Viking saline formations in the Alberta Basin. The results of that specific work were also included in the $CO_2$ resource of the PCOR Partnership as reported to DOE for inclusion into the Carbon Sequestration Atlas of the United States and Canada (U.S. DOE 2007, 2008, 2010).

Work conducted in 2010–2011 by the Geological Survey of Canada (GSC) regarding the $CO_2$ storage potential and resource in Canada has identified the Alberta Basin and the Canadian part of the Williston Basin as the region in Canada with the greatest potential for CCS implementation. In those basins, the GSC has applied DOE's methodology (U.S. DOE, 2008) to several saline formations, namely, the Elk Point, Beaverhill Lake, Woodbend, Winterburn, and Rundle–Charles Formations. The storage resource values derived in this work by GSC will be included in the upcoming 4th edition of the PCOR Partnership Atlas and the North American Atlas of $CO_2$ Storage Capacity, both to be published in 2012 (Bachu and others, 2011).

Frequent and unfortunate by-products of the individual efforts conducted in this central interior portion of North America are evaluations and related maps that show a "fault line" (discontinuity) at the U.S.–Canadian border. Evaluating the resource and effects of $CO_2$ storage in the Canadian or U.S. portions of the Williston Basin should not be done in isolation. The regional geology of sedimentary basins is not influenced by political boundaries.

Similar to the Mt. Simon Formation that overlies the Precambrian crystalline basement in the U.S. Midwest (Leetaru and McBride, 2009; Barnes and others, 2009), a basal saline system overlies the Precambrian basement in the northern Great Plains–Prairie region, extending from north of Edmonton, Alberta, to South Dakota and covering a combined area of ~1.3 million $km^2$ (~509,000 sq mi) (Figure 2). Of this, the Canadian part of the saline system covers 811,345 $km^2$ (313,285 sq mi), and the U.S. part covers 507,155 $km^2$ (~195,814 sq mi). This sequence of rock is penetrated by comparatively few wells, in the order of a few thousands only, and therefore has a correspondingly lower risk of $CO_2$ leakage. Given its characteristics and extent, this basal saline system should be considered as a prime target for the storage of $CO_2$ from large stationary

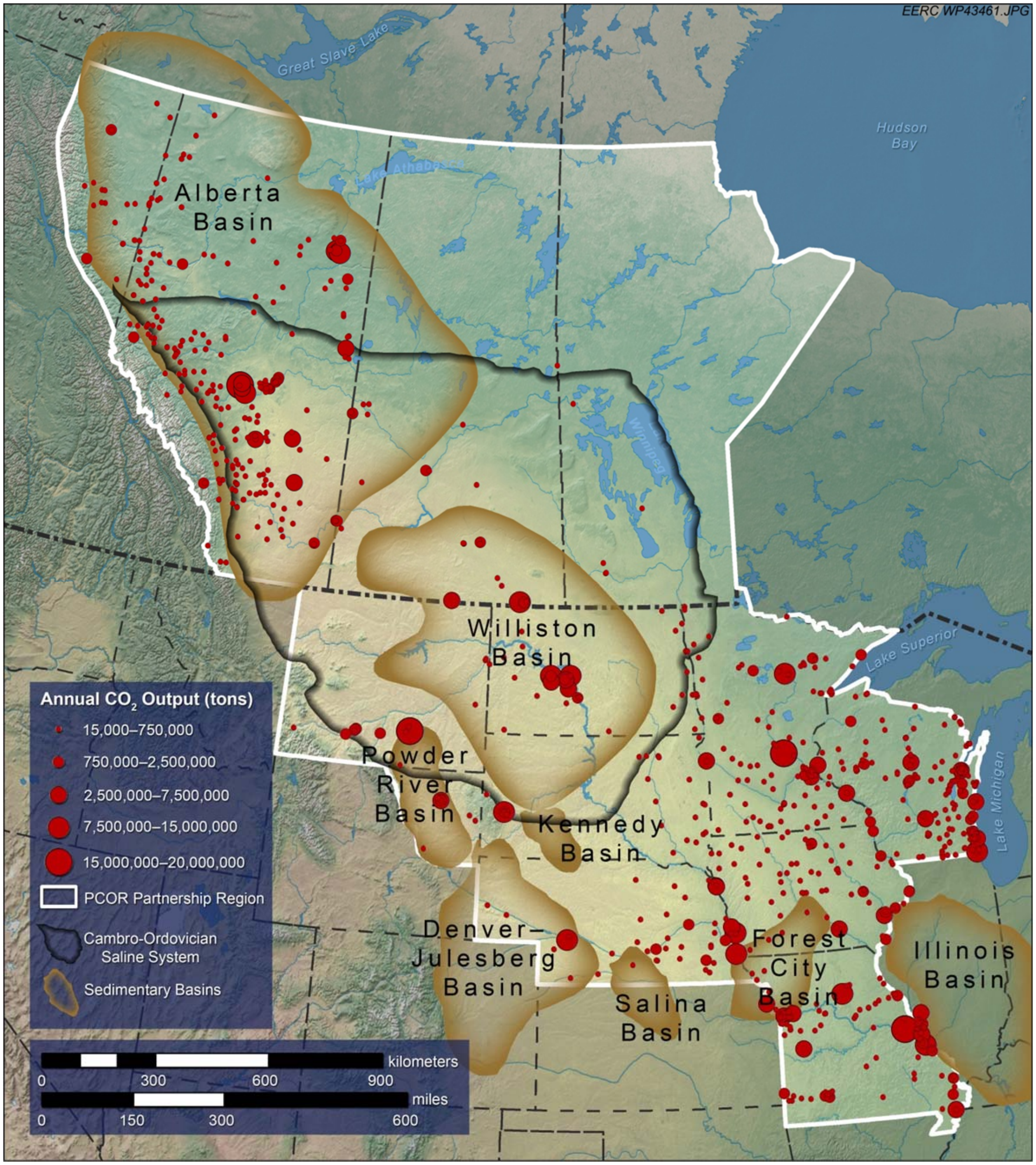


Figure 2. The PCOR Partnership region and the distribution of large stationary sources in relationship to sedimentary basins and the extent of the COSS.

sources in the northern Great Plains and Prairie region. Most of the Cambrian to Silurian strata at the base of the sedimentary succession in Williston and Alberta Basins (Figure 3) does not contain fossil fuels and also has limited prospects for unconventional oil or gas production, and as such, little of the prospective storage space is leased.

The Cambro-Ordovician Saline System (COSS) comprises several diachronous rock units of variable lithology: the Middle Cambrian Basal Sandstone in the Alberta Basin adjacent to the Late Cambrian Deadwood and Early Ordovician Black Island Formation in Saskatchewan, Manitoba, and the Dakotas. These strata are overlain by Upper Ordovician and Lower Silurian carbonates. The COSS is overlain by Cambrian shales in the Alberta Basin and by Ordovician shales or Middle Devonian tight shaly 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, to nearly 4900 m at the depocenter of the Williston Basin. The rock sequence crops out and is a source of fresh groundwater in south-central to southeastern Manitoba (e.g., Ferguson and others, 2007) and in South Dakota and Montana (Figure 3). Otherwise, water salinity in this

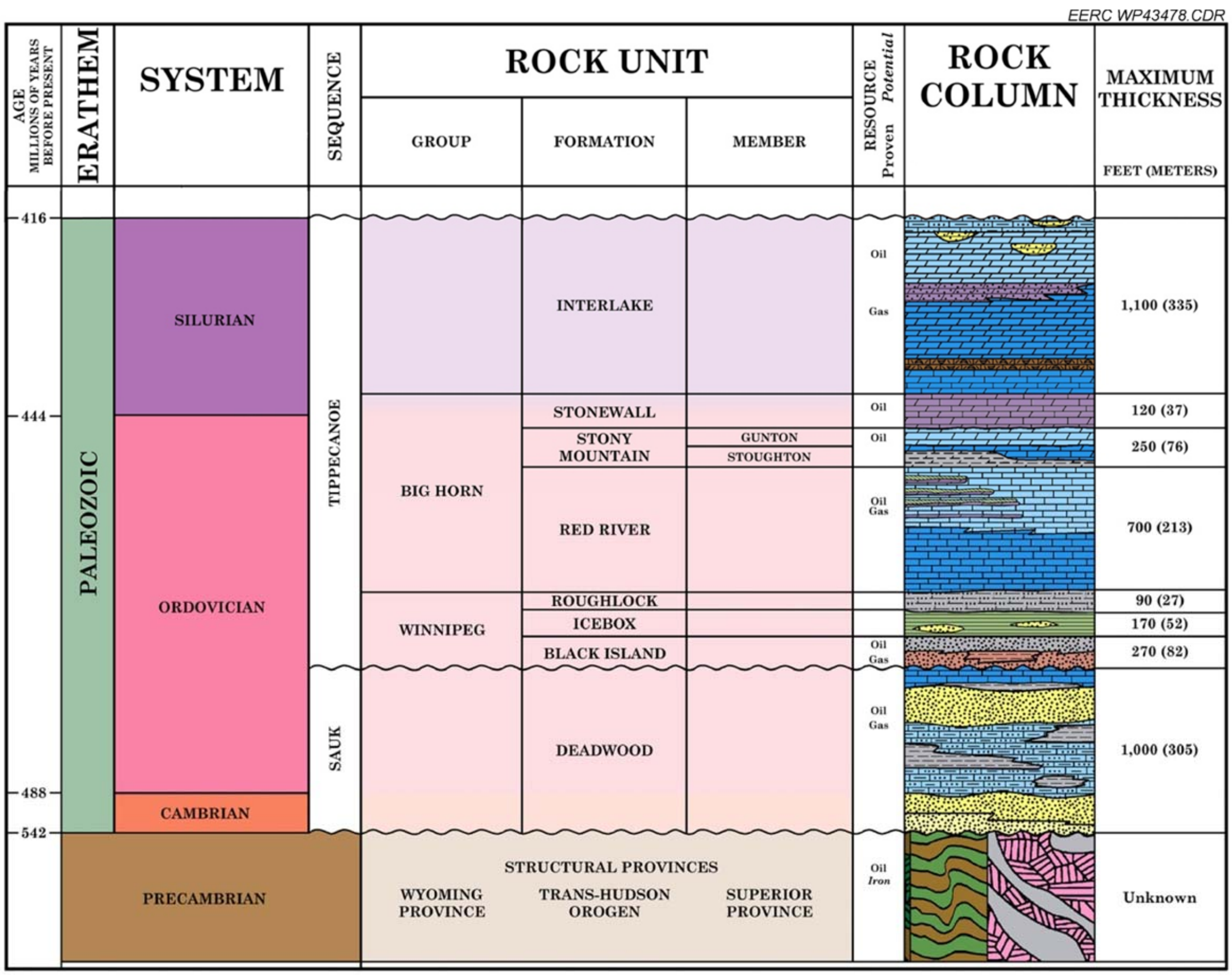


Figure 3. Stratigraphic column showing the early Paleozoic strata of the Williston Basin (modified from Murphy and others [2009]).

system increases with depth, reaching values greater than 350,000 mg/L in both Alberta and Williston Basins (Bachu, 1995; Bachu and Hitchon, 1996).

Energy production from fossil fuels is generally associated with sedimentary basins, and it is these same sedimentary basins that contain the geologic media suitable for $CO_2$ storage. This juxtaposition of large stationary sources of $CO_2$ and potential geologic storage targets makes for an opportune geographic relationship (Figure 2). This COSS is the storage target for Shell's Quest project near Edmonton, Alberta, and of the Aquistore project near Estevan, Saskatchewan. It is very possible that many large $CO_2$ emitters in the northern Great Plains–Prairie region of North America will choose to store $CO_2$ in this saline system because of its apparent large storage resource and because it is penetrated by relatively few wells, thus increasing the security of $CO_2$ storage. However, the storage resource of this saline system has not been thoroughly evaluated.

To address the evaluation of this extensive saline system, a joint binational project between Canada and the United States has been developed with the following objectives: 1) assess the volumetric $CO_2$ storage resource of the northern Great Plains–Prairie basal saline system based on its geometry, internal architecture, lithology, relative permeability and porosity, and temperature and pressure distributions; 2) assess the dynamic storage capacity of the saline system assuming that the major large $CO_2$ sources located above or in close vicinity to this saline system will choose it for $CO_2$ storage during their respective lifetime; 3) assess the effect of pressure-related changes related to the injection of large volumes of $CO_2$ on resident brine and shallow groundwater resources in areas of aquifer outcrop in Manitoba, South Dakota, and Montana; and 4) assess the effect of potential leakage of $CO_2$ and/or brine through wells that penetrate this sequence of rock on shallow groundwater aquifers.

This international effort has three broad stages. Stage I, from October 1, 2010, to September 30, 2011, has as its main objectives the characterization of the basal saline system and evaluation of its static $CO_2$ storage resource; Stage II, from October 1, 2011, to September 30, 2012, has the objective of evaluating of the fate of $CO_2$ injected into this saline system and of the displaced brine; Stage III, from October 1, 2012, to September 30, 2013, has as its main objective the evaluation of the effects of $CO_2$ in case of leakage along wells.

This report presents the results achieved during Stage I of characterization on the U.S. side of the project and on the integration of the previous completed results on the Canadian side (Bachu and others, 2011).

