Plains CO_2 Reduction (PCOR) Partnership
Practical, Environmentally Sound CO_2 Sequestration

OVERVIEW OF WILLISTON BASIN GEOLOGY AS IT RELATES TO CO_2 SEQUESTRATION

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EXECUTIVE SUMMARY

The geology of carbon dioxide (CO_2) sequestration is essentially the geology of petroleum exploration. Basically, the search for oil is the search for sequestered hydrocarbons. Therefore, the geological conditions that are conducive to hydrocarbon sequestration are also the conditions that are conducive to CO_2 sequestration. The three requirements for sequestering hydrocarbons are a hydrocarbon source, a suitable reservoir, and an impermeable trap. These requirements are the same as for sequestering CO_2, except that the source is artificial and we refer to the reservoir as a sink. Reviewing the tectonic origin and structure of a basin, as well as its hydrogeology and geology, including the petroleum geology, can lend valuable insights in any attempt to identify geological sinks for CO_2 sequestration in an oil-producing basin.

The Williston Basin is a relatively large, intracratonic basin with a thick sedimentary cover in excess of 16,000 ft. The Williston Basin is considered by many to be tectonically stable, with only a subtle structural character. The stratigraphy of the area is well studied, especially in those intervals that are oil-productive.

The Williston Basin has significant potential as a geological sink for sequestering CO_2. Geological sinks that may be suitable for long-term sequestration of CO_2 include both active and depleted petroleum reservoirs, deep saline formations, and coal seams, all of which are abundant in the Williston Basin. This topical report focuses on the general geological characteristics of the Williston Basin that are relevant to potential sequestration in petroleum reservoirs and deep saline formations. Oil fields represent numerous opportunities for geological sequestration, as there are nearly 1100 oil fields spread across the states and provinces in the Williston Basin. Many of these oil fields are good candidates for CO_2-based enhanced oil recovery operations, while others represent well-understood sites for basic sequestration. The oil fields are particularly attractive candidates for geological sequestration, as many of them already have in place key

infrastructure elements necessary for CO_2 transport. The stratigraphy of the Williston Basin also includes several formations that may be suitable for sequestration in deep saline formations. Examples include the carbonate formations of the Madison Group and the clastic formations of the Dakota Group, all of which underlie thousands of square miles of the Williston Basin. While general information on the structural geology, lithostratigraphy, hydrostratigraphy, and petroleum geology of the Williston Basin is readily available, additional characterization data for specific candidate sinks will be necessary before their utilization as CO_2 storage sites. Detailed maps of critical elements such as formation thickness, porosity, permeability, and water salinity will need to be developed, and the competency of regional traps will have to be further studied.

It is the intent of this paper to present an overview of the geology and geohydrology of the Williston Basin with respect to CO_2 sequestration in petroleum reservoirs and deep saline formations. Outlines of each formation discussing basic geology and geohydrology of that formation will be included as a supplement to this report.

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BACKGROUND

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 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 the geology, lithostratigraphy, and hydrostratigraphy of the Williston Basin. Individual formation outlines will be completed by the end of Phase I of this project, currently slated for September 2005.

During the preparation of this report, it became apparent that there are distinct differences in stratigraphic nomenclature and recognized formation boundaries differ among the various states and provinces that the Williston Basin underlies. Some of these differences are the result of geopolitical boundaries, and some are based on varied geological observation and interpretation. Geologically, there are differences between depositional facies in the basin center and along the basin margin.

As with many disciplines and technologies, a precise and descriptive vocabulary is needed. In the petroleum industry, a rock layer that contains fluid or gas is referred to as a reservoir. A rock layer that oil or gas cannot flow through is referred to as a trap or a cap. In hydrogeology, a rock layer that contains water is referred to as an aquifer. A rock layer that water cannot flow through is referred to as an aquitard or a confining bed. In CO_2 sequestration, a rock layer that is capable of containing CO_2 is referred to as a reservoir. As this report is multidisciplinary, terminology from many disciplines that deal with the subsurface are used. This report focuses on the sequestration of CO_2 in petroleum reservoirs and brine formations, referred to collectively as sequestration units. The term "geological sequestration unit" was chosen to acknowledge the legal and regulatory process that will be necessary to inject large volumes of CO_2 across areas consisting of numerous mineral ownership tracts; it was not chosen to represent a physical geologic unit or formation. The concept is to apply the process by which petroleum fields become unitized to the development of geological sequestration projects. In modern oil field practices, prior to initiation of subsurface activities that will affect the fluid distribution and production within an area, mineral ownership tracts may be legally combined to form a larger working area. The process of combining individual tracts is referred to as "unitization" and the working area created by this process is referred to as a "unit." The effective result of unitization is the protection of correlative rights of all mineral owners within the designated area, and coordinated injection and reservoir management practices that improve the efficiency of petroleum extraction. It is anticipated that a similar unitization process will need to be developed prior to large-scale injection of CO_2 for sequestration in geological formations. These sequestration units may be established in petroleum reservoirs, saline aquifers, and coalfields.

INTRODUCTION

The Williston Basin has significant CO_2 sequestration potential. The basin is considered to be tectonically stable, and the stratigraphy is well studied and documented. Many of the potential reservoirs in the basin are vertically stacked (occur above and below each other). Competent traps can be demonstrated locally and, with additional work, possibly regionally. The geohydrology of the basin is less studied than the stratigraphy, and additional work is needed to adequately characterize the hydrodynamics and intra- and inter-formational flow relationships.

