SEQUESTRATION POTENTIAL OF THE MADISON OF THE NORTHERN GREAT PLAINS AQUIFER SYSTEM
(Madison Geological Sequestration Unit)

David W. Fischer, Energy & Environmental Research Center
Steven A. Smith, Energy & Environmental Research Center
Wesley D. Peck, Energy & Environmental Research Center
Julie A. LeFever, North Dakota Geological Survey
Richard D. LeFever, University of North Dakota – Geology/Geological Engineering
Lynn D. Helms, North Dakota Industrial Commission
James A. Sorensen, Energy & Environmental Research Center
Edward N. Steadman, Energy & Environmental Research Center
John A. Harju, Energy & Environmental Research Center

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EXECUTIVE SUMMARY

A large regional aquifer system underlies much of the northern Great Plains physiographic province. The northern Great Plains aquifer system consists of a series of five aquifers that have similar geohydrological characteristics. In general, fluid flow in this system is to the north and northeast. Recharge of the aquifers is from in the Black Hills and Rocky Mountains to the west. Aquifers in the system have significant regional sequestration potential.

For the Madison Aquifer (hereafter referred to as the Madison "geological sequestration unit" [GSU]) of the northern Great Plains aquifer system, a reconnaissance sequestration volume of 60 billion tons (980 trillion cubic feet of gas [TCFG]) has been calculated (see Methodology Section) for CO_2. The Madison GSU underlies much of the Williston and the Powder River Basins.

ACKNOWLEDGMENTS

BACKGROUND/INTRODUCTION

As one of seven Regional Carbon Sequestration Partnerships (RCSPs), the Plains CO_2 Reduction (PCOR) Partnership is working to identify cost-effective carbon dioxide (CO_2) sequestration systems for the PCOR Partnership region and, in future efforts, to facilitate and manage the future demonstration and deployment of these technologies. In this phase of the project, the PCOR Partnership is characterizing the technical issues, enhancing the public's understanding of CO_2 sequestration, identifying the most promising opportunities for sequestration in the region, and detailing an action plan for the demonstration of regional CO_2 sequestration opportunities. This report focuses on briefly describing the Madison Aquifer (herein referred to as the Madison "geological sequestration unit" [GSU]) of the northern Great Plains aquifer system and reviewing its potential as a regional CO_2 sequestration unit. Using published geological data, a calculated reconnaissance storage volume shows the aquifer has significant potential as a regional sequestration unit.

EERC ES25493.CDR

Modified from:
Ross, C.P., Andrews, D.A., and Witkind, I.J., 1955, Geologic map of Montana: U.S. Geological Survey, scale 1:5,000,000, 2 sheets.
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EXPLANATION

- Lower Tertiary aquifers
- Upper Cretaceous aquifers
- Lower Cretaceous aquifers
- Paleozoic aquifers
- Not a principal aquifer
- Confining unit
- -------- Southern limit of continental glacial deposits

Aquifers and Confining Units of the Northern Great Plains Aquifer System

taken from: USGS Groundwater Atlas

http://capp.water.usgs.gov/gwa/ch_i/gif/lo49.GIF

Figure 1. Northern Great Plains aquifer system.

The Williston and Powder River Basins are part of a larger regional geohydrological province called the northern Great Plains aquifer system (Downey et al., 1987; Busby et al., Downey, 1986; Downey, 1989; Downey and Dinwiddie, 1988; Brown et al., 1984; Downey, 1984). An aquifer system is defined as a series of geologic formations (aquifers) that exhibit similar geohydrology.

The northern Great Plains aquifer system is a large (approximately 300,000-square-mile) complex geohydrological system (Downey et al., 1987; Busby et al., Downey, 1986; Downey, 1989; Downey and Dinwiddie, 1988; Brown et al., 1984; Downey, 1984). It underlies North Dakota, most of South Dakota, much of Montana, northeastern Wyoming, the northwest tip of Nebraska, southern Manitoba, and southeastern Saskatchewan (Figure 1). 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 (Figures 2 and 3). Recharge areas are primarily highlands, including the Rocky Mountains and the Black Hills to the west.

The stratigraphic column of the northern Great Plains has been divided into a series of five principal aquifers and four principal confining units (Downey et al., 1987; Busby et al., Downey, 1986; Downey, 1989; Downey and Dinwiddie, 1988; Brown et al., 1984; Downey, 1984). Each aquifer is a potential regional sequestration unit. The aquifers have been numbered in ascending order, with the prefix AQ representing an aquifer system and TK representing a confining unit or aquitard. Although not discussed by Downey or USGS, Bachu and Hitchon (1996) recognize a similar geohydrological system in Canada (Figure 4).

USGS has published a Web-based groundwater atlas that includes the northern Great Plains system at http://capp.water.usgs. gov/gwa/ch_i/ I-text1.html.

MADISON GEOLOGICAL SEQUESTRATION UNIT (AQUIFER)

The Madison GSU (aquifer) underlies both the Williston and Powder River Basins. It has the potential to be a significant sequestration unit in the PCOR Partnership region.

In the Williston Basin, the Madison is given group status and divided into three formations, which in ascending order are the Lodgepole, Mission Canyon, and the Charles. Rocks of the Lodgepole and Mission Canyon Formation are carbonates and have porosity; the Charles Formation is dominated by evaporites (salts and anhydrites) and lacks permeability; together they are classified as the Madison (AQ2; USGS designation) GSU. These formations are conformable in the basin center and unconformable along the basin margin. The Madison Group is the primary oil-producing interval in the Williston Basin. In the Powder River Basin, the Madison is not subdivided, and the equivalent stratigraphic unit is called the Madison limestone.