In addition to the leading organizations of the EERC and AITF, other partners in the project are DOE, Lawrence Berkeley National Laboratory, and Princeton University in the United States and Saskatchewan Industry and Resources, Manitoba Water Stewardship, Manitoba Innovation – Energy and Mines, CanmetENERGY, Natural Resources Canada, TOTAL E&P Ltd., and the University of Regina Petroleum Technology Research Centre in Canada.

## PHYSIOGRAPHIC SETTING

The central interior portion of North America covered in this report encompasses the northern Great Plains–Prairie region of the United States and the southern Interior Plains of 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 the 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.

## GEOLOGY

The central interior region of North America is underlain by deep, broad 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 $CO_2$. The prominent sedimentary basin of this region, and the focus of this study, is the Williston Basin. Strata of the Williston Basin represent every period of geologic time. In particular, the focus is the sequence of strata at the base of the sedimentary succession of the greater Williston Basin area (Figure 3). These basal strata are referred to as the COSS in this report. The context of the greater binational effort also includes the Alberta Basin to the northwest (Figure 2).

### Depositional History

Most of the geologic characteristics of the U.S. portion of the COSS can be attributed to major changes in sea level, subsidence of the Williston Basin, and intermittent reactivation of Precambrian basement structural features. Two major transgressions and regressions occurred within the study area from the Cambrian through the Ordovician, correlating to two major unconformities and depositional sequences (Figure 3) (Gerhard and others, 1982; Sloss, 1963). Subsidence of the Williston Basin and intermittent reactivation of Precambrian basement features have affected thicknesses, porosity, and facies distribution of sediments from all three sequences throughout the study area.

### Basin Evolution

The intracratonic Williston Basin occupies most of North Dakota, northern South Dakota, eastern Montana, southern Saskatchewan, and southwestern Manitoba (Figure 4). It is bordered to the north and northeast by the exposed Precambrian Shield and to the south and southeast by the Transcontinental Arch and the Sioux Uplift. A series of arches, domes, and uplifts border the basin from the southwest to the northwest, including the Black Hills uplift, the Miles City Arch, and the Sweetgrass Arch (or Bow Island Arch), which separates the Williston Basin from the Alberta Basin to the northwest (Figure 4). At the deepest part of the basin, located in northwestern North Dakota, sediments are over 4900 meters thick (Figure 5). The basin rests on

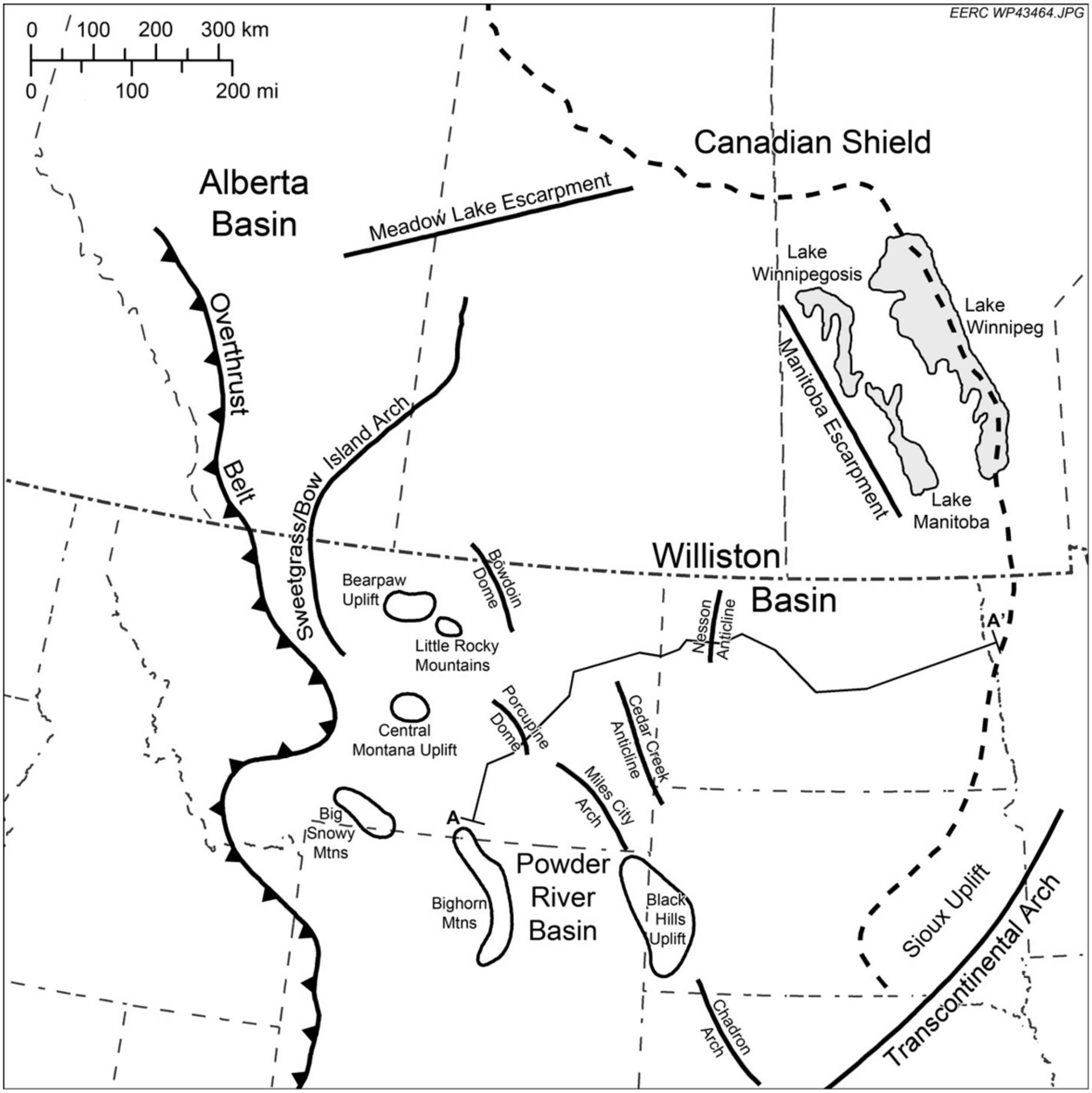


Figure 4. Major structural features of the project region (modified from Bachu and Hitchon [1996], Downey and Dinwiddie [1988], and Peterson and others [1984]).

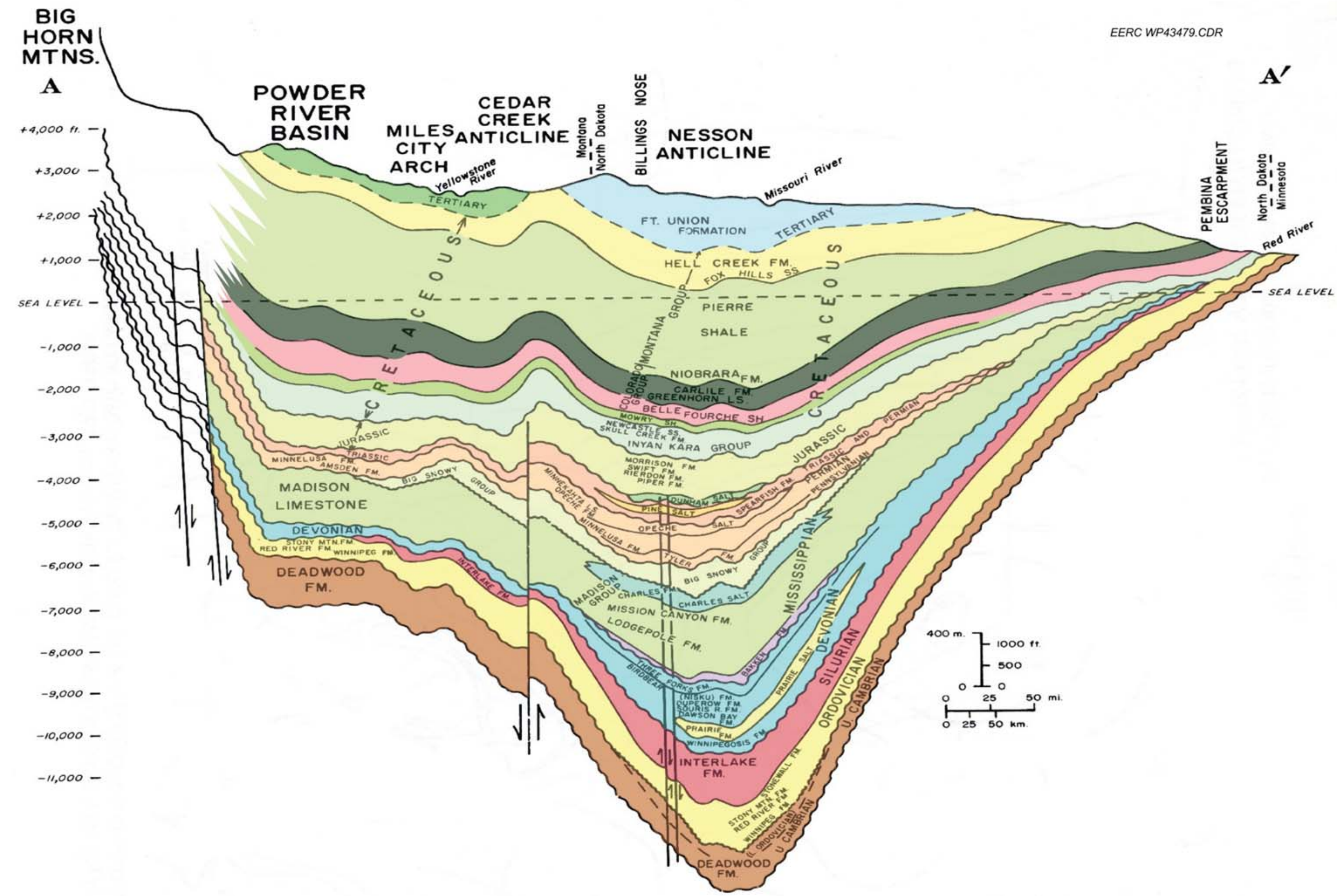


Figure 5. General west-east cross section of the Williston Basin. Line of cross section is shown in Figure 4 (modified from Downey and Dinwiddie [1988]).

a crystalline Precambrian basement that consists of the Wyoming and Superior provinces (Archean) and the Trans-Hudson orogen (Proterozoic) (Figure 3). Previous studies suggest the basin is of thermal origin and is related to the breakup of a Precambrian Supercontinent (Ahern and Ditmars, 1985; Crowley and others, 1985; Klein and Hsui, 1987). LeFever and others (1987) suggest that subsidence of the basin began as early as Late Cambrian to Early Ordovician because of a thickening of sediments near the center of the basin during that time period.

## Stratigraphy

### *Cambrian to Early Ordovician (Sauk Sequence)*

Deposition of the U.S. portion of the COSS began in the Middle Cambrian as the Cambrian Sea transgressed eastward across proto-North America, depositing a diachronous basal sandstone unit (Figures 6a–c). This basal sandstone unit varies in age from early Middle Cambrian in Central Montana to Early Ordovician in eastern North Dakota and rests nonconformably on the Precambrian surface. It is referred to as the Flathead Sandstone in most of Montana and Wyoming and is equivalent to the basal sandstone unit of the Deadwood Formation in North and South Dakota and the informal Basal Cambrian Sandstone throughout most of Alberta, Saskatchewan, and Manitoba (Figures 7 and 8). This extensive unit is composed of coarse- to fine-grained quartzose and glauconitic sandstone and is locally conglomeratic at its base (Bell, 1970; Carlson and Thompson, 1987; Macke, 1993; and LeFever, 1996). The depositional environments have been interpreted as marine foreshore to shoreface, tidal flat and, where conglomeratic, fluvial to alluvial (LeFever, 1996). Deposition began with the infilling of Precambrian topographic lows, which is one reason for the variable thickness throughout the unit. This basal sandstone blankets the Precambrian basement throughout much of the northern Great Plains area and is a main component of potential $CO_2$ storage in the COSS.

As the Cambrian Sea continued its eastward transgression, it began to deposit fine siliciclastics and eventually carbonates to the west, some of which extend into central North Dakota as part of the Deadwood Formation (Figure 9). They correlate to the Grand Cycles of Aitken (1978) in the southern Canadian Rocky Mountains and represent minor transgressive-regressive cycles within the Sauk Sequence. The nomenclature for these alternating beds of fine siliciclastics and carbonates overlying the Basal Cambrian Sandstone varies throughout the study area. In parts of Montana and Wyoming, they are referred to as the Gros Ventre and Gallatin Groups and are equivalent to parts of the Emerson Formation in the Little Rocky Mountains area of Montana and the Deadwood Formation in North and South Dakota. The Gros Ventre Group is made up of the Wolsey Shale, the Meagher Limestone, and the Park Shale. The Gallatin Group consists of the Pilgrim Limestone, the Snowy Range Formation (which consists of the Dry Creek Shale and the Sage Pebble Conglomerate), and the Grove Creek Limestone (which is sometimes included within the Snowy Range Formation) (Macke, 1993) (Figure 8). This alternating sequence of fine siliciclastics and carbonates acts a seal to the COSS throughout most of Montana, Alberta, and Saskatchewan. In eastern Montana, these formations begin to grade into the more clastic-rich Deadwood Formation. The lithology of the Deadwood varies greatly throughout North Dakota, eastern Montana, and northern South Dakota (Figure 10). Multiple layers of sand make for good targets for potential CO2 storage, whereas multiple layers of shale create many minor seals (baffles).