There is a relatively thick sedimentary section present in the basin, in excess of 16,000 ft at the basin center. Deposition from the Cambrian Period through the lower Ordovician was predominantly siliciclastic (sandstones and shales). Carbonates (limestones and dolomites) and evaporites (anhydrites and salts) were the dominant lithologies from the middle Ordovician through most of the Mississippian. Siliciclastics again became the dominant lithology in the Pennsylvanian and have been through the Holocene.

Most of the hydrocarbons produced in the Williston Basin are from carbonate reservoirs that range in age from the Ordovician through the Mississippian. As such, they are some of the most studied rocks in the basin. Although these carbonates represent a potentially significant sink for CO_2 sequestration, porosity distribution within these intervals is not uniform and, where present, is often compartmentalized. Porosity, and permeability to some extent, is controlled by depositional environments. The stratigraphy of these environments is complex and changes rapidly, both vertically and horizontally. As such, including the knowledge of the various hydrocarbon-producing intervals is an essential step in searching for potential CO_2 sinks. In such reservoirs, detailed stratigraphic studies on both a regional and localized scale will have to be utilized to characterize the targeted sink.

Porosity and permeability also vary greatly in siliciclastics deposited from the Cambrian through the lower Ordovician. Lithostatic pressures have significantly reduced porosities and permeabilities in some locations. Because of reservoir heterogeneity, detailed regional and localized stratigraphic studies will be needed prior to CO_2 sequestration.

Two main categories of reservoirs are recognized: conventional and unconventional. Conventional reservoirs are herein considered to be nonargillaceous or “clean” lithologies that have preserved porosity and permeability (Figure 1). Nonconventional reservoirs are those that may be porous but lack permeability or are “dirty” (Figure 2). Loss of permeability in a porous reservoir may be due to the presence of organic detritus in the rock matrix. The distinction between conventional and nonconventional reservoirs is made for a number of reasons, as follows:

- Because of inherent porosity and permeability, injection into conventional reservoirs may not require significant borehole stimulation, while injection into unconventional reservoirs will require significant stimulation, including fracturing the rock layer prior to injection.

- For conventional reservoirs, the presence of bounding or confining units will have to be well demonstrated and understood, as this will be the trapping mechanism for injected CO_2. Unconventional reservoirs, because of the inherent lack of permeability, may be self-trapping.

- Conventional reservoirs will be less sensitive to economic constraints.

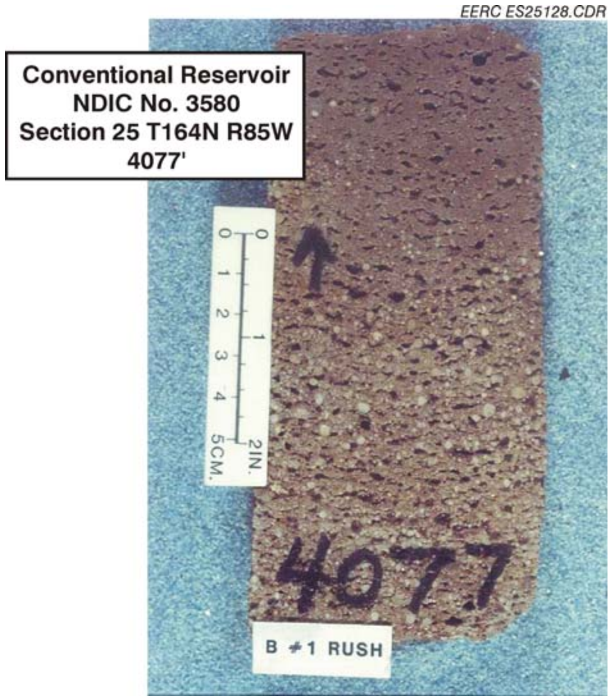


Figure 1. Core photograph of a porous and permeable carbonate—a conventional reservoir.

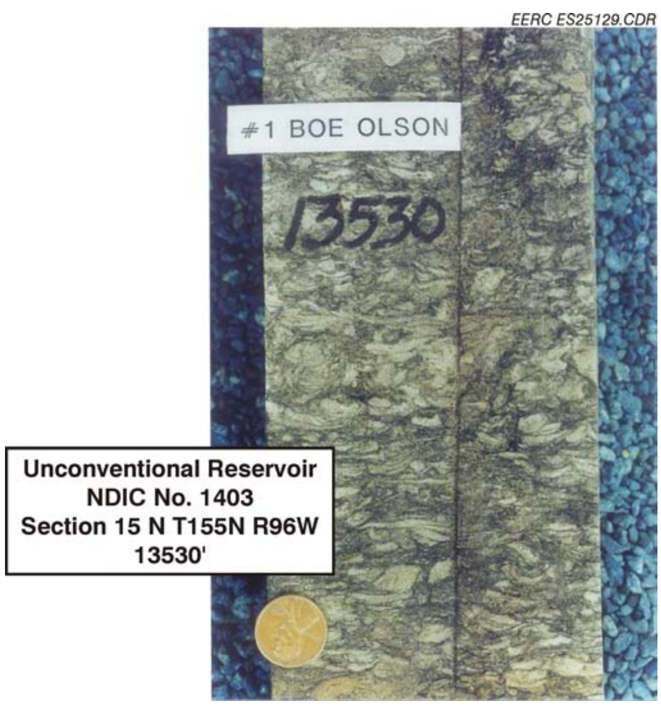


Figure 2. Core photograph of a nonpermeable (clay-rich) sandstone—an unconventional reservoir.