Madison sediments were deposited in a relatively stable, broad, and shallow epicontinental sea. Depositional facies of the Madison are carbonates and evaporites. They were deposited in a series of shallowing, upward-regressive cycles in an offlapping or regressive relationship. The Mission Canyon and Charles Formations are further subdivided into informal intervals. In ascending order, the intervals of the Mission Canyon are the Tilston and the Frobisher Alida. The Charles Formation is subdivided into a lower Ratcliffe interval and upper Poplar interval. In addition, these intervals are further subdivided into informally named beds (Harris et al., 1965; Voldseth, 1987).
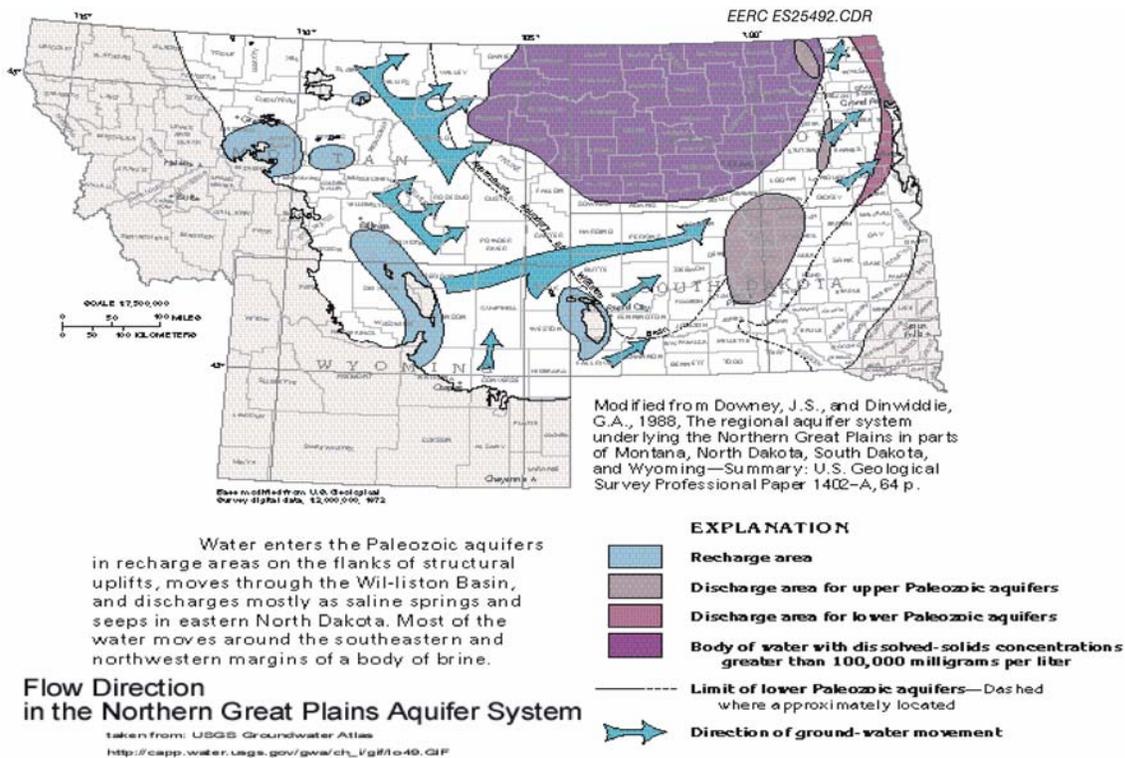
Figure 2. Flow direction in the northern Great Plains aquifer system.
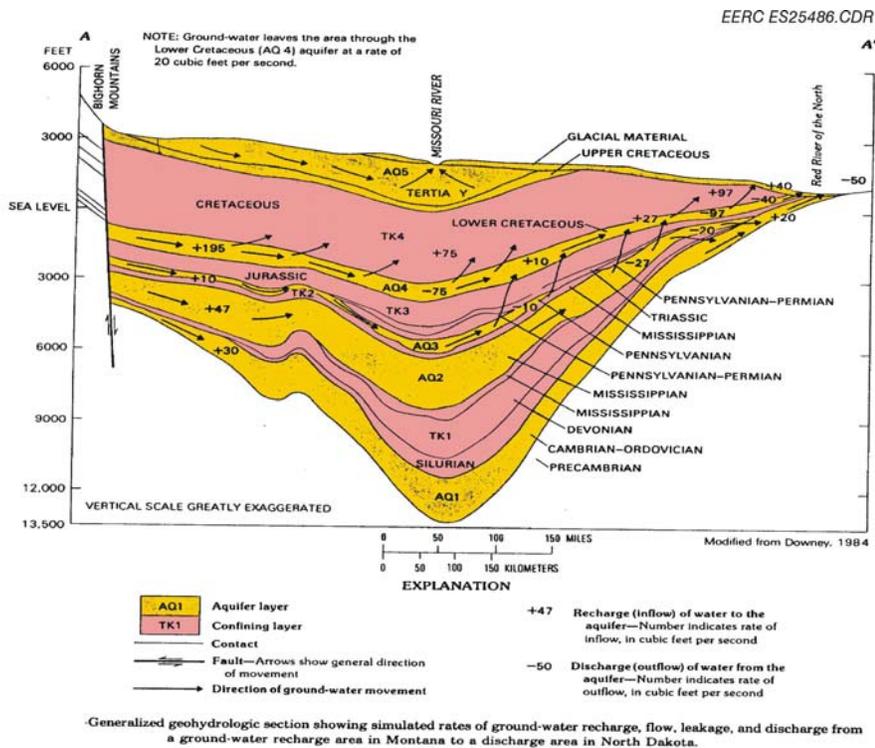
Figure 3. Generalized geohydrological section of the northern Great Plains aquifer system.

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Age Units			YBP (Ma)	Rock Units (Groups, Formations) USA[1] (ND)	Canada[2] (SK)	Hydrogeologic Systems[3] USA	Canada	Sequences[4]	Potential Regional Sequestration Units
Phanerozoic	Cenozoic	Quaternary	1.8		Wood Mountain Fm	AQ5 Aquifer	Upper Aquifer System	Tejas	
		Tertiary	66.5	White River Grp / Golden Valley Fm / Fort Union Grp	Ravenscrag Fm				Fort Union Coal Seams
	Mesozoic	Cretaceous	146	Hell Creek Fm, Fox Hills Fm, Pierre Fm, Judith River Fm, Eagle Fm, Niobrara Fm, Carlile Fm, Greenhorn Fm, Belle Fourche Fm, Mowry Fm, Newcastle Fm, Skull Creek Fm, Inyan Kara Fm (Colorado Group / Dakota Group)	Frenchman Fm, Whitemud Fm, Eastend Fm, Pierre Fm, Bearpaw Fm, Judith River Fm, Milk River Fm, First White Speckled Shale, Niobrara Fm, Carlile Fm, Second White Specks, Belle Fourche Fm, Fish Scales Fm, Westgate Fm, Viking Fm, Joli Fou Fm, Mannville Group	TK4 Aquitard	Cretaceous Aquitard System	Zuni	
						AQ4 or Dakota Aquifer	Viking Aquifer / Joli Fou Aquitard / Mannville Aquifer System		Dakota Sequestration Unit
		Jurassic	200	Swift Fm, Rierdon Fm, Piper Fm	Success Fm, Masefield Fm, Rierdon Fm, Upper Watrous Fm	TK3 Aquitard	Mississippian-Jurassic Aquitard System		
		Triassic	251	Spearfish Fm	Lower Watrous Fm			Absaroka	
	Paleozoic	Permian	299	Minnekahta Fm, Opeche Fm	Missing				
		Pennsylvanian	318	Broom Creek Fm, Amsden Fm, Tyler Fm (Minnelusa Group)		AQ3 Aquifer			Minnelusa Sequestration Unit
		Mississippian	359	Otter Fm, Kibbey Fm, Charles Fm, Mission Canyon, Lodgepole Fm (Madison Group)	Charles Fm (Poplar Mbr, Ratcliffe Mbr, Midale Mbr), Mission Canyon Fm (Frobisher Mbr, Alida Mbr, Tilston Mbr), Lodgepole, Souris Valley (Madison Group)	TK2 Aquitard / AQ2 or Madison Aquifer	Mississippian Aquifer System	Kaskaskia	Oil Fields and Madison Seq. Unit / Lodgepole Mud Mounds
		Devonian	416	Bakken Fm, Three Forks, Birdbear, Duperow, Souris River, Dawson Bay, Prairie, Winnipegosis, Ashern	Bakken Fm, Big Valley Fm, Three Forks, Birdbear, Duperow, Souris River, Dawson Bay, Prairie, Winnipegosis, Ashern	TK1 Aquitard	Bakken Aquitard / Devonian Aquifer System / Prairie Aquitard / Winnipegosis Aquifer / Silurian/Devonian Aquitard		Winnipegosis Seq. Unit
		Silurian	444	Interlake Fm	Interlake Fm			Tippecanoe	
		Ordovician	488	Stonewall Fm, Stony Mountain Fm, Red River Fm, Winnipeg Grp	Stonewall Fm, Stony Mountain Fm, Red River Fm, Winnipeg Grp	AQ1 Aquifer	Basal Aquifer System		Red River Oil Fields / Sands of Winnipeg Grp
		Cambrian	542	Deadwood Fm	Deadwood Fm			Sauk	Sands and Oil Fields
Precambrian	Proterozoic		2500	Metasedimentary rocks of the Trans Hudson Orogen					
	Archaen			Granites and greenstones of the Superior Craton and metamorphic rocks of the Wyoming Craton					

1) Bluemle, J.P., Anderson, S.B., Andrew, J.A., Fischer, D.W., and LeFever, J.A., 1986, North Dakota Stratigraphic Column, North Dakota Geological Survey, Miscellaneous Series #66.