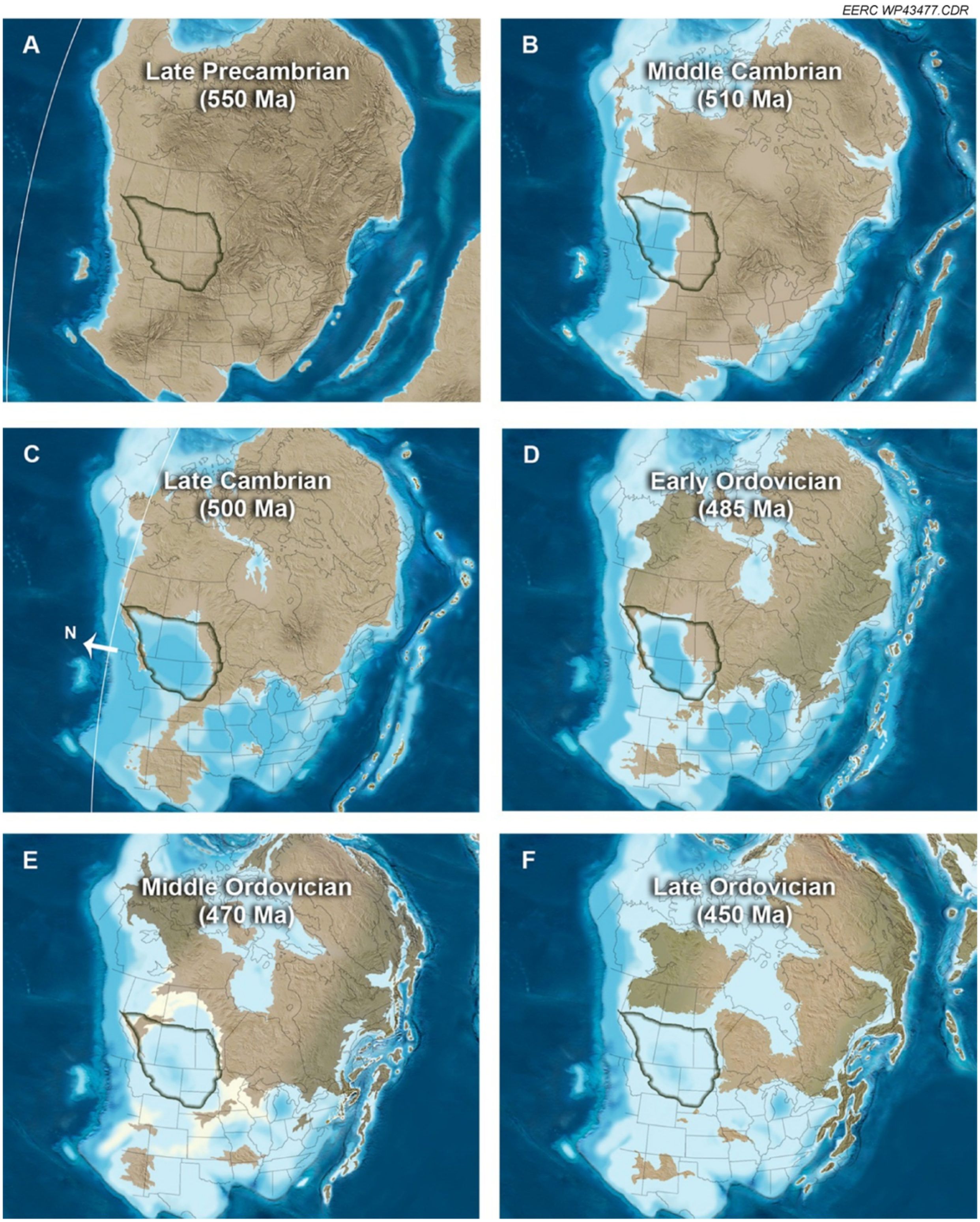


Figure 6. Paleogeographic maps of North America. The extent of the COSS has been added for reference (maps from Blakey [2011]).

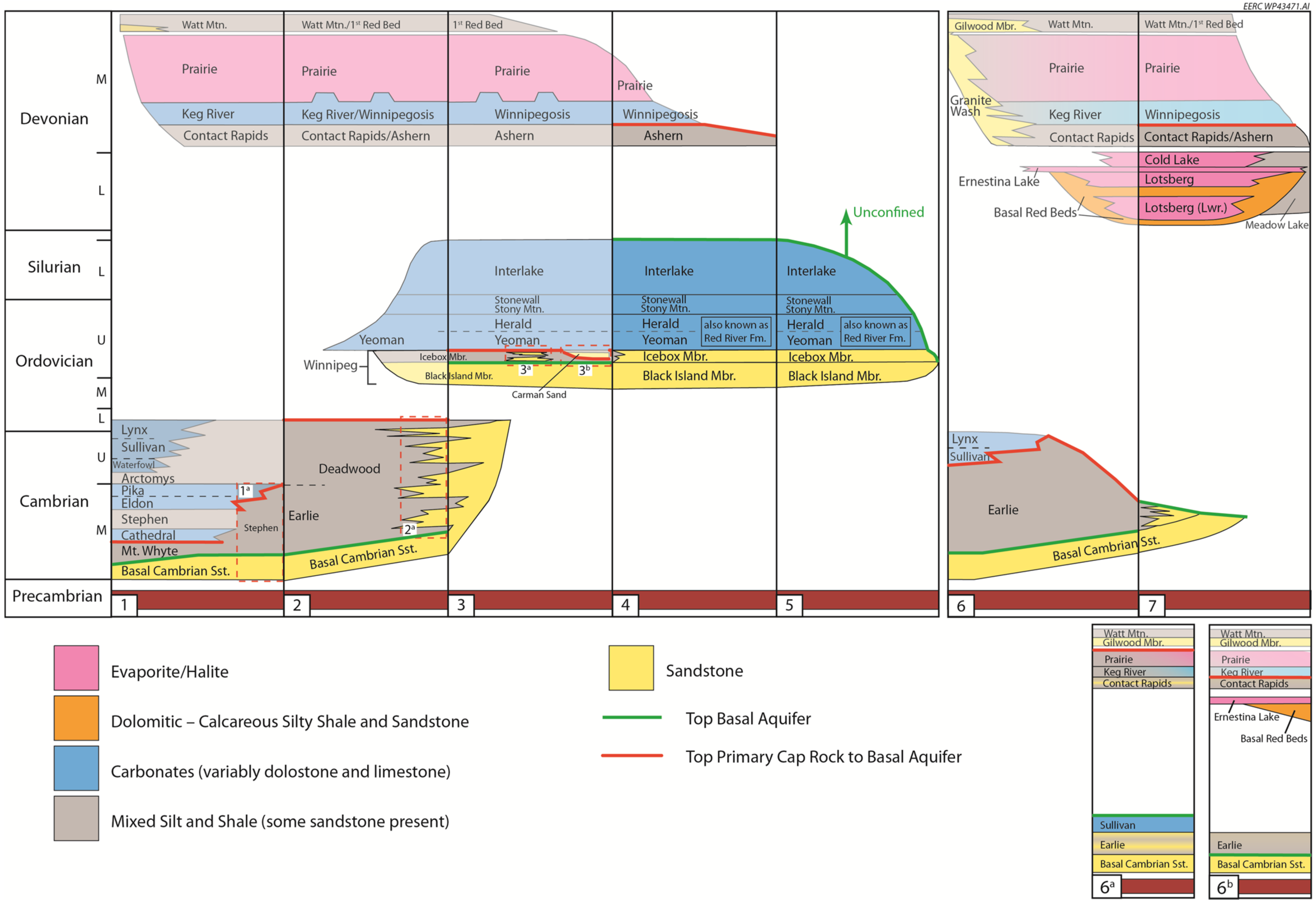


Figure 7. Stratigraphic correlation chart for the Canadian portion of the study region. The location of the numbered stratigraphic sections is shown on the map in Figure 8 (modified from Bachu and others [2011]).

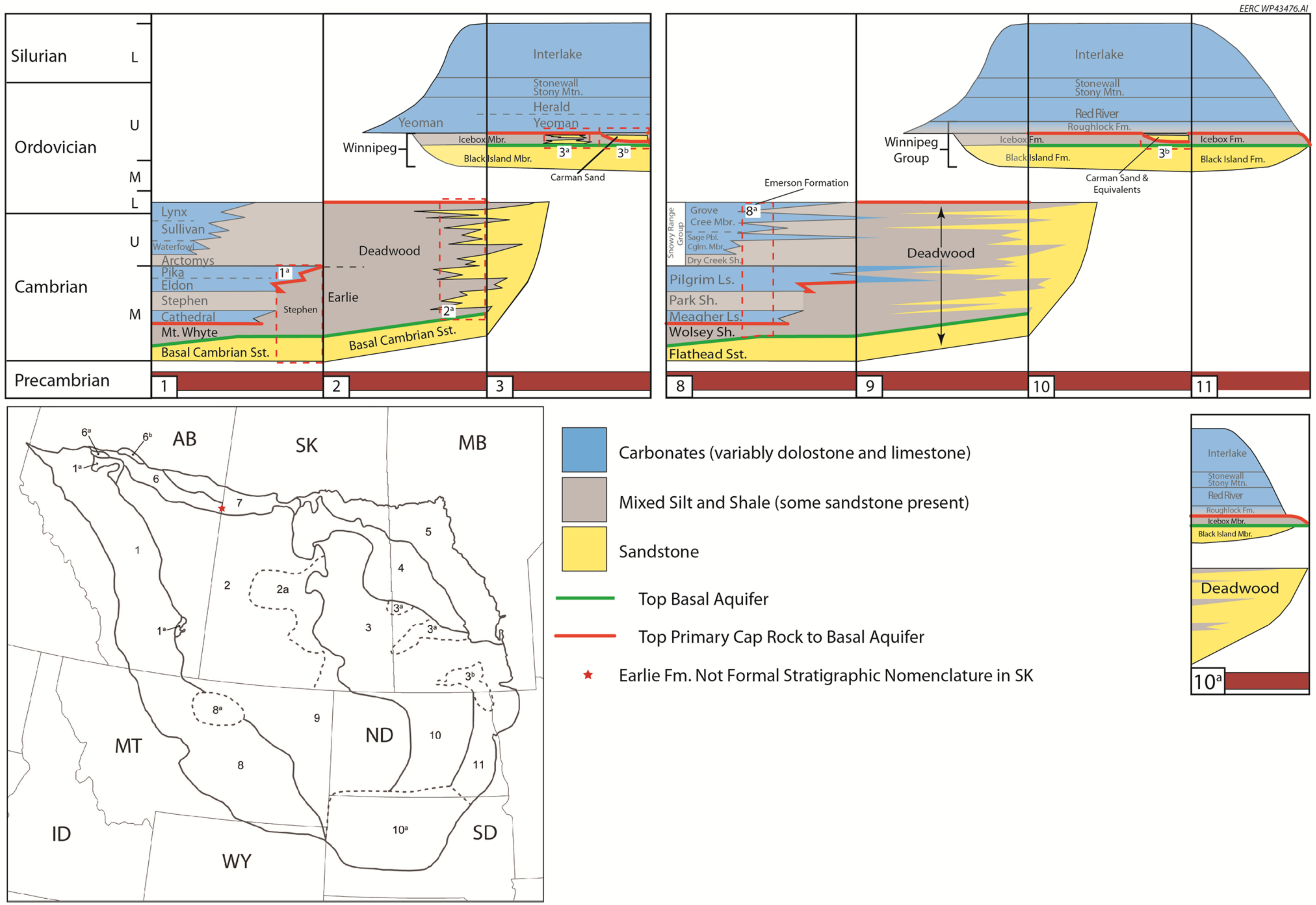


Figure 8. Stratigraphic correlation chart comparing the U.S. portion of the study region with the adjacent Canadian portion (modified from Bachu and others [2011]). The numbers on each stratigraphic column correlate to a region on the map. Nomenclature changes across the U.S.–Canadian border. Region 8a signifies a change in nomenclature, not lithology, in the Little Rock Mountains area.