- Unconventional reservoir sinks that have a component of organic-rich material need to be investigated as to the capacity, if any, of the organics to fix CO_2.

A distinction is also made between regional and local CO_2 sequestration reservoirs. A regional reservoir would be a layer with considerable lateral continuity capable of sequestering a significant amount of CO_2. A local CO_2 sequestration reservoir would be a less continuous, perhaps isolated, rock layer.

GENERAL GEOLOGIC SETTING

The Williston Basin is a large, roughly circular depression on the North American Craton. It covers several hundred thousand square miles across parts of North Dakota, South Dakota, Montana, and the Canadian provinces of Manitoba and Saskatchewan (Figure 3). Deposition in the Williston Basin occurred during all periods of the Phanerozoic. The basin began to subside during the Ordovician Period, around 495 million years ago, and has undergone episodic subsidence throughout the rest of the Phanerozoic Eon.

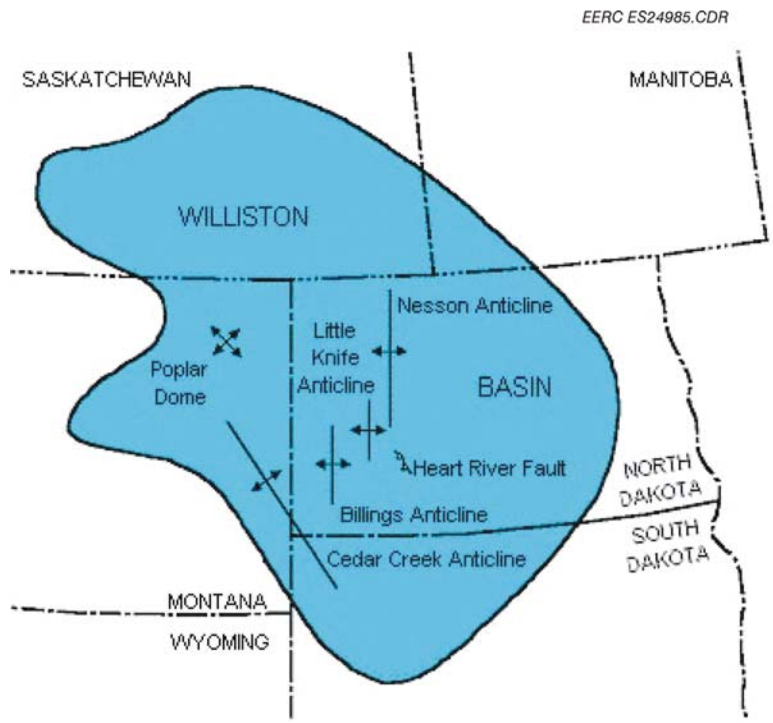


Figure 3. Index map of the Williston Basin with some major structures (modified from Gerhard et al., 1982).

The Williston Basin contains an unusually complete rock record compared to many basins (Figure 4). Erosion dominated a significant amount of the Phanerozoic Era, but some rocks from each Phanerozoic Period are preserved. Sedimentation during the Phanerozoic occurred during cycles of marine transgressions, followed by marine regressions. The basin's deepest point is thought to be near Watford City, North Dakota, where the Precambrian is more than 16,000 ft below the surface. The basin is neither structurally complex nor considered tectonically active.

STRUCTURAL GEOLOGY

The earliest sedimentary and structural history of the basin is difficult to study because the Precambrian rocks do not crop out and are only penetrated by a few wells. The present understanding of the early geologic history of the basin is pieced together from outcrops in adjacent states and provinces, from seismic data, and from well data.

Three ancient geological provinces are present in the Precambrian basement under the Williston Basin (Green et al., 1985). Two of the provinces are Archean and represent cratons (protocontinents) (Figure 5). They are separated by oceanic sediments that are Proterozoic in age. Rocks of the Superior Craton underlie most of eastern North and South Dakota, as well as Manitoba and consist primarily of granites and greenstones. The Wyoming Craton underlies eastern Montana, western Saskatchewan, western South Dakota, and southwestern North Dakota.