2) Saskatchewan Industry and Resources, 2003, Geology and Mineral and Petroleum Resources of Saskatchewan, Miscellaneous Report 2003-7.

3) Bachu, S., and Hitchon, B., 1996, Regional-scale flow of formation waters in the Williston Basin: AAPG Bulletin, v. 80, no. 2, p. 248–264.

4) Fowler, C.M.R., and Nisbet, E.G., 1985, The subsidence of the Williston Basin: Canadian Journal of Earth Sciences, v. 22, no. 3, p. 408–15.

Figure 4. Regional stratigraphic column including hydrogeological systems.
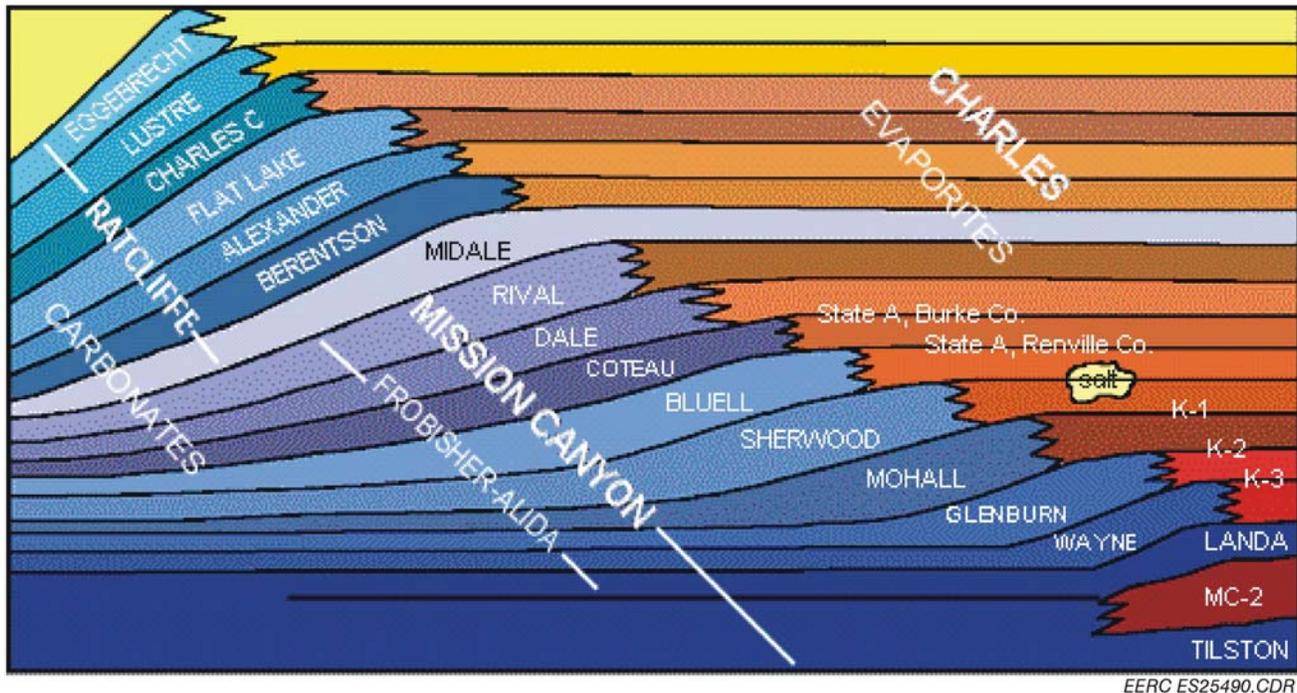
Figure 5. Generalized Madison depositional sequence.

Each bed represents an individual shallowing, upward cycle, culminating in evaporite deposition of the Charles Formation (Figure 5).

Madison-age sediments are present throughout most of the northern Great Plains. The Madison GSU (AQ2) underlies over 200,000 square miles of the northern Great Plains (Downey, 1984). Sediment thickness is in excess of 2000 feet in the center of the Williston Basin (Figure 6). Generally, the lower portion of the Madison is described as being limestone, massive to thinly bedded, argillaceous, and cherty in part (Peterson, 1984). The middle portion of the section is generally limestone, with some dolomites. The dolomites are better developed along the depositional margins and best developed along the northeast flank of the Williston Basin. The upper part of the Madison comprises bedded limestones, dolomites, anhydrites, and

halite. The anhydrites are thought to represent shoreline (sabkha) deposition. The halites most often are found in the basin center and represent restricted marine conditions.

Porosity distribution in the Madison GSU is highly variable and discontinuous (Peterson, 1984). In general, the porosity appears to be best developed in dolomites along the eastern portion of the Williston Basin. Better porosities are often found in association with nearshore or island shoaling (Hendricks et al., 1987). USGS has prepared a regional reconnaissance porosity thickness and distribution map of the Madison Aquifer (Figure 7). Understanding the distribution of porosity is the critical factor in calculating CO_2 sequestration volume. The currently available data will only allow for a rough estimation (order of magnitude) of a sequestration volume. In order to calculate

EXPLANATION

MISSISSIPPIAN OR OLDER ROCKS—Exposed at land surface

—600— LINE OF EQUAL THICKNESS OF MADISON LIMESTONE—Interval 200 feet

PROJECT-AREA BOUNDARY
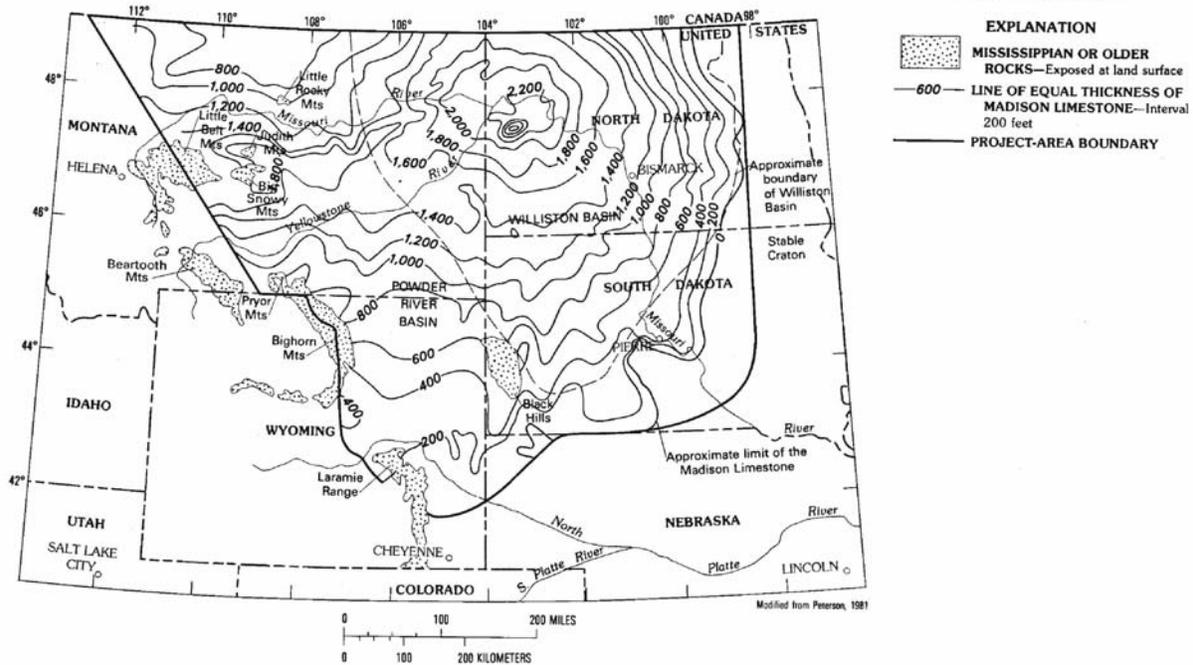
Thickness and extent of the Madison Limestone of Mississippian age in the northern Great Plains.