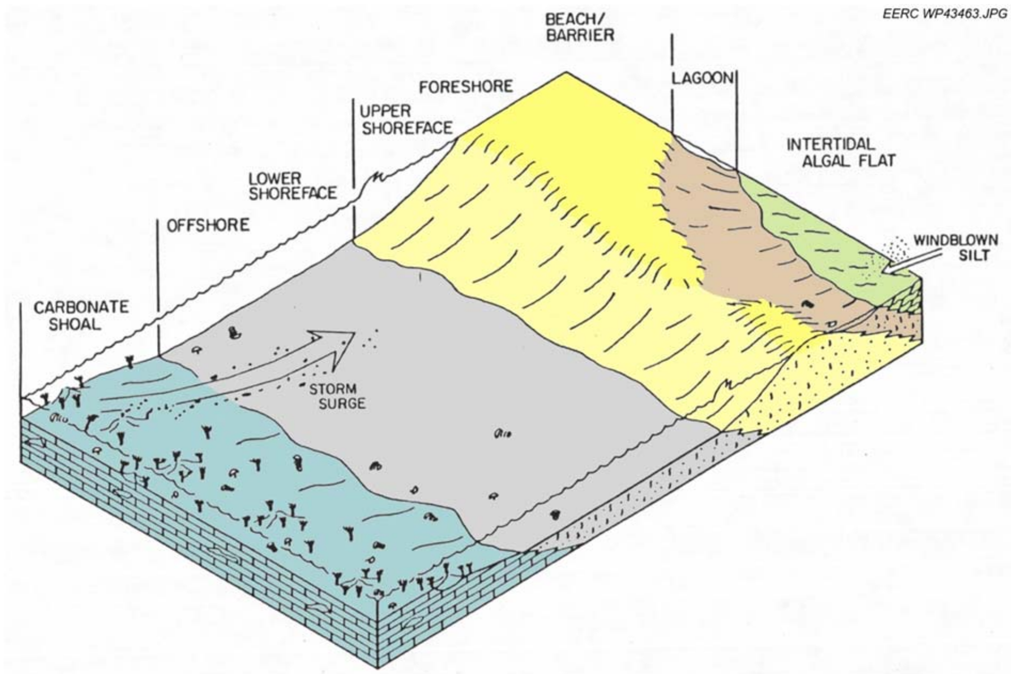


Figure 9. Depositional model for the Lower Ordovician part of the Deadwood Formation (modified from Anderson [1988]).

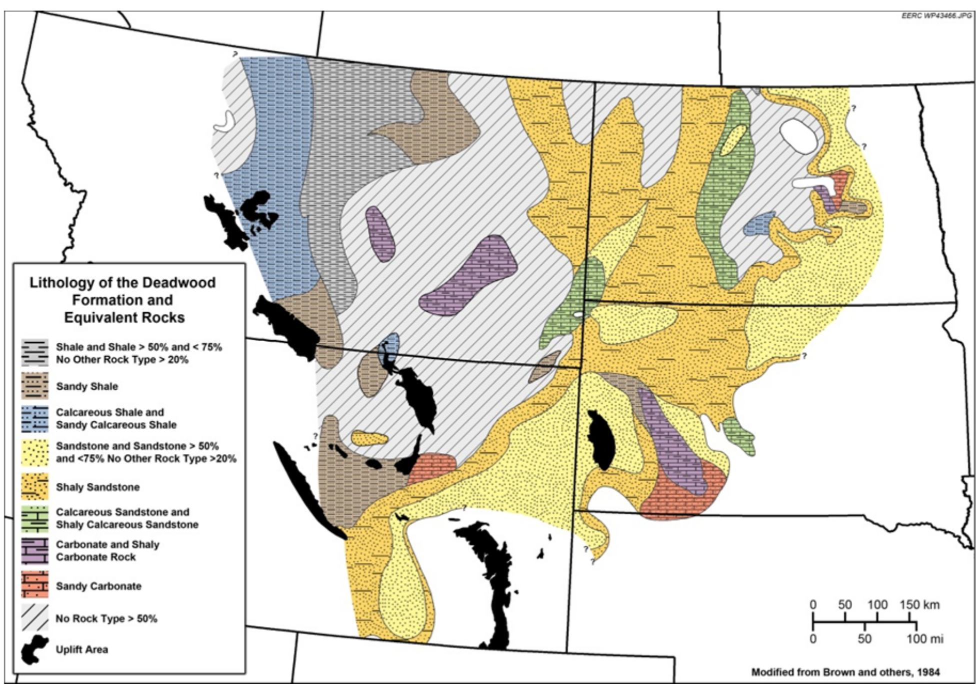


Figure 10. Lithology (facies) distribution map of the Deadwood Formation as interpreted by Brown and others (1984).

The Deadwood and equivalent Sauk Sequence sediments are truncated by a major unconformity across most of the study area (Figure 6d). This unconformity represents a major drop in sea level resulting in subaerial exposure and erosion. This hiatus of deposition is interpreted as being established by late Early Ordovician and lasting until the Middle Ordovician when sea level began to rise again (Figures 6e and 6f), marking the start of the Tippecanoe Sequence beginning with the deposition of the Winnipeg Group (LeFever and others, 1987).

### *Ordovician to Silurian (Tippecanoe Sequence)*

The Winnipeg Group consists of, in ascending order, the Black Island, Icebox, and Roughlock Formations (Figure 3). The Black Island Formation consists predominantly of sandstones with minor amounts of shale. It unconformably overlies the Deadwood Formation throughout eastern Montana and most of North Dakota, except in parts of eastern North Dakota where it lies nonconformably on the Precambrian basement. Deposition is interpreted as beginning in fluvial and deltaic environments and transitioning to a shallow marine environment as sea level continued to rise and transgress eastward (LeFever, 1996). The sands of the Black Island Formation are included in the COSS and, in some places, are hydrologically connected to the Deadwood Formation. Continued rise in sea level led to the deposition of the Icebox and Roughlock Formations in offshore environments. The Icebox consists mainly of shales with some sand bodies to the east and northeast (Kessler, 1991). It conformably overlies the Black Island Formation in eastern Montana and most of North Dakota. However, the Icebox Formation extends farther south into northern South Dakota where it unconformably overlies the Deadwood Formation (Figure 8). This shale unit acts as a thick seal, capping the Black Island and Deadwood Formations throughout most of North Dakota, eastern Montana, and northern South Dakota. The Roughlock Formation consists of calcareous shales and conformably overlies the Icebox Formation. It is a transitional unit between the underlying shales of the Icebox Formation and the clean carbonates of the overlying Red River Formation. A thick sequence of carbonates including the Red River, Stony Mountain, Stonewall, and Interlake Formations overly the Winnipeg Group (Figure 3). These carbonates range in age from Middle Ordovician through the Silurian and are truncated by a pre-Devonian unconformity that marks a major drop in sea level and the end of the Tippecanoe Sequence.

## Structures

The relief of the Precambrian basement and reactivation of various structures have affected thickness, porosity, and facies distribution of the COSS. Probably the most significant of these structural features is the Williston Basin, which began to subside as early as the Late Cambrian to Early Ordovician and steadily continued to the Jurassic (Kent, 1987). Sedimentation kept up with subsidence throughout deposition of the COSS, which is the main reason we observe the thickest sections of most formations to be located near the center of the basin. Subsidence of the Williston Basin also helped to preserve many formations during times of low sea level, which led to subaerial exposure and eventual erosion of sediments around the basin’s edges. The informal members (A–F) of the Deadwood Formation from LeFever and others (1987) are a good example of this. The younger members are more constrained to the basin center, whereas the older members have a much larger aerial extent.

The COSS is bordered to the south and southeast by the Transcontinental Arch (Figure 4). This northeast-trending structure was a Precambrian high before the initial transgression of the Cambrian Sea and served as a source area for sediment throughout most of the Paleozoic Era (Macke, 1993). The Deadwood Formation and Winnipeg Group onlapped the arch during their deposition; however, sediments from both are thin to nonexistent on the structure. It is hard to tell the extent of deposition on the Transcontinental Arch because of postdepositional erosion removing nearly all evidence of their existence.

Intermittent reactivation of major faults along the Nesson Anticline near the center of the Williston Basin (Figure 4) affected porosity and facies development of the COSS. The Nesson Anticline is interpreted as existing before the initial transgression of the Cambrian Sea (a Precambrian structure), in which lower sediments of the Deadwood Formation onlapped the structure (Gerhard and others, 1982). This led to coarser-grained sands to be deposited on and around the Nesson Anticline, because of increased wave energy, resulting in better initial porosity development. Reactivation of faults along the Nesson affected deposition of the Winnipeg Group in a similar way. Both Deadwood and post-Winnipeg pre-Devonian sediments are thinner on the anticline because of predepositional relief and postdepositional erosion (Gerhard and others, 1982).

Many other structures within the study area did not form until after the Silurian and, therefore, did not significantly affect deposition of the Deadwood, Winnipeg, and their equivalent formations. However, many of these post (Cambro/Ordovician) depositional uplifts have become outcrop areas for Ordovician, Cambrian, and even Precambrian rocks. Many of these uplifts now act as recharge areas, such as the Central Montana uplift, the Black Hills, the Big Horn Mountains, the Little Rocky Mountains, and the Big Snowy Mountains (Figure 4). Others act as subsurface structural barriers between sedimentary basins. The Sweetgrass/Bow Island Arch separates the Williston Basin from the Alberta Basin, and the Miles City Arch separates the Williston Basin from the Powder River Basin (Figure 4).

### Hydrogeologic System

Hydrogeologically, sedimentary strata can be classified as aquifers, aquitards, or aquicludes, depending on their permeability. A hydrostratigraphic unit comprises one or more geologic units (often formations) that are in contact and exhibit similar hydraulic characteristics. Bachu and Hitchon (1996) describe hydrostratigraphic systems as complex groups of hydrostratigraphic units that exhibit certain common overall characteristics at a regional scale and behave as aquifers, aquitards, or aquicludes.

Previous work by the U.S. Geological Survey (USGS) described the Williston Basin as part of a larger regional geohydrological province called the northern Great Plains aquifer system (Downey and others, 1987; Busby and others, 1995; Downey, 1984, 1986, 1989; Downey and Dinwiddie, 1988; Brown and others, 1984). As defined by the USGS, the northern Great Plains aquifer system is a large (approximately 300,000-square-mile) complex geohydrological system underlying North Dakota, most of South Dakota, much of Montana, northeastern Wyoming, the northwest tip of Nebraska, southern Manitoba, and southeastern Saskatchewan. The general flow direction in the northern Great Plains aquifer system is to the east and the northeast. Some of the aquifers in the system subcrop in the east. Recharge areas are primarily western highlands, including the Rocky Mountains and the Black Hills. The stratigraphic column of the northern Great Plains aquifer system has been divided into a series of five principal aquifers and four principal confining units. Each aquifer is a potential regional sequestration unit. The aquifers have been numbered in ascending order (Figure 11), with the prefix AQ representing an aquifer system and TK representing a confining unit or aquitard. In an effort to expand the definition of this aquifer system, Bachu and Hitchon (1996) recognize a similar geohydrological system beneath the Prairie region of Canada. The lowermost aquifer (saline system) is referred to as AQ1 and consists of sandstones, siltstones, and carbonates and is the basis for the definition of the COSS.

It should be noted that the formation waters in these aquifer systems range widely with respect to total dissolved solids (TDS). In the central portion of the Williston Basin, TDS levels reach nearly 350,000 mg/L for AQ1 through AQ3 (Downey and Dinwiddie, 1988). These levels taper off toward the basin margins where TDS levels are in the 5000–10,000 mg/L range. The lower TDS values reflect the impact of freshwater recharge on water quality. The U.S. Environmental Protection Agency (EPA) defines potable water as having TDS levels less than 3000 mg/L and underground sources of drinking water as having less than 10,000 mg/L (U.S. EPA, 2012). EPA definitions classify a large portion of the waters in the northern Great Plains aquifer system and, in particular, the COSS as not being underground sources of drinking water.

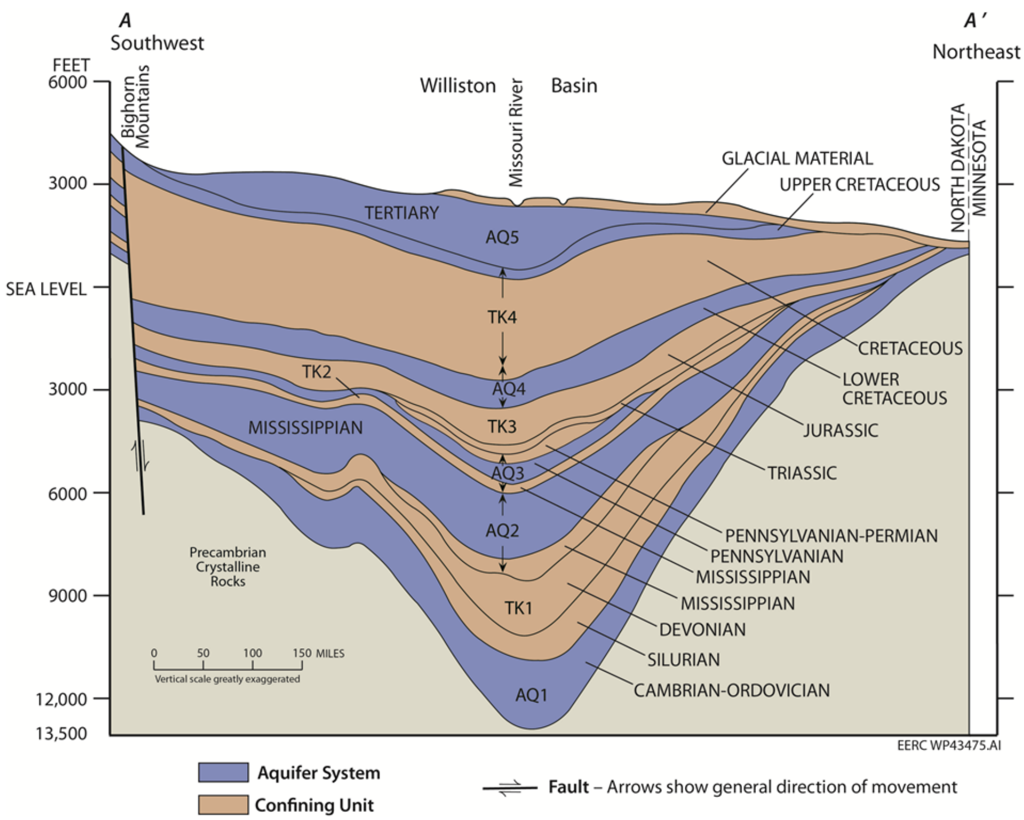


Figure 11. West-east cross section of the Williston Basin showing the delineations of saline systems and confining units as defined by Downey and Dinwiddie (1988).