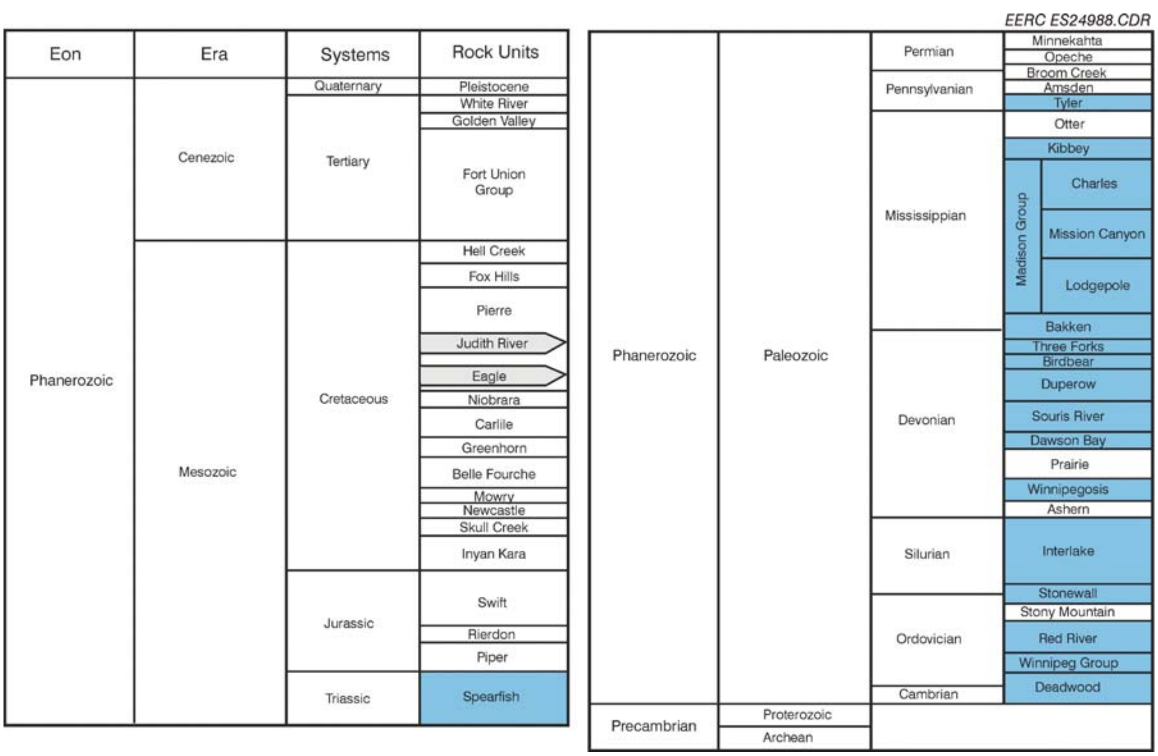


Figure 4. Generalized stratigraphic column of the North Dakota Williston Basin. Red denotes gas production; blue denotes oil production (modified from Gerhard et al., 1982).

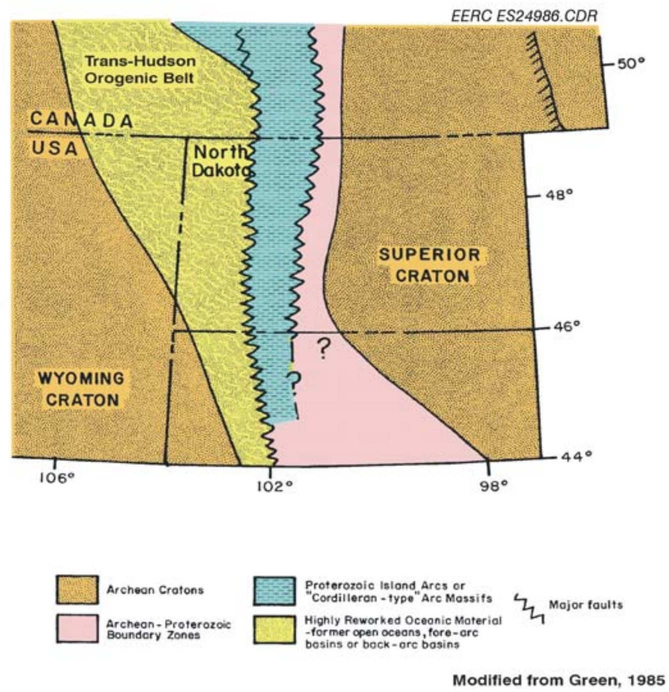


Figure 5. Basement terrane of the Williston Basin (modified from Green et al., 1985).

It consists of quartz-rich rocks including gneisses. Both cratons are approximately the same age.

Proterozoic sediments representing the Trans-Hudson Orogen lie between the two cratons and underlie most of western North Dakota. Sediments of the Trans-Hudson Orogen are composed of oceanic materials that were accreted between the active continental margins between the two cratons (Green et al., 1985).

Rocks representing highly reworked oceanic materials from former open oceans and fore-arc or back-arc basins, as well as rocks believed to be associated with island arc formation, have been correlated to the orogen. The depositional history of the rocks appears to be complex. Rocks are interpreted to represent initially a rifting event between the two cratons and later their collision, which clearly shows the instability of the craton during this time. These collisions form a north–south-oriented fabric that comprises an underlying fault system etched upon the basement.

The basement is dissected into blocks (Figure 6) by a series of tectonic features referred to as lineaments (Brown and Brown, 1987). Lineaments are best defined as zones of structural weakness. Similar to faults and, possibly, the sites of faulting, lineaments are believed to be responsible for the origin of structures within the basin and depositional patterns within the basin. Lineaments are an important component in the formation of the basin. They formed in response to external basinal stresses and, once formed, served as a conduit to transmit and release stresses.