Taken from USGS Professional Paper # 1402 F

Figure 6. Thickness of the Madison in the northern Great Plains.

more exact sequestration values, more detailed mapping of the porosity distribution will be needed. Determining the competency of upper and lower confining units for the Madison GSU is not straightforward.

With respect to the lower confining unit, all but the eastern part of it is underlain by a regional confining unit that consists of tight limestones of Silurian and Ordovician age and impermeable shales of the Bakken Formation of Mississippian/Devonian age (TK1; USGS designation). No confining beds underlie the aquifer in the very eastern portion of the basin. In this area, water flow will occur from the AQ2 into the underlying AQ1 and eventually be discharged into surface sediments in eastern North Dakota (Figure 3).

There is not a single continuous seal above the Madison. Overlying much of the AQ2 are evaporites of the Mississippian-age Charles Formation (TK2; USGS designation). Where present, these evaporites may represent a very competent primary seal. Beyond the depositional limit of that seal in central North Dakota, Downey (1984) suggests the overlying confining layer is absent or thin (Figure 8). Downey et al. (1987) recognize potential for vertical leakage from it (Figure 3).

Beyond the limit of the primary confining unit are rocks of Jurassic and Triassic age. Primarily impermeable carbonates and clastics, they have been classified as the TK3 (USGS designation). Work done by the International Energy Agency (IEA) greenhouse gas (GHG) Weyburn CO_2

8
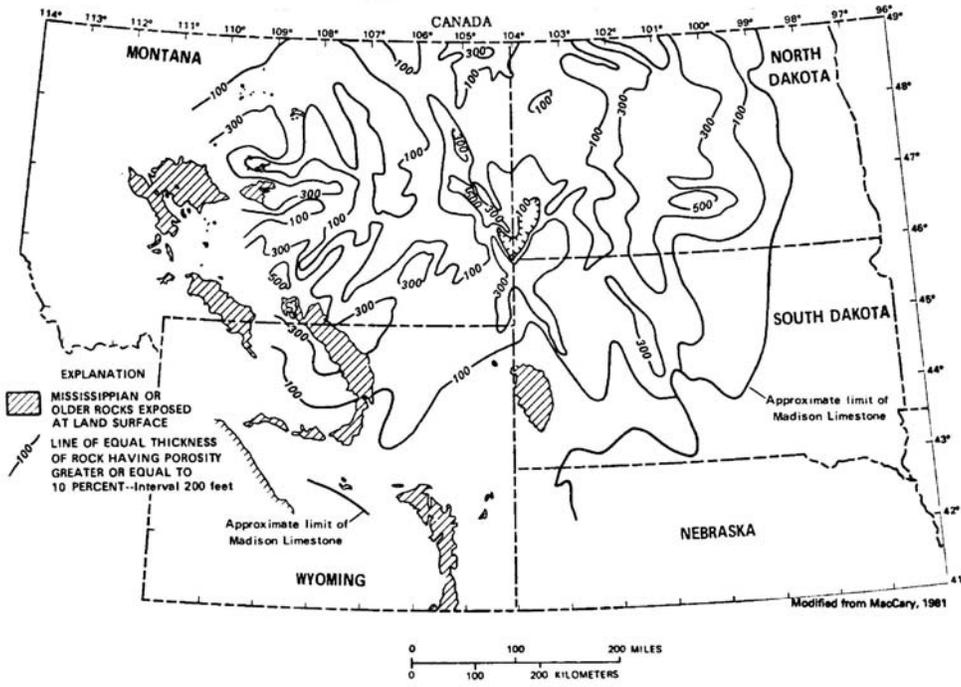
Figure 7. Porosity distribution in the Madison.
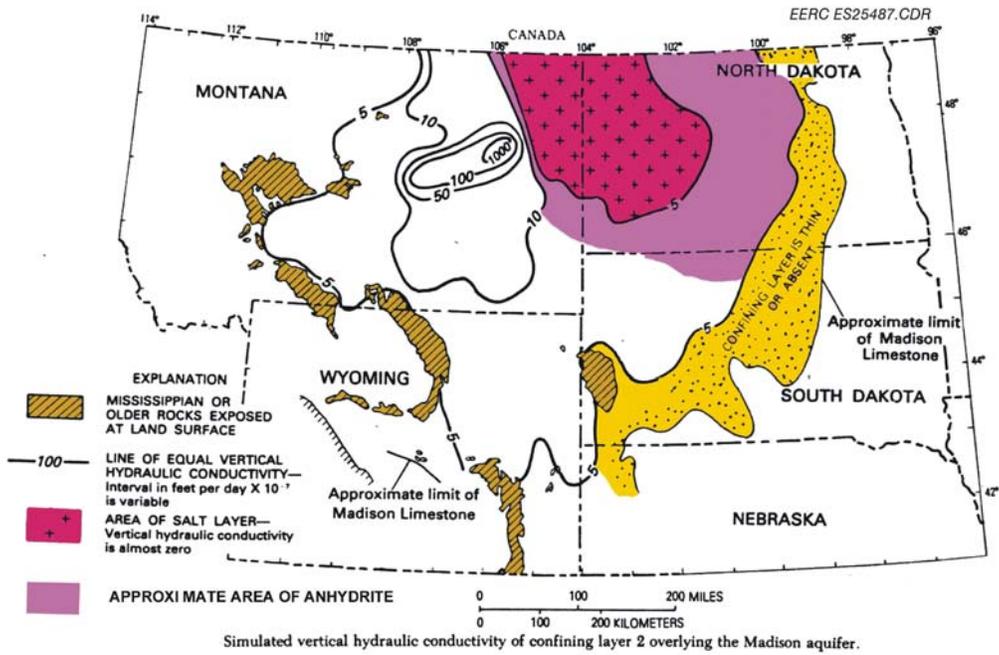
Figure 8. Simulated vertical hydraulic conductivity of unit overlying the Madison.

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Monitoring and Storage Project (2004) has concluded that rocks of the Jurassic and Triassic (TK3 equivalent) "form a regionally extensive and competent aquitard." Additional work will be needed to determine the stratigraphic relationship between the sequestration unit and the potential top seals to determine the regional competency of that seal. Fluid flow is also possible through faults and fractures that may be associated with lineaments. Flow in these conduits, if present, will be faster than regional flow rates.

Fluid flow in the Madison Aquifer is from the west, southwest to the north, northeast (Figure 2). Recharge of the aquifer occurs in highland areas to the west, in the Rocky Mountains and the Black Hills. Flow direction appears to be reversed in a portion of southwestern Manitoba (LeFever, 1998). This anomaly is due to pseudorecharge associated with the local disposal of produced oil field brines into the aquifer. Flow rates in the Madison vary from a few feet a year to about 75 feet a year (Figure 9).