From the practical aspect of calculating the volumetric storage resource of the COSS, the Deadwood and overlying Black Island Formations will be treated as a single unit. The primary cap rock for this geologic storage resource is the Icebox Shale Formation and overlying formations mentioned earlier which collectively correspond to TK1 as defined by Downey and others (1987).

## $CO_2$ STORAGE POTENTIAL

### $CO_2$ Storage Classification

The classification of $CO_2$ storage and the terminology that has evolved is intended to provide a comparable basis for assessing $CO_2$ storage potential from regulatory and business perspectives. The definitions of the terms are meant to convey varying degrees of confidence in the storage assessment values that are generated.

A hierarchy of classification terminology has been developed over the past 5 years that leverages increasing confidence with increasing data and a smaller geographic area of interest. These relationships were first illustrated by the technoeconomic resource–reserve pyramid defined by the Carbon Sequestration Leadership Forum (CSLF) (2007). This graphical representation of terms shows the trend from broad-based resource estimations to small-scale, site-specific characterizations (Figure 12), each with differing degrees of certainty. Moving up the pyramid requires more detailed data in a more focused geographic extent along with the application of increasing constraints such as technical, geological, and economic to the $CO_2$ storage capacity, as defined by CSLF.

Gorecki and others (2009) proposed a refined classification incorporating terms defined by DOE (U.S. DOE, 2008) that distinguish between storage estimates defined by physical and chemical constraints (resource) and those with added economic and regulatory constraints (capacity) (Figure 13). The first two divisions within this proposed classification framework, theoretical and characterized storage resource, are equivalent to the theoretical capacity of the CSLF pyramid. The effective storage resource refines the broader level estimates by integrating geologic and engineering limitations. This level is equivalent to the CSLF's definition of effective storage capacity, although here it is defined as a resource since economic considerations have not been implemented.

As mentioned earlier, the approach to estimating the $CO_2$ storage volume, as well as the required level of detail for the required data, will vary depending on the geographic scale of the assessment effort. In its Phase 2 final report, CSLF (2007) presented five terms representing scales of geographic extent for the assessment of $CO_2$ storage. These terms, in order of decreasing area, are country, basin, region, local, and site. Confidence in the calculated storage potential increases as the geographic scale decreases. Gorecki and others (2009) augment this geographic hierarchy by incorporating a level of spatial scale as defined by political subdivisions (Figure 14). Using the terminology presented in the previous paragraphs, this study purposes to estimate the effective storage resource of the COSS at the basin/regional scale across the northern Great Plains and Prairie regions of the central interior of North America.

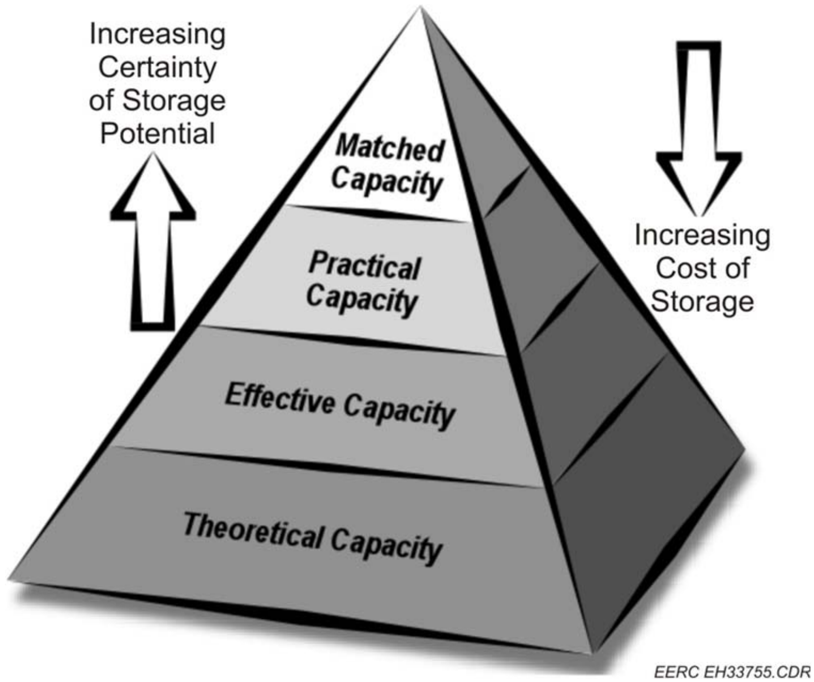


Figure 12. CSLF technoeconomic resource–reserve pyramid (CSLF, 2007).

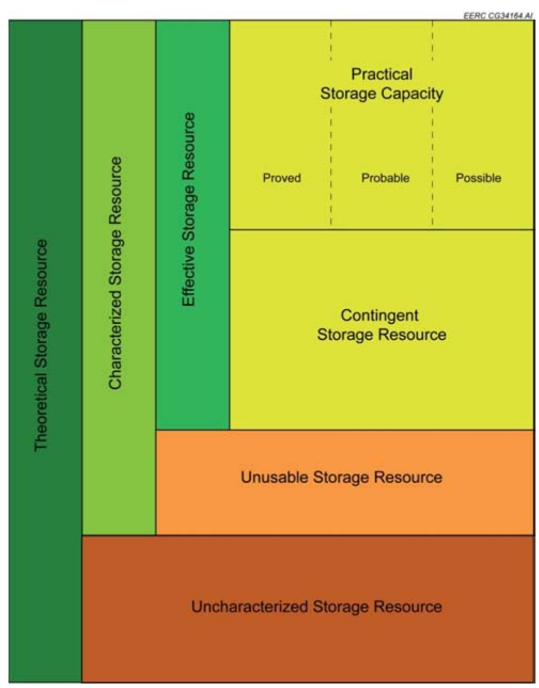


Figure 13. $CO_2$ storage classification framework.

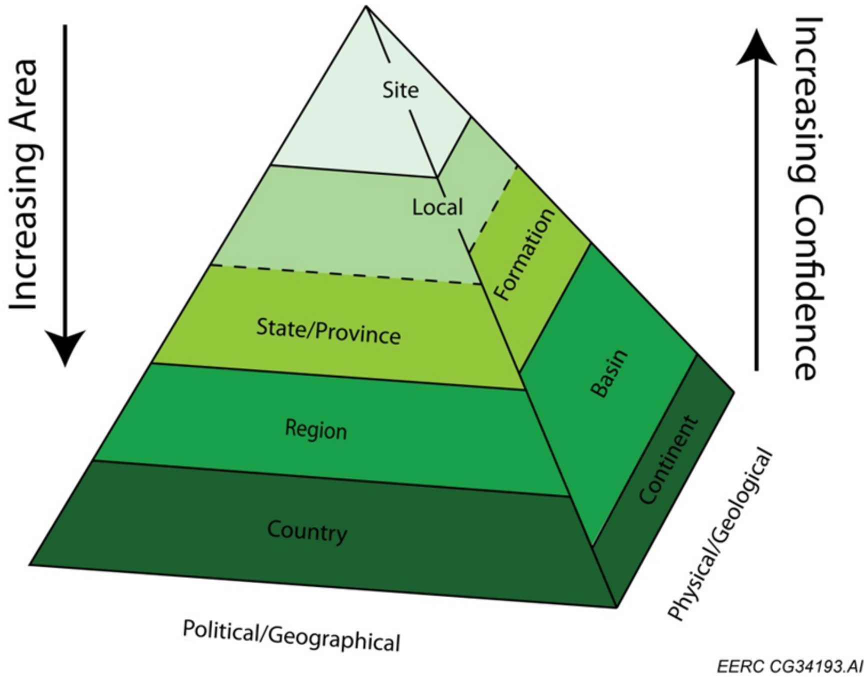


Figure 14. Political/geographic, physical/geologic pyramid of assessment area types and scales.

**Methodology**

The methodology used in this study follows the approach described in DOE Atlas III (U.S. DOE, 2010) which builds on the IEAGHG work of Gorecki and others (2009). It is based on the volumetric approach for estimating $CO_2$ storage resource potential saline formations. The volumetric equation to calculate the $CO_2$ storage resource mass estimate for geologic storage in saline formations is:

$$M_{CO2e} = A \times h \times \phi \times \rho CO_2 \times E \qquad \text{[Eq. 1]}$$

The total area (A), gross formation thickness (h), and total porosity ($\phi$) terms account for the total bulk volume of pore space available. The value for $CO_2$ density ($\rho$) 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 $CO_2$ sequestration and displacement efficiency components that reflect different physical barriers inhibiting $CO_2$ from contacting 100% of the pore volume of a given basin or region. Volumetric methods are applied when it is generally assumed that the formation is open and that formation fluids are displaced from the formation or managed via production. The COSS is assumed to be an open system for the purpose of this study. A comprehensive discussion of the derivation of the methodology and the efficiency factor is presented in Gorecki and others (2009), U.S. DOE (2010), and Goodman and others (2011).

The storage efficiency factor used in this study (2.4%) is the same as employed by AITF in its completed characterization of the Canadian portion of the COSS (Bachu and others, 2011). This efficiency factor was taken from the work of Goodman and others (2011). Goodman and others established a range of efficiency factors for a variety of lithologies for the P10, P50, and P90 probability categories. The 2.4% value represents the P50 value for siliciclastics. The value for siliciclastics was chosen because the COSS is dominated by this lithology classification.

The methodology used in this project is intended to produce high-level, basin/regional-scale $CO_2$ resource estimates of potential geologic storage. This would be considered the effective storage resource of Gorecki and others (2009). The high degree of uncertainty associated with this approach means that these estimates should not be used as a substitute for site-specific characterization and assessment.

### Two-Dimensional Modeling Approach

The primary product of this research project was the creation of a $CO_2$ storage resource distribution map of the COSS. To create this map a 2-D model of the COSS was generated. This model was developed through integration of data derived from deep wells drilled as part of hydrocarbon exploration and production activities. Well data used in the development of the 2-D model across the U.S. portion of the COSS were obtained from the online databases of the North Dakota Industrial Commission and the Montana Board of Oil and Gas. Data were also obtained from the Montana Geological Society and the South Dakota Geologic Survey. Data from these organizations included formation tops, well files, which included core measurements, wireline logs in raster and, in many cases, Log ASCII (LAS) format. The greater Williston Basin area has been explored for oil and gas resources for over 70 years and thus has had a large number of wells drilled into it. For this effort only wells that penetrated the contact of the Black Island and overlying Ice Box Formations or deeper were examined. This restriction resulted in a database of 323 wells (Figure 15). Of these, 156 wells actually pierced the entire COSS and reached the Precambrian surface. Of primary importance with respect to the wells was the availability of LAS files which provide for a wide range of analytical capability when incorporated into modeling software such as Schlumbereger's Petrel. Ninety-four of the well control points had LAS files available and were either obtained from the respective state agency or acquired from the TGS-NOPEC Geophysical Company (TGS).

For this phase of the 3-year study, a two-dimensional deterministic geologic modeling approach was used. Deterministic modeling methods generally form a two-dimensional grid from which properties can be estimated at unsampled locations. For this phase of the effort, the kriging and cokriging geostatistical estimation algorithm was used.