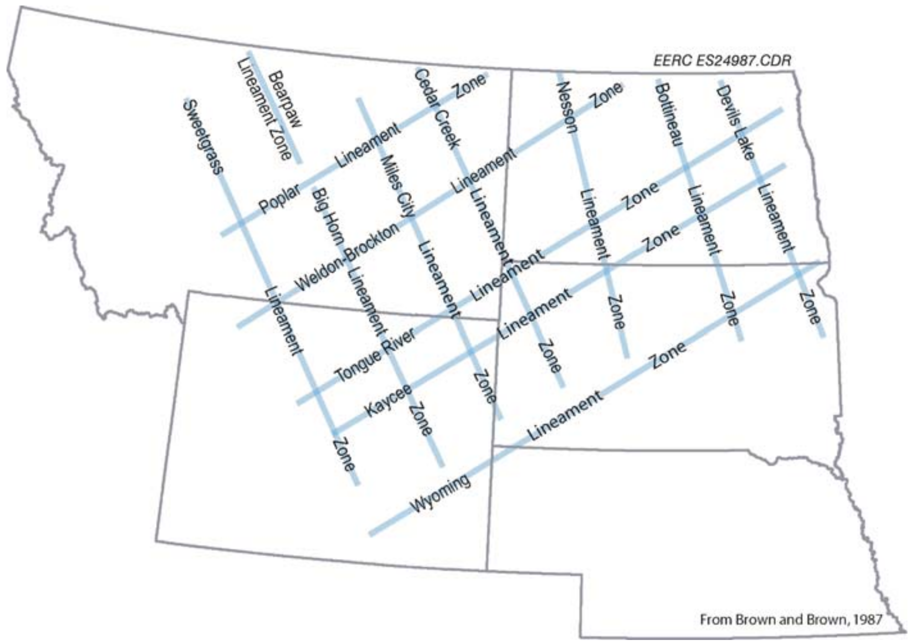


Figure 6. Major Paleozoic structural lineaments (from Brown and Brown, 1987).

The Williston Basin may have formed as a tensional sag on the craton in response to a left lateral shearing movement between two regional lineaments: the Weldon–Brockton (commonly referred to as the Brockton–Froid) and the Wyoming (Gerhard et al., 1982).

Other tectonic features in the Williston Basin include faulting and folding. These features formed in response to either subsidence or the sporadic movement of individual linear bounded basement blocks.

Faulting is difficult to recognize among the subtle structures of the basin. Faults are less well-documented in the Williston Basin than in other basins, and the magnitude of faulting is slight when compared to faulting in other Rocky Mountain Basins. Some faults, such as those on the west flank of the Cedar Creek Anticline (Clement, 1987), the west flank of the Nesson Anticline (1987), and the Heart River Anticline (Chimney et al., 1992), are identifiable on a seismic survey (Figure 7). They show these faults to be steeply dipping, almost vertical. Clement (1987) further reports that faults along the Cedar Creek Anticline have undergone recurrent near-vertical and wrench movements. He also reports that the displacement direction along some of these faults changed over time.

Faults have been inferred elsewhere, but well control is insufficient to prove their existence, and the seismic data are proprietary. These faults probably have similar characteristics as the previously discussed faults.

Williston Basin structures formed in a number of ways. Throughout time, the basin has reacted to regional orogenic events which are thought to have contributed to the formation of structures such as the Nesson, Cedar Creek, and Heart River Anticlines (Figure 8). Other structures, such as the Newburg Syncline, formed as collapsed features in response to

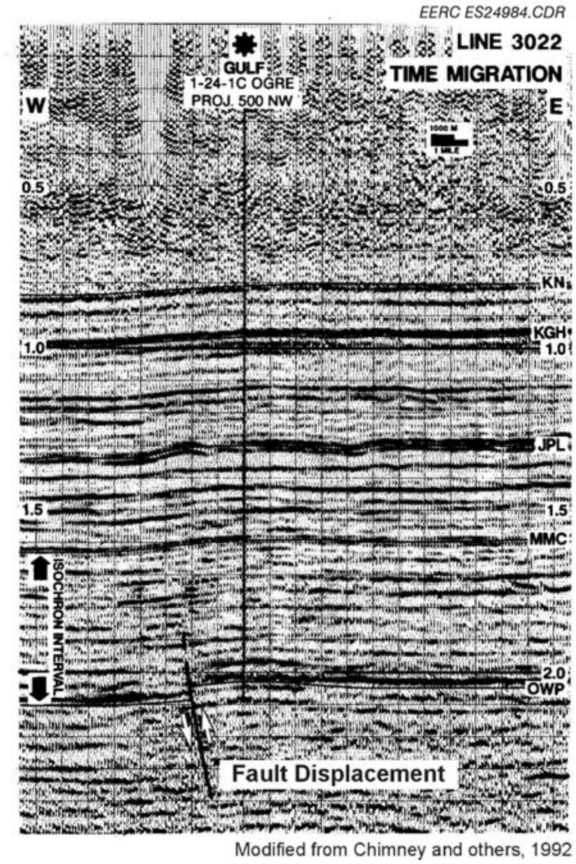


Figure 7. Seismic line transecting Heart River Anticline, Stark County, North Dakota (modified from Chimney et al., 1992).

the dissolution of underlying salts, notably the Devonian Prairie salt. Structures may also be the result of deposition and recurrent movement over a hummocky or horsted (fault-block) Precambrian basement. The Beaver Lodge Field on the Nesson Anticline and the Newporte Field in north-central North Dakota are examples of where there are hundreds of feet of relief on the Precambrian surface (Figure 9). Many other minor unnamed anticlinal structures exist in the basin.

Some of these structures, such as the Nesson, Cedar Creek, Little Knife, Billings, and Heart River Anticlines and the Bowdoin Dome produce gas and oil; others, such as the Burleigh and Stutsman High, do not.

LITHOSTRATIGRAPHY

Sediments in the basin can be subdivided into intervals based on major transgressive events bounded by unconformities. Sloss (1963) recognized the importance of these intervals in defining the sedimentological history of the North American Craton. He subdivided the Phanerozoic Era into six sequences. These sequences are, in ascending order, the Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni, and Tejas (Figure 10). It is convenient to reconstruct the sedimentological history of the Williston Basin based on those sequences.