Water quality in the Madison Aquifer varies greatly. Dissolved solids range from less than 500 mg/L near the Black Hills uplift to in excess of 300,000 mg/L in the center of the Williston Basin (Figure 10). Flow direction in the AQ2 aquifer system may be modified by an area of high-density brine (Figure 2) in the central portion of the basin (Downey et al., 1987; Brown et., 1984; Downey, 1984). Downey considers three hypotheses regarding hydrologic flow in the brine area. The first is that the brine is static. Second, the brine area is static, with low but consistent flow velocities through it. The third is that the brine area is migrating with regional waterflow to the northeast in an "attempt to adjust to changes to recharge and discharge associated with the end of Pleistocene glaciations." Downey et al. believe that the second hypothesis seems to be the best fit

to his digital models. Each hypothesis will have to be considered in modeling CO_2 sequestration in these aquifer systems. Downey (1984) prepared a detailed simulation model for the Madison GSU. In this model, he calculated the transmissivity (Figure 11) as well as the vertical hydraulic conductivity of the overlying TK2 confining unit (Figure 8).

METHODOLOGY FOR CALCULATING SEQUESTRATION VOLUME

In order to calculate the sequestration potential for the Madison GSU, a model was developed to produce a continuous gridded surface representing the volume of CO_2 that could be sequestered per square kilometer. In general, the model is based on existing data relating to hydrological studies of regional aquifer systems; oil, gas, and water well data; and existing GIS (geographic information system) map data.

The calculation used is a straightforward estimate that relates the pore volume in the reservoir (area × thickness × porosity) and the solubility of CO_2 as a function of NaCl concentration in the reservoir water at spatially varying pressures and temperatures. Solubility factors for temperatures and concentrations in excess of 200°F and 200,000 ppm NaCl, respectively, were not readily available at the time of this study (temperatures and concentration values are routinely above these values in the Powder and Williston Basins). As such, data were extrapolated to above 500°F and 300,000 ppm from tables provided through personal communication with the Indiana Geological Survey (April 2004) in order to attain the necessary solubility correction factors. This methodology is a modification of the MIDCARB CO_2 sequestration tool. The MIDCARB CO_2 sequestration tool was modified by extrapolating the solubility parameters of CO_2 in water to account for the higher temperature and salinity present in the study area.
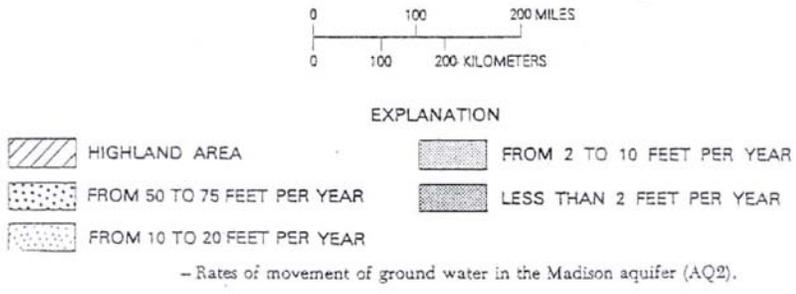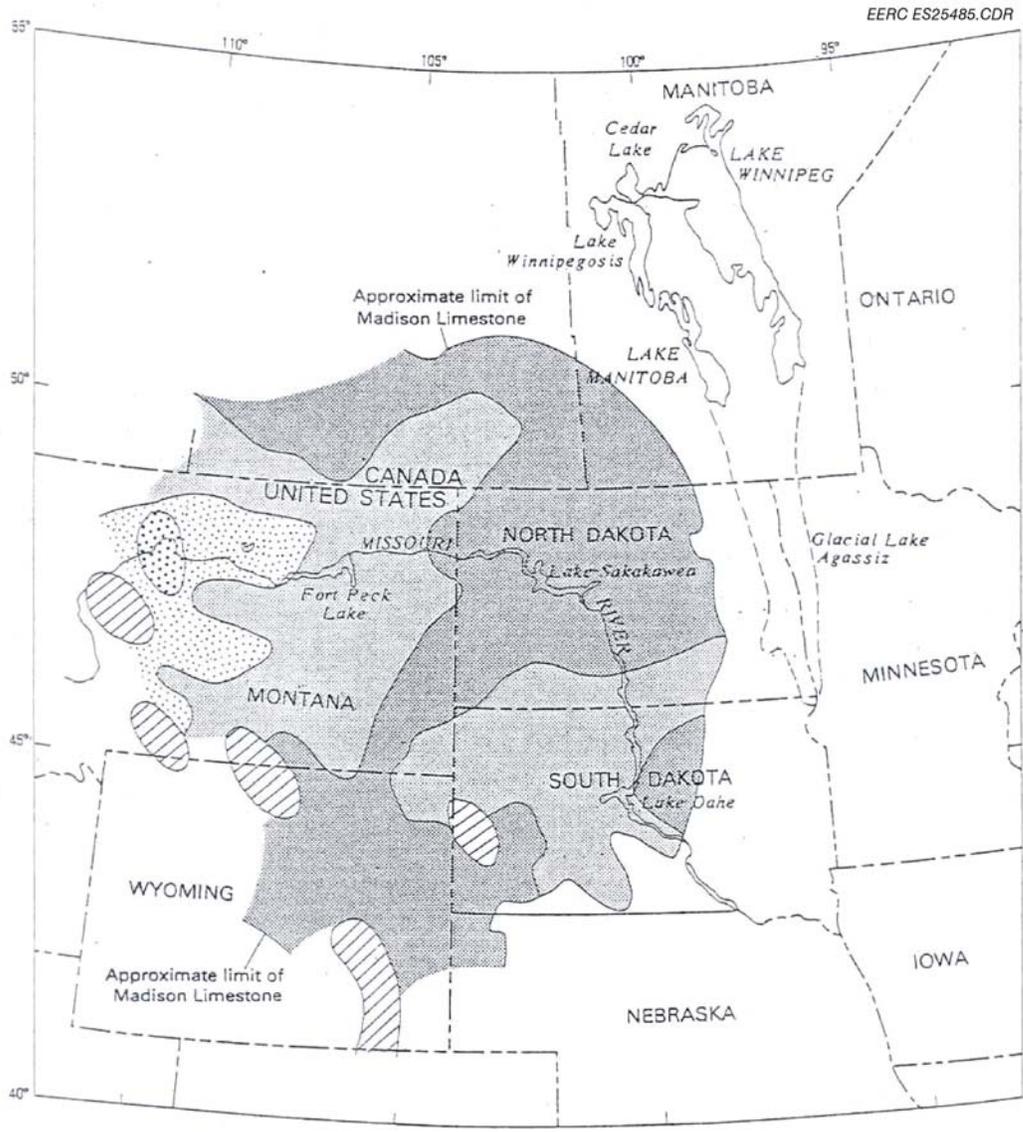
Figure 9. Rates of water movement in the Madison.
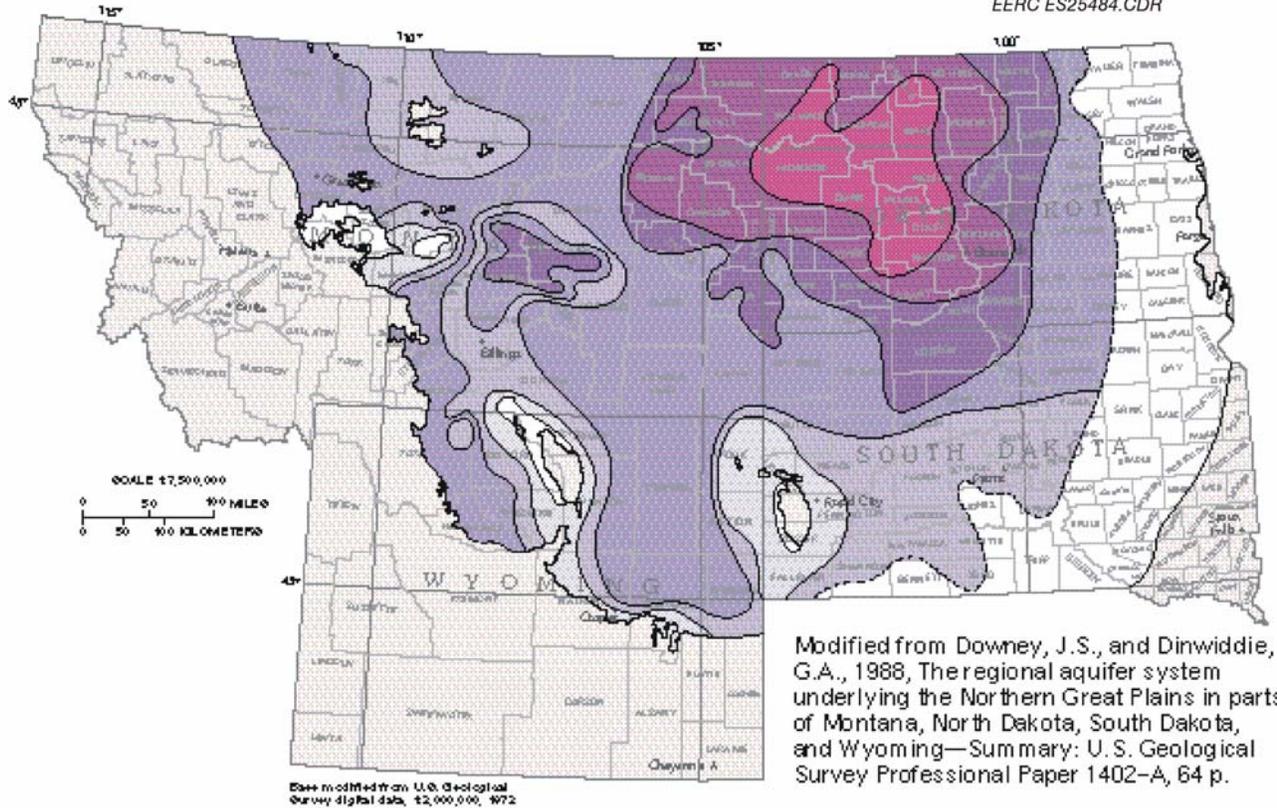
Figure 10. Dissolved solids in the northern Great Plains aquifer system.