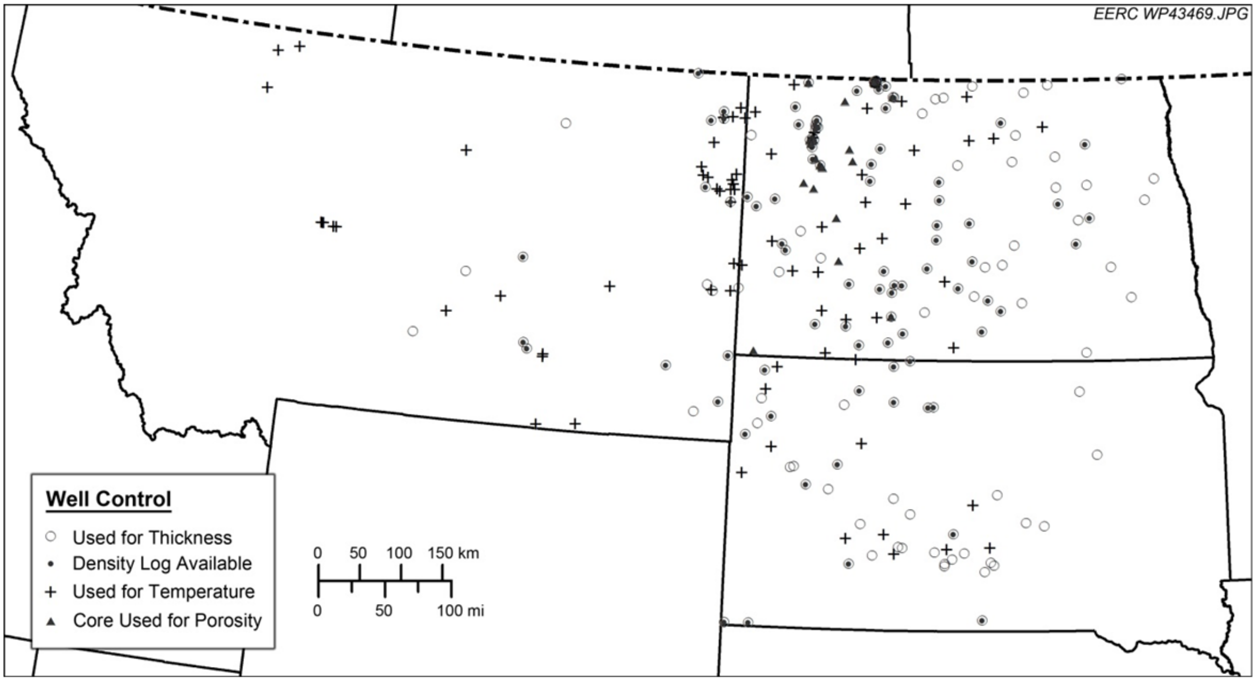


Figure 15. Map showing the distribution of data points used in the development of the 2-D model.

**Determination of Pore Volume** $V_{CO_2,DOE_T}$

The theoretical volumetric $CO_2$ resource estimate calculated for the COSS is based on the DOE open system methodology described in DOE Atlas III (U.S. DOE, 2010). This methodology takes fundamental formation characteristics into account including area (A), gross thickness (h), and total porosity (ϕ) (Equation 2).

$$V_{CO_2,DOE_T} = A * h * \phi \quad \text{[Eq. 2]}$$

**Determination of Area** $A$

In this effort, area is defined by the resolution of the model cell size was 7500’ × 7500’. The total area of the region being studied is then represented by the sum of the area of all the cells in the model.

**Determination of Thickness** $h$

Thickness for the COSS is defined as the interval between the Precambrian basement rock and the top of the Black Island Formation, thus encompassing both the Black Island and Deadwood Formations. Initially the procedure for defining this zone included incorporating previously published or available well top data. However, through petrophysical analysis of wireline and core data, some of the model tops were adjusted through a second iteration of well top picking based on the use of a common static measure such as a major litho- or depofacies change along the well bore using a facies log. The kriging algorithm was used to model the thickness extent of the COSS based on the 156 control points that provided a full thickness of the system. This step provided a thickness value for each cell in the model (Figure 16).

### Determination of Total Porosity $\phi$

The DOE "open" system methodology using the $E_{saline}$ storage coefficient uses total porosity ($\phi$). In this model, total porosity was derived from density logs. Density logs were available for 94 of the 156 LAS files described above. In addition, 24 wells in the region were identified having standard core analysis data from the COSS. For this study, well file data containing core porosity and core grain density were obtained from state regulatory agencies. The density log described as Rhob or bulk density is an in situ downhole measurement of mass per unit volume. The standard equation for density is shown in Equation 3. Rhom is the matrix density or grain density and Rhof is the fluid density in the pores. Pore fluids can be oil, water, gas or a combination thereof. The bulk density equation is described in text as grain volume $(1-\phi)$ multiplied by grain density (*Rhom*) and added to total porosity ($\phi$) multiplied by the fluid density (*Rhof*). Total porosity for the COSS interval was calculated from the 94 density logs using a derivative of Equation 4 specific for different matrix types:

$$Rhob = (Rhom * (1-\phi)) + (Rhof * \phi) \quad \text{[Eq. 3]}$$

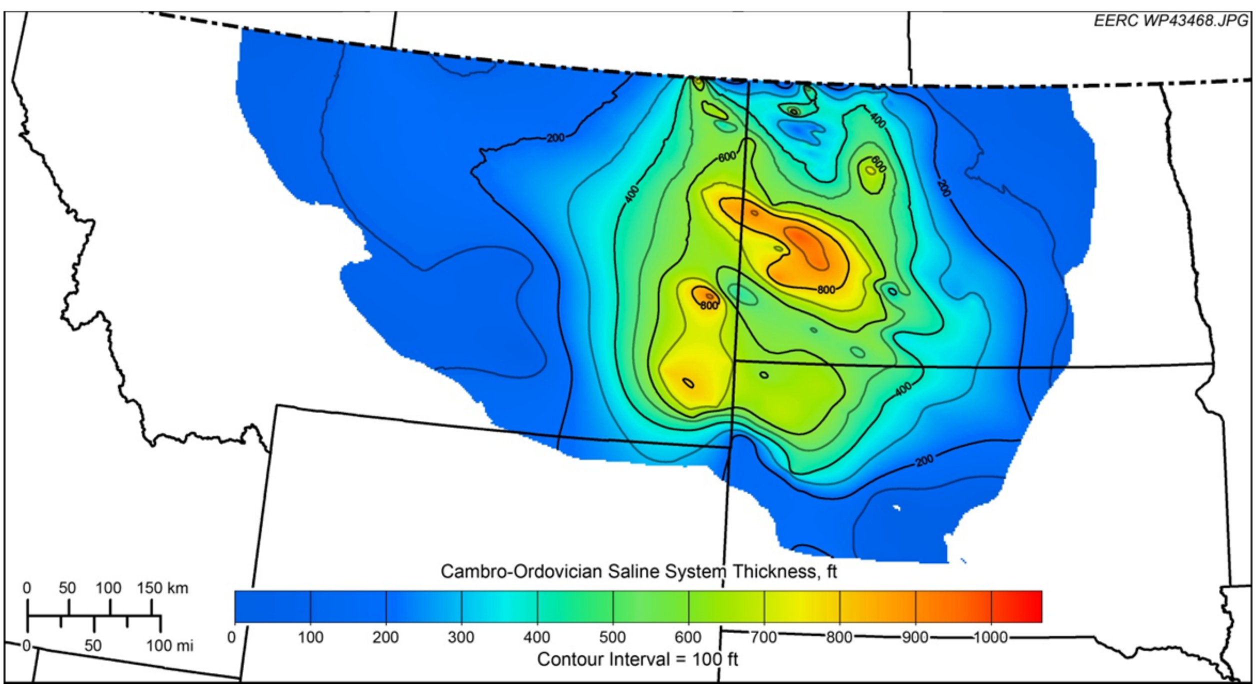


Figure 16. Isopach map of the U.S. portion of the COSS.

Equation 3 can be rearranged to give Equation 4, which is the general equation for total porosity.

$$\phi = \frac{Rhom - Rhob}{Rhom - Rhof} \qquad \text{[Eq. 4]}$$

PHIT = IF(Rhob<2.675,(2.675- Rhob)/(2.675-0.95), IF (Rhob <2.73,(2.73- Rhob)/(2.73-0.95),if(Rhob <2.83,(2.83- Rhob)/(2.83-0.95),(3.4- Rhob)/(3.4-0.95)))) [Eq. 5]

The if/then statement represented in Equation 5 is translated to text as:

$$Phit\_CLASTIC = if\ Rhob\ is\ less\ than\ 2.675\ \frac{g}{cm^3}$$
$$then\ \frac{2.675\ -\ Rhob}{2.675 - 0.95}$$
$$ELSE$$
$$Phit\_LIMESTONE = if\ Rhob\ is\ less\ than\ 2.73\ \frac{g}{cm^3}\ but\ more\ than\ 2.675\ \frac{g}{cm^3}$$
$$then\ \frac{2.73\ -\ Rhob}{2.73 - 0.95}$$
$$ELSE$$
$$Phit\_DOLOMITE = if\ Rhob\ is\ less\ than\ 2.83\ \frac{g}{cm^3}\ but\ more\ than\ 2.73\ \frac{g}{cm^3}$$
$$then\ \frac{2.83\ -\ Rhob}{2.83 - 0.95}$$
$$ELSE$$
$$Phit\_Fe\_CARBONATE = if\ Rhob\ is\ less\ than\ 3.4\ \frac{g}{cm^3}\ but\ more\ than\ 2.83\ \frac{g}{cm^3}$$
$$then\ \frac{3.4\ -\ Rhob}{3.4 - 0.95}$$

In this process, Equation 5 was iteratively calibrated to core porosity by allowing the three main mineral density bins (clastic, limestone, and dolomite) as shown in Figure 17 and represented by Rhom in Equations 4 and 5, to fluctuate across a minimum and maximum range until the R-squared value of the correlation between core porosity and calculated porosity reached a maxima (Figure 18). The three main matrix components were defined as clastic with a density of 2.675 g/cm$^3$, limestone with a density of 2.73 g/cm$^3$, and dolomite with a density of 2.83 g/cm$^3$. After applying the modified and calibrated density equation (Equation 5) to wireline bulk density, it was determined that a fourth minor matrix component was needed based on some intervals in the wireline data having very high bulk densities. These high bulk densities are interpreted to be siderite, an iron-rich carbonate mineral, which has a density of roughly 3.95 g/cm$^3$. Not adding the fourth component resulted in the generation of negative porosities.

Through the review of the core analysis data and corresponding wireline signatures, it was observed that some of the core depth values were off by up to 60 feet. To correct for this offset, the core was depth-shifted by matching the core gamma values against wireline gamma ray. A principal reason for this correction effort was to ensure that a given core analysis was indeed from the COSS interval. Any core data shifted outside of the COSS interval were not used.

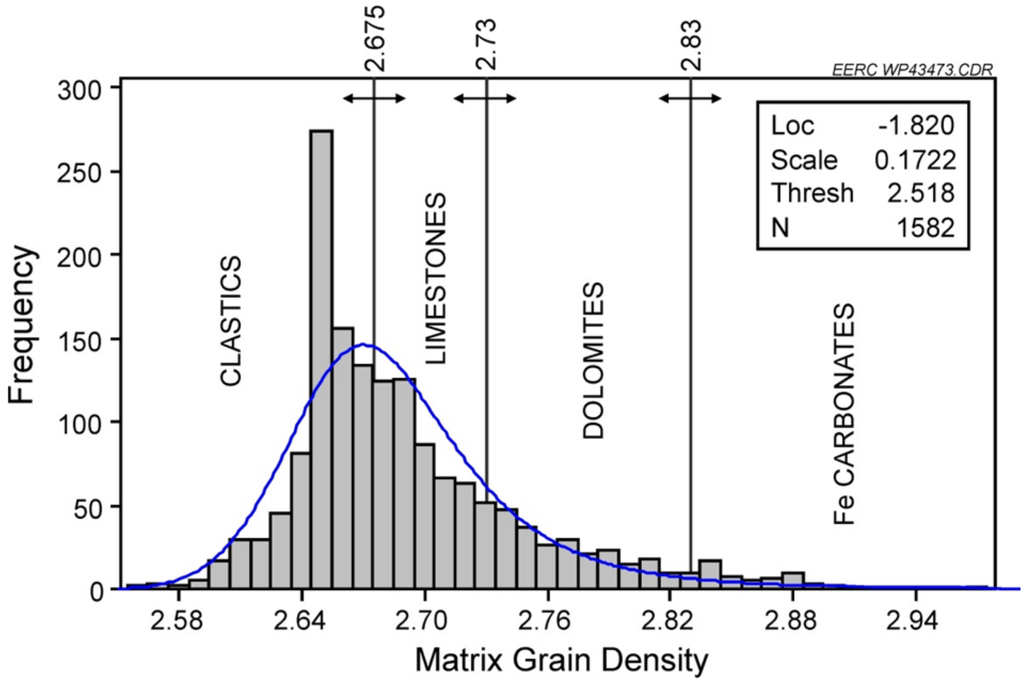


Figure 17. Histogram of core-derived grain density values with mineral bins.