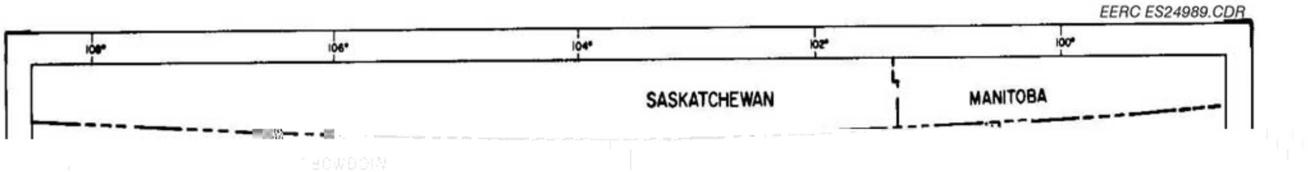


Figure 8. Structural elements in the vicinity of the Williston Basin (Gerhard et al., 1982).

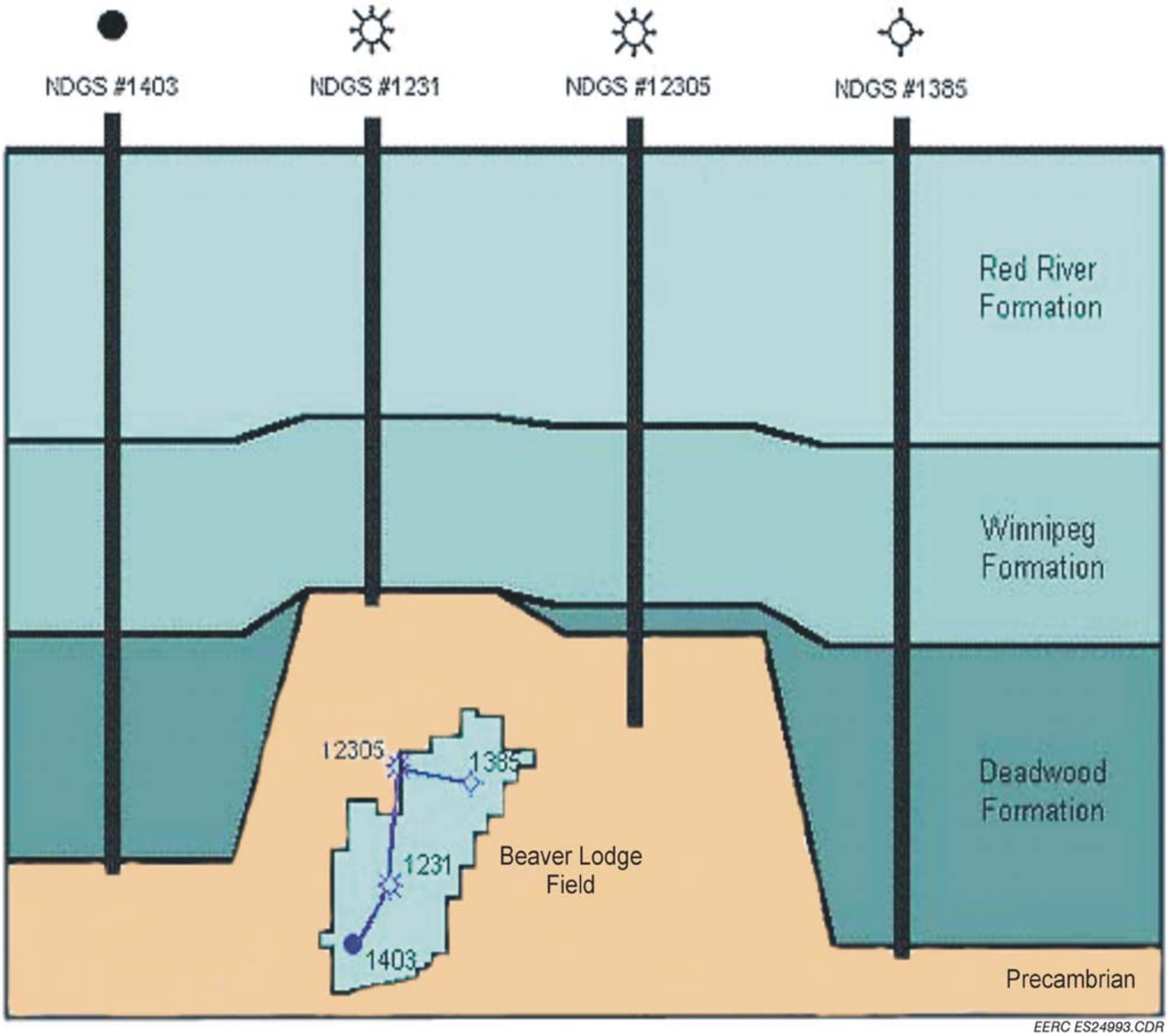


Figure 9. Cross section across Beaver Lodge Field of the Ordovician to Precambrian section. Note the relief on the Precambrian surface and the missing Deadwood section over the Precambrian High (taken from North Dakota Geological Survey Web site).