The calculation is as follows:

$$Q = 7758 * (A) * (T) * (\varphi) * (CO_2s)$$

where Q = CO_2 remaining in the aquifer after injection (ft³), 7758 = (43,560 ft²/acre) × (0.178 bbl/ft³), A = area (acres), T = producing interval thickness (ft), Φ = average reservoir porosity (%), and CO_2s = solubility of CO_2 (ft³/bbl).

Surfaces of continuous data were generated from digitizing specific analog maps of the Williston and Powder River
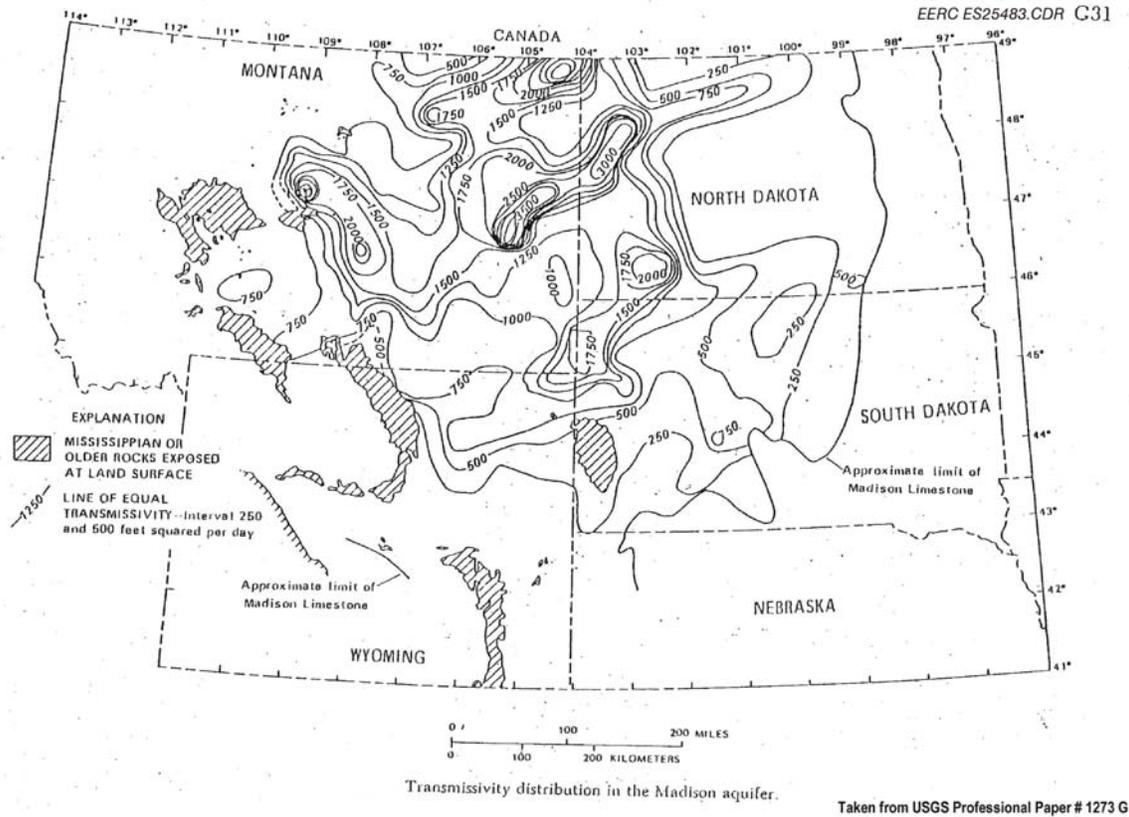
Figure 11. Transmissivity distribution of the Madison.

Basins. The natural neighbor method of grid generation was applied to the digitized data. This method was used for both interpolation and extrapolation of results, as it generally works well with clustered scattered points. A list of the maps used is shown below:

- Porosity/thickness distribution (Downey, 1984)
- Total dissolved solids (Downey, 1984)
- Structure contour map (Peterson, 1984)

The depth to the top of the Madison Group (North Dakota definition), or equivalent, was obtained from log top databases for Montana, North Dakota, and South Dakota. Data for the northern portion of the Powder River Basin were derived from an analog map of the Madison Formation (Peterson, 1984). The combined data set

was used to create a continuous surface depth map. From this, a new set of maps was generated for pressure and temperature of the Madison throughout the region. It should be noted that these maps are based on average temperature and pressure gradients of (15°F/1000 ft) + 60°F and 0.46 psi/ft, respectively, obtained from Schlumberger oil field services Web site (www.glossary.oilfield.slb.com). The net result of the exercise was the creation of a continuous surface map at 1-kilometer resolution (based on the above discussion) that represents an estimate of the total storage capacity of the Madison GSU.

SEQUESTRATION POTENTIAL

A reconnaissance sequestration volume of 60 billion tons (980 trillion cubic feet of gas [TCFG]) has been calculated (see Methodology Section) for CO_2 dissolved in

saline water for the Mississippian Madison GSU in a portion of the northern Great Plains, including a large part of the Williston Basin and the Powder River Basin (Figures 12 and 13). Additional data will need to be collected in order to calculate a sequestration volume in Saskatchewan and Manitoba and to refine this calculation.