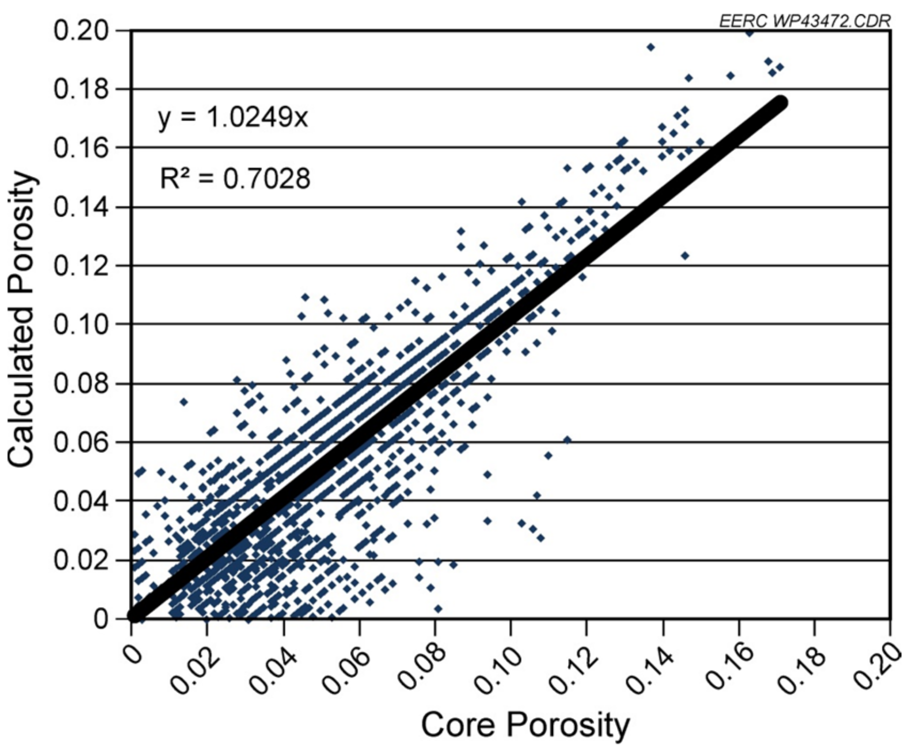


Figure 18. Calibration curve of core porosity versus calculated porosity.

Equation 5 was applied to each density value within each of the 94 wells having a LAS density curve. The resulting porosity values within each well were averaged over their respective interval thicknesses to create an average porosity for the control point. The porosity values range from 2% to 21%, with 8% being the mean on the U.S. side of the study.

It is recognized that a large area of eastern Montana has relatively few control well points for this effort. To propagate porosity values into this low-data-density area, a correlation between formation depth and porosity was derived (Figure 19). This relationship was used as a cokriging variable in the two-dimensional modeling methodology used to propagate porosity throughout the U.S. portion of the COSS region. Kriging models estimate values between known locations by a weighted averaging of nearby data based on a function of the geographic distance between the data points. Cokriging takes advantage of a correlation that may exist between the primary variable of interest, in this case porosity, and a more easily measured variable (depth). Cokriging is a versatile and rigorous statistical technique for spatial point estimation when both primary and secondary (covariate) attributes are available (Eldeiry and Garcia, 2009) (Figure 20).

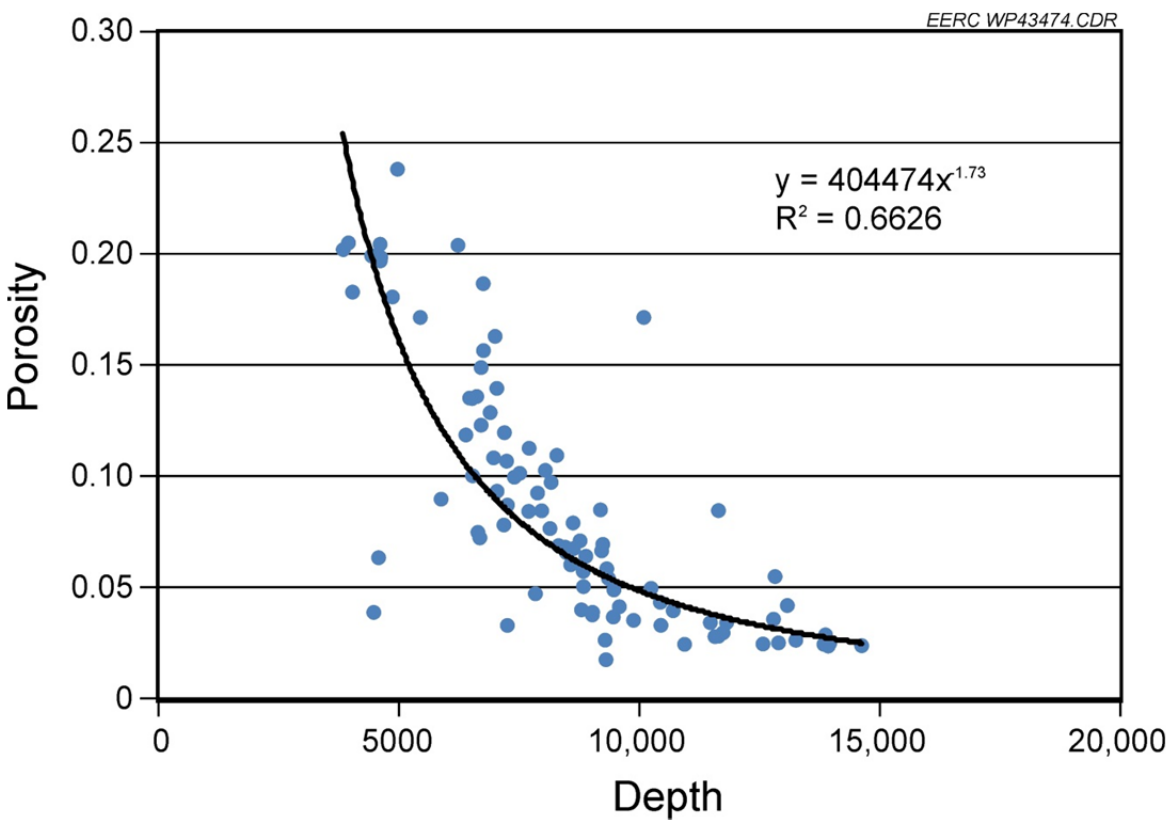


Figure 19. Correlation curve of measured depth versus porosity.

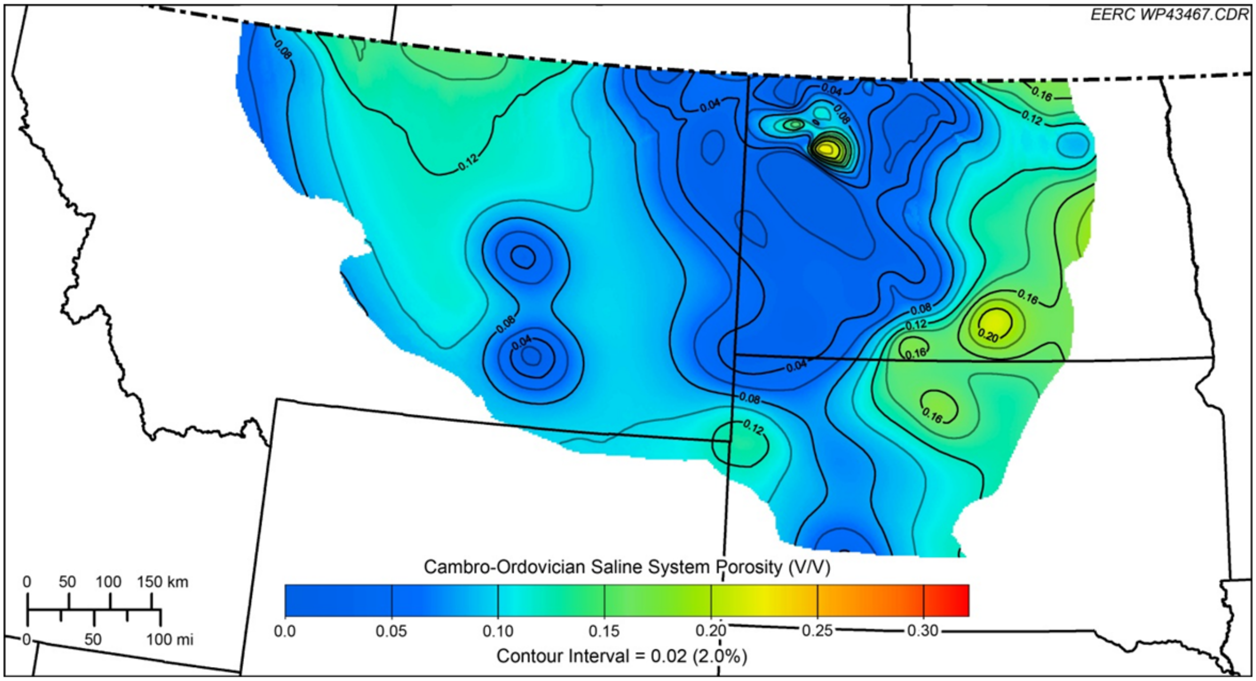


Figure 20. Porosity distribution map of the U.S. portion of the COSS.

## Determination of $CO_2$ Density

### *Temperature, Pressure, and $CO_2$ Density*

Formation temperature was derived by using calculated local gradients throughout the study area at the locations shown in Figure 15. These gradients extended across younger formations just overlying the COSS such as the Red River Formation. These gradients were then extrapolated down into the Cambrian-Ordovician Deadwood and Ordovician Black Island Formations of the COSS. These data were gathered from Tonnsen (1985) and Gosnold (1991). Most of the spatial locations of these points are local averages based on either the geometric centers of Montana oil and gas fields or groups of wells centered around North Dakota cities.

To determine pressure at the top of the COSS, a gradient of 14.7 + 0.6 psia/ft was used (Gorecki and others, 2009). Bachu and others (2011) reported minimal difference ($<10$ kg/m$^3$) between the density of $CO_2$ at the base and top of the COSS; thus, for all practical purposes, $CO_2$ density in this region can be regarded as constant within the system in the vertical direction at any particular point.

The calculated temperatures at the top of the COSS were then used with calculated pressures at depth to derive specific $CO_2$ densities at locations shown in Figure 15. The relationship of pressure, temperature, and density used in this effort was defined by the National Institute of Standards and Technology (2003). These densities were then interpolated across the U.S. portion of the COSS using the kriging function (Figure 21).

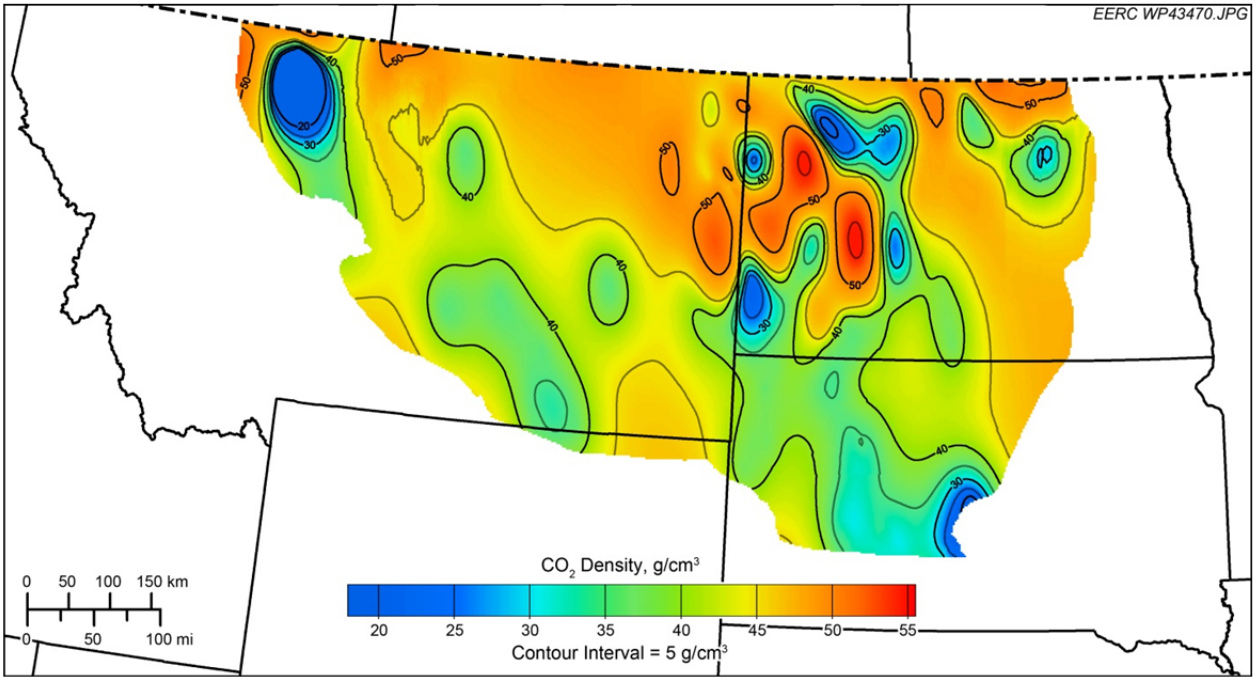


Figure 21. $CO_2$ density distribution map of the U.S. portion of the COSS.

### Determination of Mass

At this point in the modeling process, each grid cell has a value for thickness, area, porosity, and density. Each of these parameters was then multiplied together along with the efficiency factor of 2.4%. The product of this equation is the mass of $CO_2$ for each grid cell.