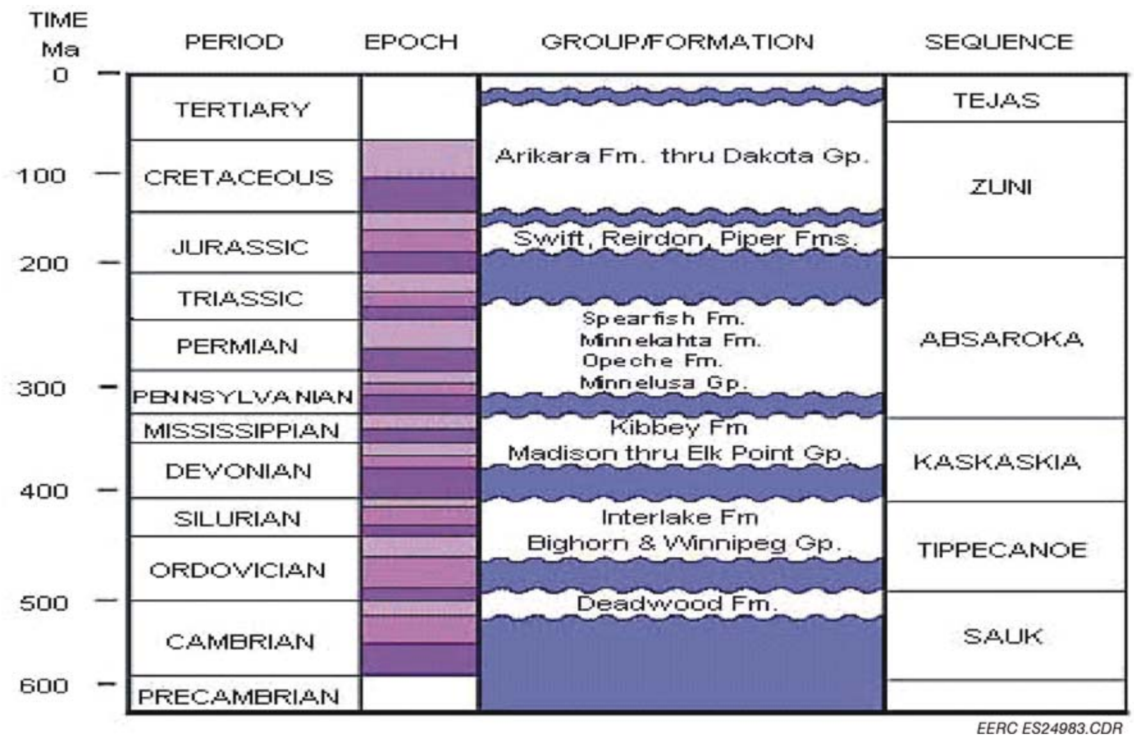


Figure 10. Time-stratigraphic column of the North Dakota Williston Basin (modified from Fowler and Nisbet, 1985).

Each sequence contains geological formations (Figure 10) defined independently of sequence boundaries. Sequestration units will be defined on the boundaries and rock properties of those formations.

Sauk Sequence (Cambrian–Lower Ordovician)

Sauk Sequence rocks record the earliest Phanerozoic sedimentation in the Williston Basin (Peterson and MacCary, 1987). The Cambrian sea transgressed eastward into an embayment on the edge of the Cordilleran shelf (Carlson, 1960; Lochman-Balk, 1972) and deposited siliciclastic sediments (sands and shales). During the lower Ordovician, carbonate deposition began (LeFever et al., 1987). Basin subsidence had begun by the end of Sauk deposition. Petroleum reservoirs and sands of the Winnipeg Group and Deadwood Formation may provide opportunities for CO_2 sequestration in the Sauk Sequence.

Tippecanoe Sequence (Ordovician to Silurian)

Tippecanoe transgression (Figure 11) occurred through a southwestern connection. The initial deposits were siliciclastic, with carbonate deposition following. Oil fields of the Red River Formation may be suitable sequestration targets within the Tippecanoe Sequence.

Kaskaskia Sequence (Devonian–Mississippian)

Kaskaskia Sequence deposition in the Williston Basin occurred during two transgressive cycles (Figure 11). Limestones dominate the Kaskaskia Sequence rock record, but two major evaporite sections are preserved. Rocks of the lower cycle record a northwest connection into the Elk Point Basin, while