Areas of maximum sequestration potential are coincident with the depositional margin of the basin during Madison time. Porosity distribution and water salinity appear to be the primary mechanisms in controlling sequestration volumes in the northern Great Plains. Porosity in the Madison is better developed along the basin margin (Peterson, 1984; Hendricks et al., 1987) associated with increased dolomitization and/or shoaling events. Salinity may be the single most critical factor in adversely affecting the solution of CO_2 in a brine in the region, certainly in the Williston Basin. A large area of very dense brine (in excess of 300,000 ppm TDS [total dissolved solids]) is present in the center of the Williston Basin. The effect of high salinity is to decrease the solubility of CO_2 in the water by severalfold.

In general, the location of major CO_2 sources is a good match with the maximum Madison sequestration potential (Figure 12). A concentration of power-generating plants in central North Dakota is located favorably for sequestration of CO_2 in the Madison GSU. The potential is present to sequester 2 billion tons within a 50-mile radius of the approximate center of the plant grouping (Figure 14). Normal lateral groundwater flow rates in the Madison in central North Dakota are to the northeast and are less than 2 feet per year. Transit times are, therefore, favorable for long-term regional storage. Locally, evaporites of the TK2 and, more regionally,

impermeable rocks of the TK3 confining units overly the top of the Madison sequestration unit and may represent a competent top seal.

RESULTS

The estimated storage capacity of the Madison, as calculated using the method described previously, represents 700 years of CO_2 production from all sources in North Dakota, Montana, South Dakota, and Wyoming that lie above the aquifer. Practically speaking, the actual volume of CO_2 that may be stored in the Madison will be significantly lower than the calculated estimates shown above. Large portions of the Madison may be ruled out for a variety of reasons, including regions with incompetent seals that may allow leakage, areas of inadequate porosity and excessively high salinity that will limit dissolution to the point of impracticality, and prohibitive distance of some areas from large CO_2 sources. Additional work will be necessary prior to development of more exact sequestration volume calculation. Specifically, a more detailed porosity thickness and distribution map is required. Detailed porosity data are not available and will need to be generated.