## MERGING THE DATA

The 2-D model for the Canadian side of the COSS study region was completed by AITF independently and prior to the U.S. effort. AITF had finalized the raster GIS maps for the storage resource distribution and each of the variables needed to calculate $CO_2$ resource capacity of the COSS (Bachu and others, 2011). This meant that the effort to combine the two sides would require 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 would ensure that the spatial propagation of the values for parameters such as thickness, porosity, and density on the U.S. side near the Canadian border would honor the existing data distribution on the Canadian side. To accomplish this effort, a strip of data from the Canadian side was incorporated into the data on the U.S. side along with well control points. The width of the strip was one degree of latitude and thus extended from the 49th to the 50th parallel. It was judged that this width would be sufficient to allow for a smooth transition of the data across the international line. The sequence of diagrams in Figure 22 illustrates the basic steps that were taken to create a seamless transition across the international border, thus eliminating any "border faults" that might otherwise occur. The number and distribution of well control points in the diagram, as well as the grid size, are only an example. Figure 22a shows an area near the U.S.–Canada border and the well control that will be used on the U.S. side to generate continuous surface maps of various geologic properties and, ultimately, the distribution of $CO_2$ storage resource capacity across this region. In Figure 22b, a strip of the existing Canadian data grid is incorporated along the border. The values for these individual grid cells are then converted to data points, as shown in Figure 22c. The density of the grid cell data points was thinned as the distance from the border increased. This thinning allowed the variogram associated with the Canadian data to remain valid. This validation was also supported by incorporating well control points on the Canadian side as shown in Figure 22c. The resulting set of data points on the Canadian side became part of the overall well control data set and was used when the geospatial algorithms were applied to create a continuous surface. Figure 22d shows the extent of the resulting data grid across the U.S.–Canada border. In the next step, the Canadian side of this result was clipped out, and the entire data grid from the Canadian side was joined to the newly created U.S. data grid, as shown in Figure 22e. The last step was to combine the two data grids into one complete version for the whole COSS region as shown in Figure 22f.

### Salinity Cutoff

In order to restrict the extent of the COSS suitable for $CO_2$ storage, a consideration for the salinity of the formation water has to be made. The current restriction states that $CO_2$ storage should take place in regions where water salinity is greater than 10,000 mg/L in order to protect underground sources of drinking water as defined by EPA. The delineation of the 10,000 mg/L isoline in the U.S. portion of the study region was developed in cooperation with AITF. Control for the line is based on drillstem tests from several wells in Montana, North Dakota, and South Dakota. The delineation in southeastern North Dakota is based on the work of Downey (1984). Gridded storage values outside the 10,000 mg/L isoline were clipped out of the preliminary modeling results. This trimming process removed a sizable portion of the model in east-central Montana and southeastern North Dakota and can be seen when comparing Figures 16 and 23.

## RESULTS

The integration of the various datasets of spatially distributed geologic properties of the COSS results in a $CO_2$ storage resource value of 28 Gt for the U.S. portion of the COSS. 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 the U.S. portion of the map shown in Figure 23. This final map illustrates the seamless spatial distribution and variability of the geologic storage resource of the COSS across the study region. When combined with the 85 Gt reported by Bachu and others (2011) for the Canadian portion, it results in a grand total of 113 Gt of $CO_2$ storage resource potential at the P50 probability level for the COSS. 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 is shown in Table 1. The saline efficiency factors used in the table are from Goodman and others (2011).

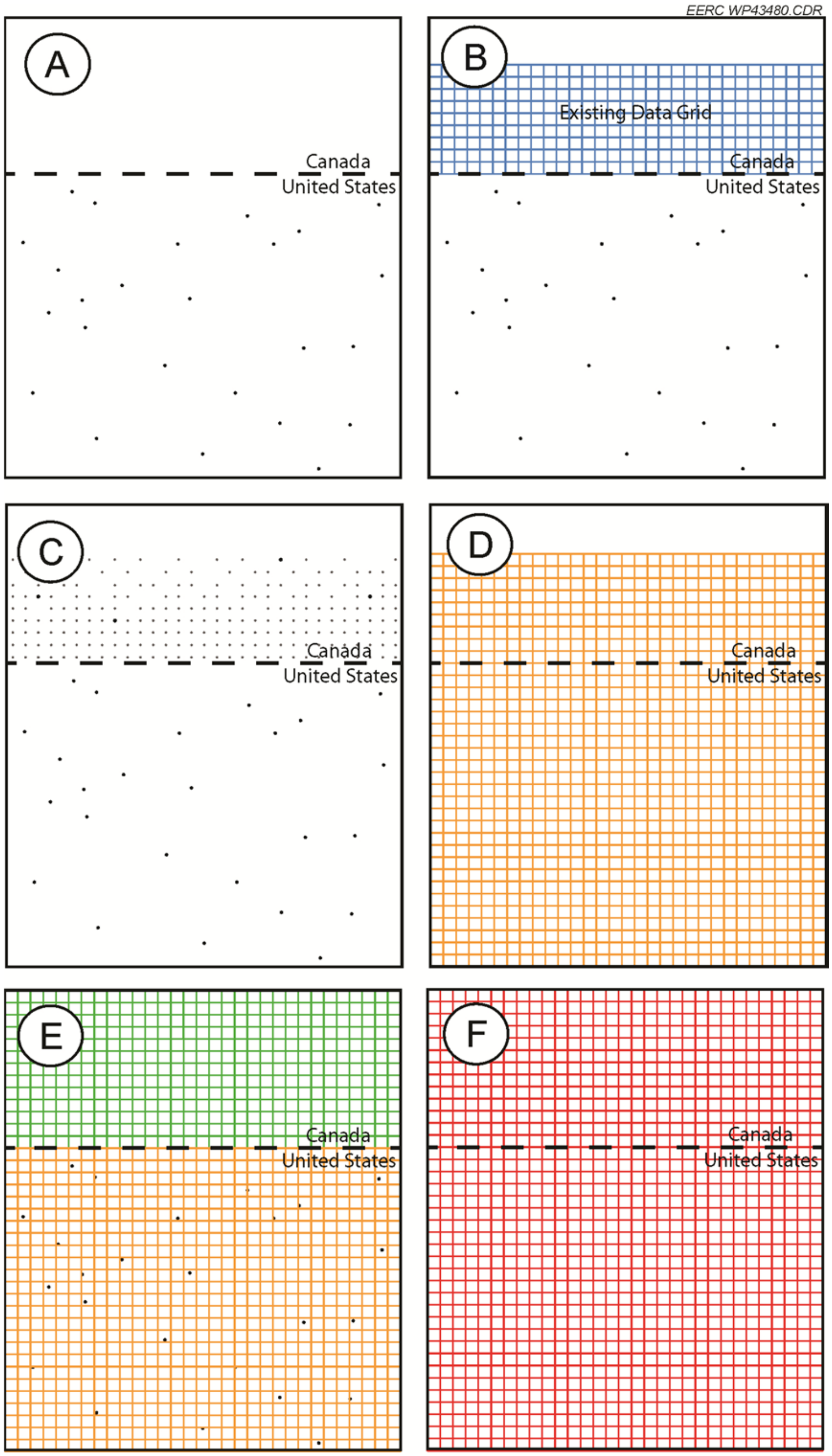


Figure 22. Graphical representation of the steps taken to apply the diffusive aggregation method to join the Canadian and U.S. data sets.

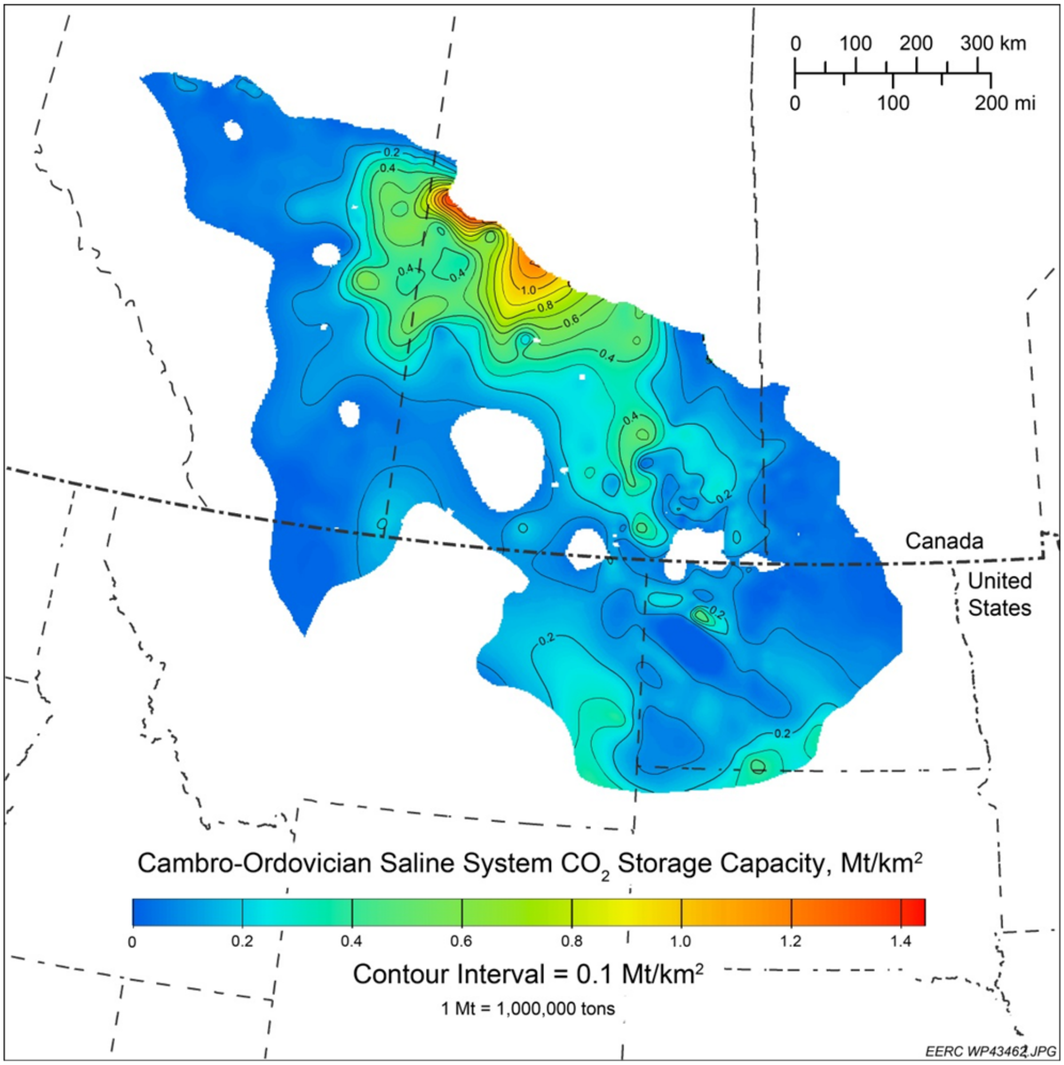


Figure 23. Final seamless $CO_2$ storage distribution map for the entire COSS.

**Table 1. Range of $CO_2$ Resource Estimates for the U.S. and Canadian Portions of the COSS at the P10, P50, and P90 Probability Levels**

| | | | |
|---|---|---|---|
| Saline Formation Efficiency Factor | 1.2% | 2.4% | 4.1% |
| Probability | P10 | P50 | P90 |
| United States | 14 Gt | 28 Gt | 48 Gt |
| Canada | 43 Gt | 85 Gt | 145 Gt |
| Total | 57 Gt | 113 Gt | 193 Gt |

## THE NEXT STEP

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 average values for the 2-D model will contribute significantly to the $CO_2$ storage resource in the 3-D model.

## SUMMARY

At the base of the sedimentary succession in the Williston and Alberta Basins of the northern Great Plains–Prairie region of North America is a saline system composed of variable lithology which includes a variety of clastic and carbonate facies deposited across a range of depositional 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 encompass 1.34 million-$km^2$ and extend from west-central Alberta into Saskatchewan and southwestern Manitoba and then south into Montana, North Dakota, and South Dakota to form an extensive saline system generally devoid of hydrocarbon resources. A 3-year binational effort between the United States and Canada is under way to characterize this basal system in the northern Great Plains–Prairie region of North America and to evaluate the potential for, and effects of, $CO_2$ storage in this system.

The initial phase of this project focused on delineating and characterizing separately the Canadian and U.S. portions of the COSS. This report describes the effort to characterize the U.S. portion of the region and how the data from the two countries were brought together into a single geologic model. The completed 2-D model incorporates the geologic data collected in the baseline characterization effort and distributes the various rock properties throughout the study region through geostatistical methods. Data regarding depth, thickness, and porosity were distilled to produce components needed to compute the $CO_2$ storage resource of this saline system following the Esaline formula detailed by the DOE methodology.

Frequent and unfortunate by-products of the individual efforts conducted in this central interior portion of North America are evaluations and related maps that show a "fault line" (discontinuity) at the U.S.–Canada border. Evaluating the capacity and effects of $CO_2$ storage in the Canadian or U.S. portions of the Williston basin should not be done in isolation. The regional geology of sedimentary basins is not influenced by political boundaries. To ensure that an international "fault line" was not part of the final product, a significant part of the effort was to match the work done on the U.S. side of the study region with the data sets generated by Alberta Innovates Technology Futures (AITF) for the Canadian side. A diffusive aggregation method was successfully employed near the U.S.–Canadian border to form a seamless $CO_2$ 2-D model and $CO_2$ storage distribution map for the entire COSS international study region.

The $CO_2$ storage resource derived from the resulting 2-D model for the U.S portion of the COSS was determined to be 28 Gt at the P50 probability level. When added to the 85 Gt of storage resource determined from the Canadian effort, this results in a combined $CO_2$ storage resource of 113 Gt. This work also provides the groundwork for the development of a massive 3-D geologic model encompassing the entire study area.

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