The regional leakage potential, although likely small, will have to be further investigated. Tectonic zones of weakness (refer to PCOR Partnership topical report: An Overview of the Tectonic History of the Williston Basin) will have to be investigated for leakage potential prior to large-scale regional sequestration. Detailed stratigraphic study will have to be done to determine the areal extent, character, and relationship between the beds confining the sequestration unit and the unit itself. More detailed geohydrodynamic modeling may also be required to better characterize inter- and intraformational fluid flow.
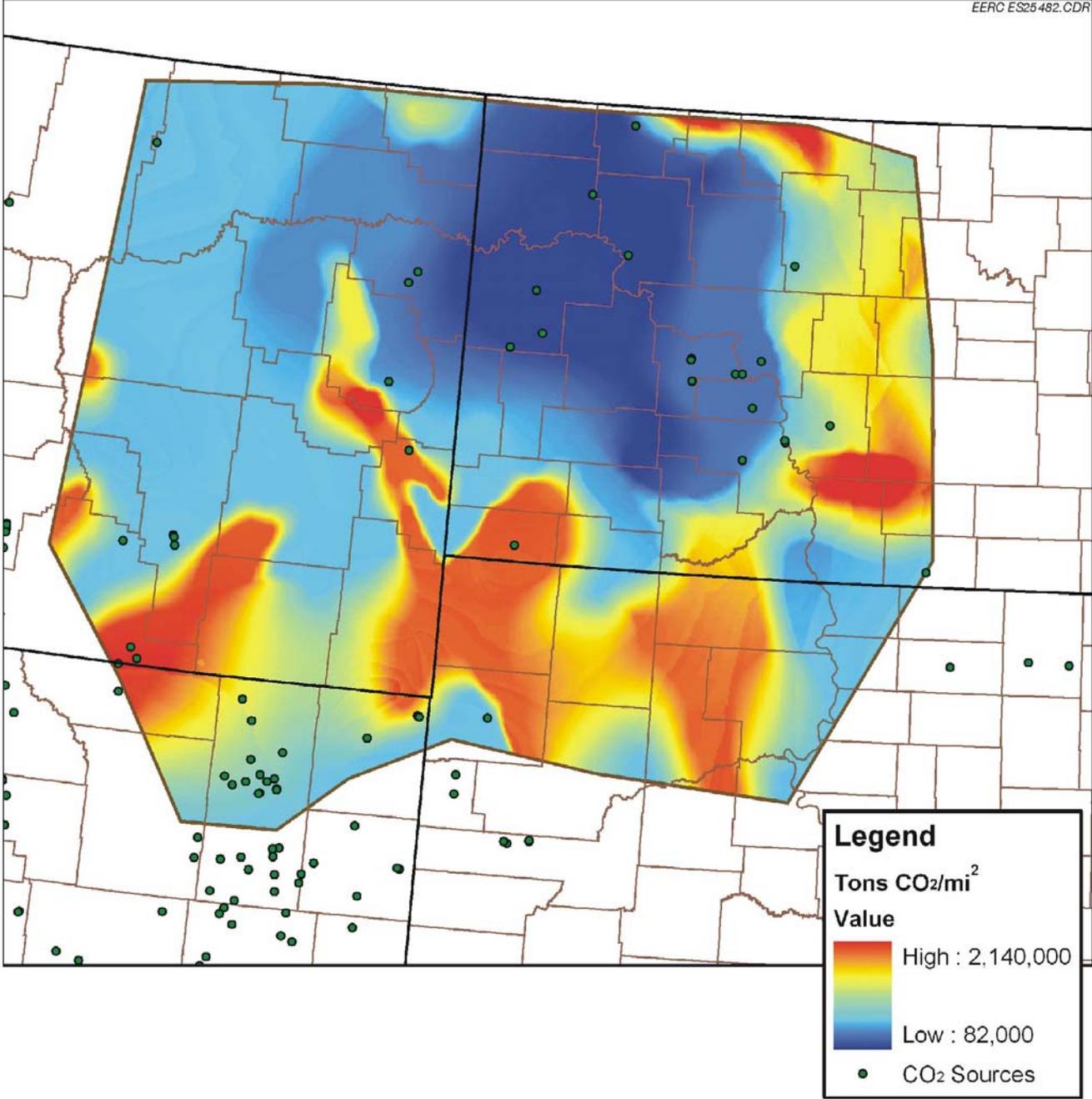
Figure 12. Sequestration storage volume for CO_2 in an aqueous solution.
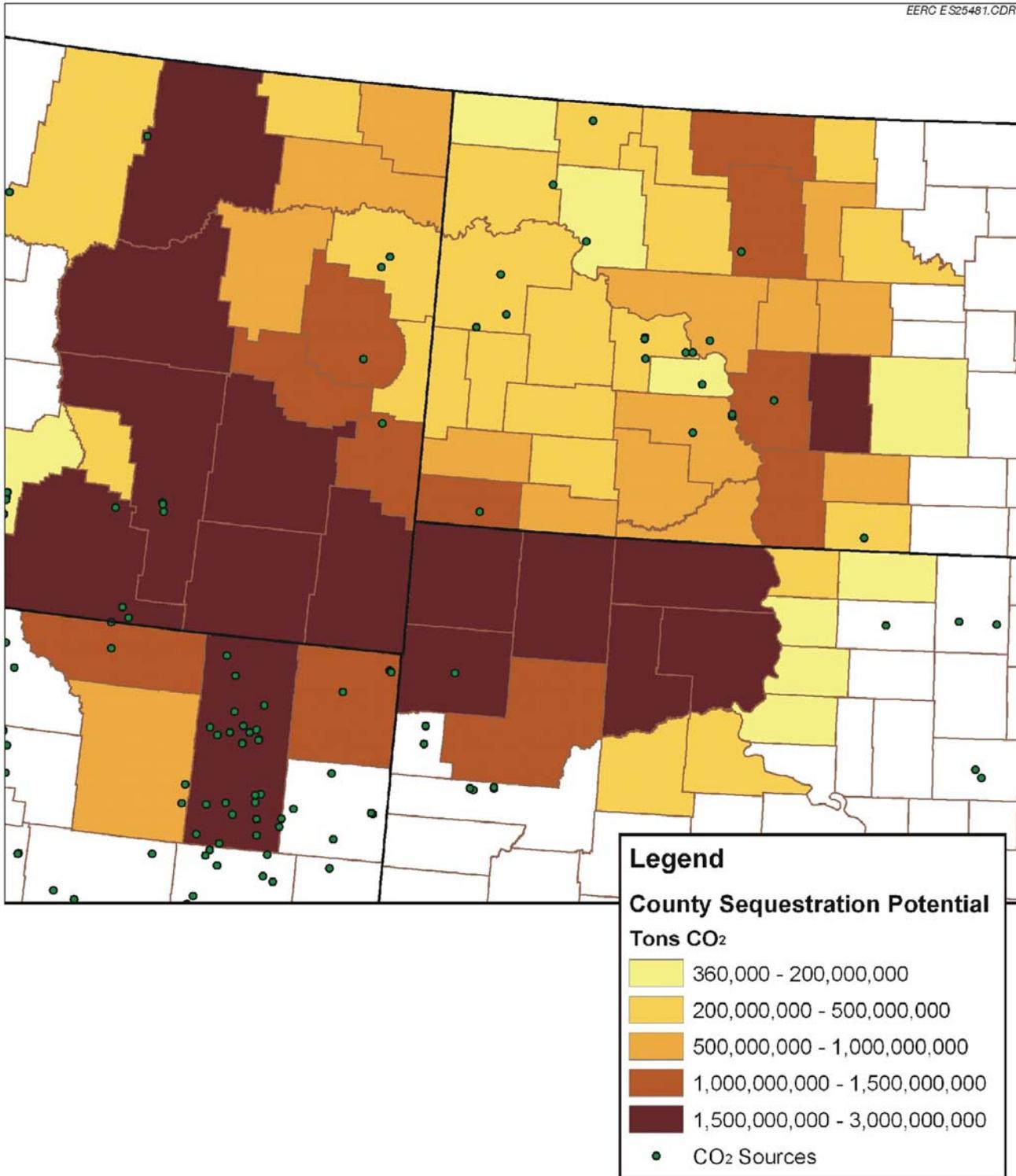
Figure 13. Sequestration storage volume for CO_2 in an aqueous solution, by county.
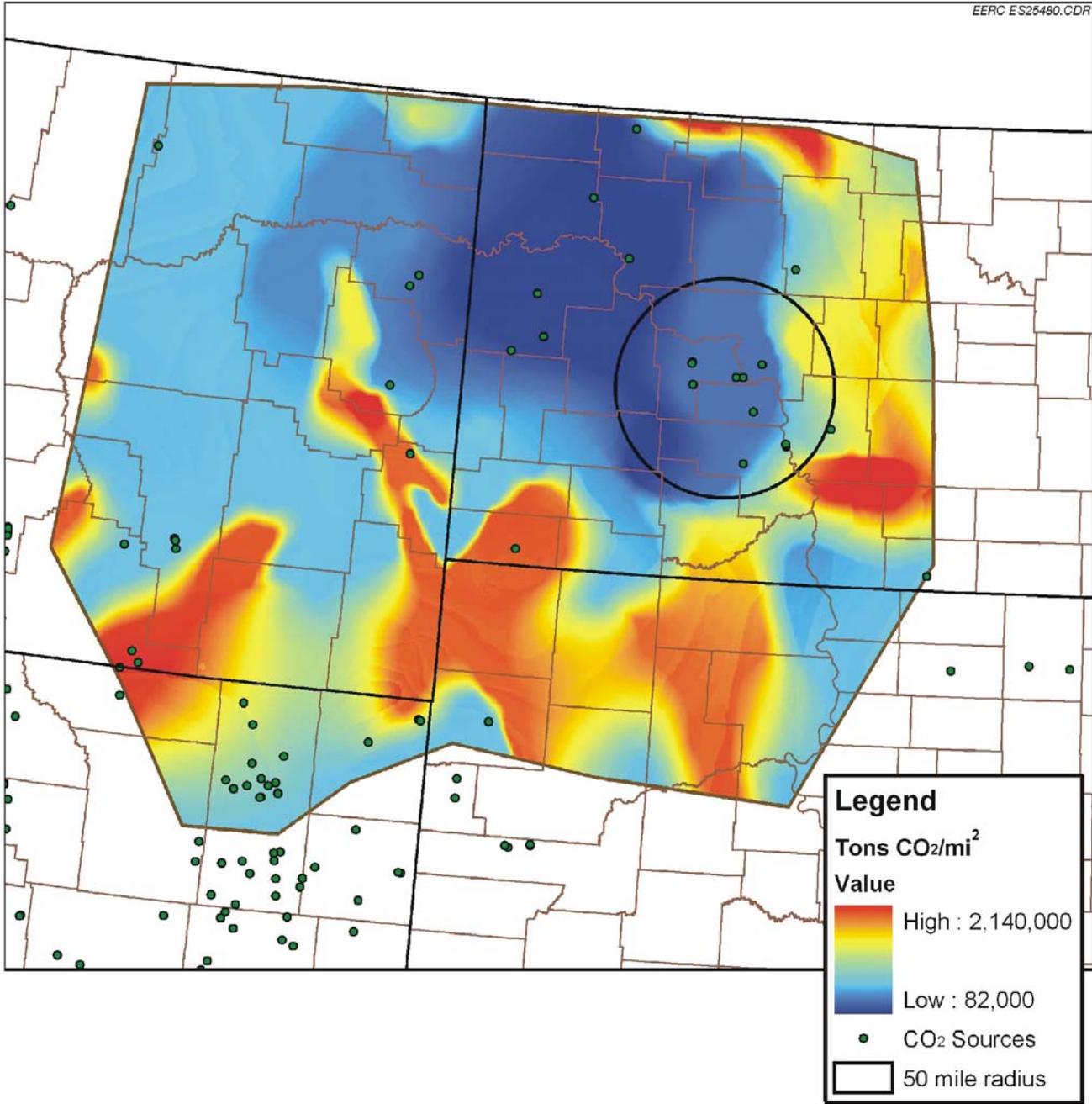
Figure 14. Sequestration storage volume for CO_2 in an aqueous solution within a 50-mile radius of major power generation plants in north central North Dakota.

CONCLUSION

The Madison GSU of the northern Great Plains aquifer system primarily lies within the boundaries of the Powder River and Williston Basins. Carbonates are the primary rock type present in the interval, with limestone the prominent lithology. Dolomites are present and more common along the margin of the interval and in particular along the northeast flank of the Williston Basin. Porosity in the Madison is erratic and discontinuous, although porosity pods may be interconnected through fractures. The Madison is the primary oil-producing interval of the Williston Basin, which means some of the infrastructure necessary for large-scale CO_2 injection may already be in place in some areas. Regional calculations based largely on USGS reconnaissance mapping indicate that the Madison may be a significant candidate for CO_2 sequestration. The calculations suggest that the total CO_2 storage capacity of the entire Madison may exceed 60 billion tons (980 Tcf). The volume that may be practically and safely sequestered is likely to be much lower, but still represents a significant regional sink. There may be some potential for leakage along the northeast flank of the Williston Basin, where the formation subcrops, and along some tectonic features.

Prior to sequestration, additional detailed porosity mapping will be required. Porosity data will need to be acquired. It is recommended that that data be derived from digital well logs converted to LAS (Log ASCII standard) format.

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