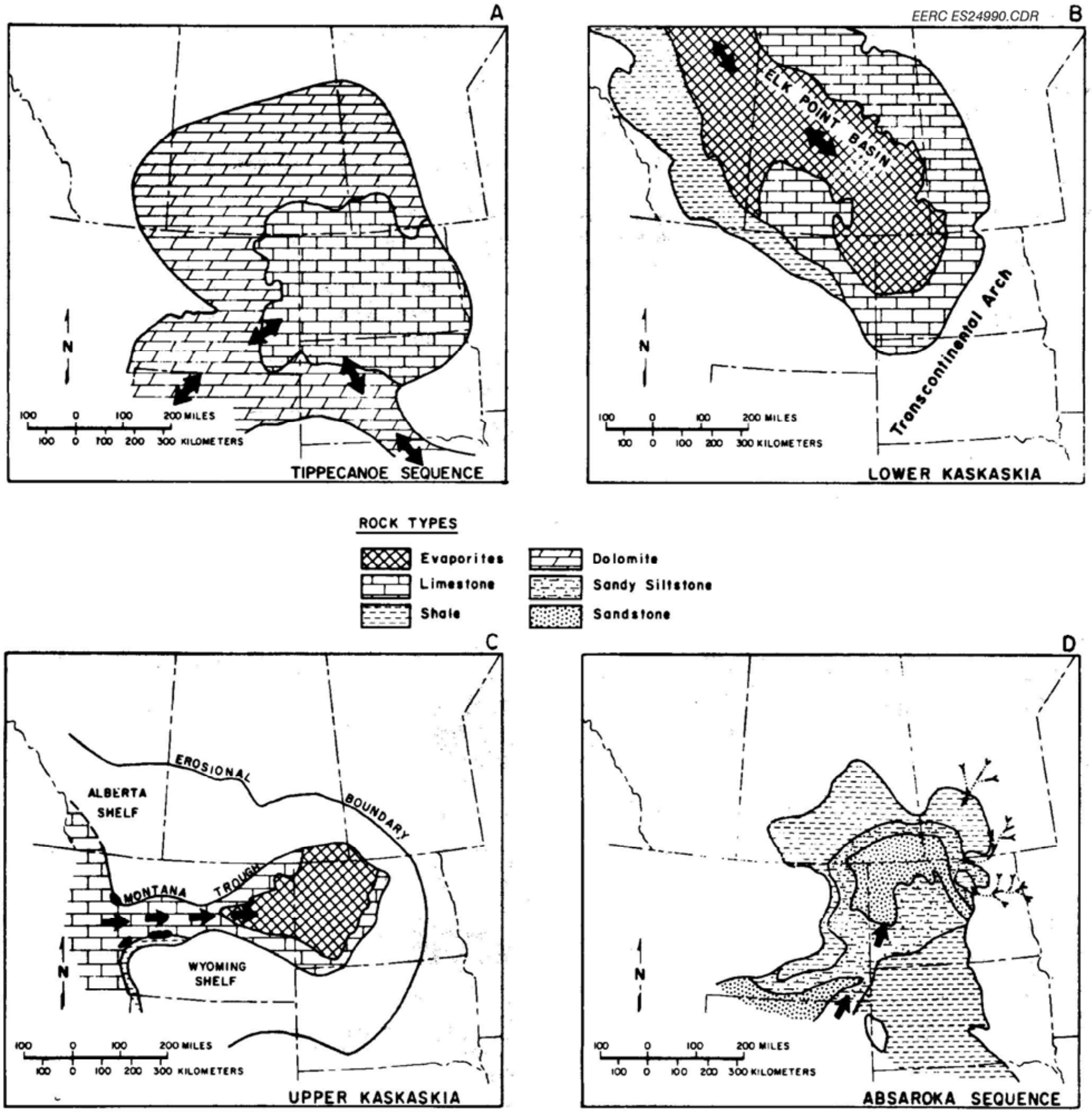


Figure 11. Marine communication with the Williston Basin during selected sequences (Gerhard et al., 1982).

deposition in the upper cycle records a westward connection into the Central Montana Trough. The Madison Group likely provides the most significant opportunities for sequestration in oil reservoirs and saline formations within the Kaskaskia Sequence.

Absaroka Sequence (Pennsylvanian–Triassic)

During Absaroka deposition, marine transgressions were from the southwest, and deposition was concurrent with tectonic activity southwest of the Williston Basin (Figure 11). Interbedded marginal marine evaporites and terrestrial rocks record sedimentation within the basin. Saline formations of the Minnelusa Group may provide sequestration opportunities in the Absaroka Sequence.

Zuni Sequence (Jurassic–Early Tertiary [Eocene])

Zuni Sequence sedimentation marks a shallow marine transgressive event during the Jurassic. The top of the Jurassic is marked by marine regression and subareal exposure. A second and significant transgressive event occurred, and deposition continued in shallow marine conditions throughout most of the sequence. Sedimentation during the later portion of this second transgressive phase is marked by an increase in clastic deposition. The clastics were sourced by the erosion of the Laramide Rockies. The last marine sediments in the Williston Basin were deposited during early Paleocene in the late Zuni Sequence. Sands of the Dakota Group are likely the most significant targets for sequestration in the Zuni Sequence.

Tejas Sequence (Tertiary to Quaternary)

Few lower Tejas sediments are present in the Williston Basin. Where present, these sediments consist of localized limestones and shaly sandstones that are correlative to White River formation sediments elsewhere. Formations within the Tejas Sequence are likely to be too shallow for long-term sequestration of CO_2.

Throughout much of the basin, glacial sedimentation defines the upper Tejas Sequence. Thick glacial till and drift can be found throughout much of Manitoba, eastern Montana, Saskatchewan, and North Dakota.

HYDROSTRATIGRAPHY

Injection of CO_2 into formations containing brine (sometimes referred to as deep saline aquifers) is considered by many to have the greatest potential for large-scale regional sequestration (White et al., 2003). As such, it is critical to understand the regional hydrostratigraphy as it relates to fluid composition, flow characteristics within a sequestration unit, and interunit flow relationships.

The stratigraphic column of the Williston Basin can be subdivided into a series of major geohydrologic units (Downey et al.; 1987; Bachu and Hitchon, 1996). In the United States, Downey proposed nine major units. In Canada, Bachu and Hitchon (1996) proposed 13 units (Figure 12). The differences in interpretation of the characteristics of these units are primarily due to nondeposition, erosion of units, or variations in lithologic characterwithin units. These variations may reflect deposition along the basin shelf versus the basin center.

Each of the major divisions may be further subdivided to reflect the hydrogeology of individual formations, members within a formation and, in some cases, lithofacies within a member. For example, Benn and Rostron (1998) identify seven discrete aquifers and seven discrete aquitards from the Cambrian through the Devonian.

Five major aquifers (Downey, 1984, 1986; Downey et al., 1987) are recognized in the

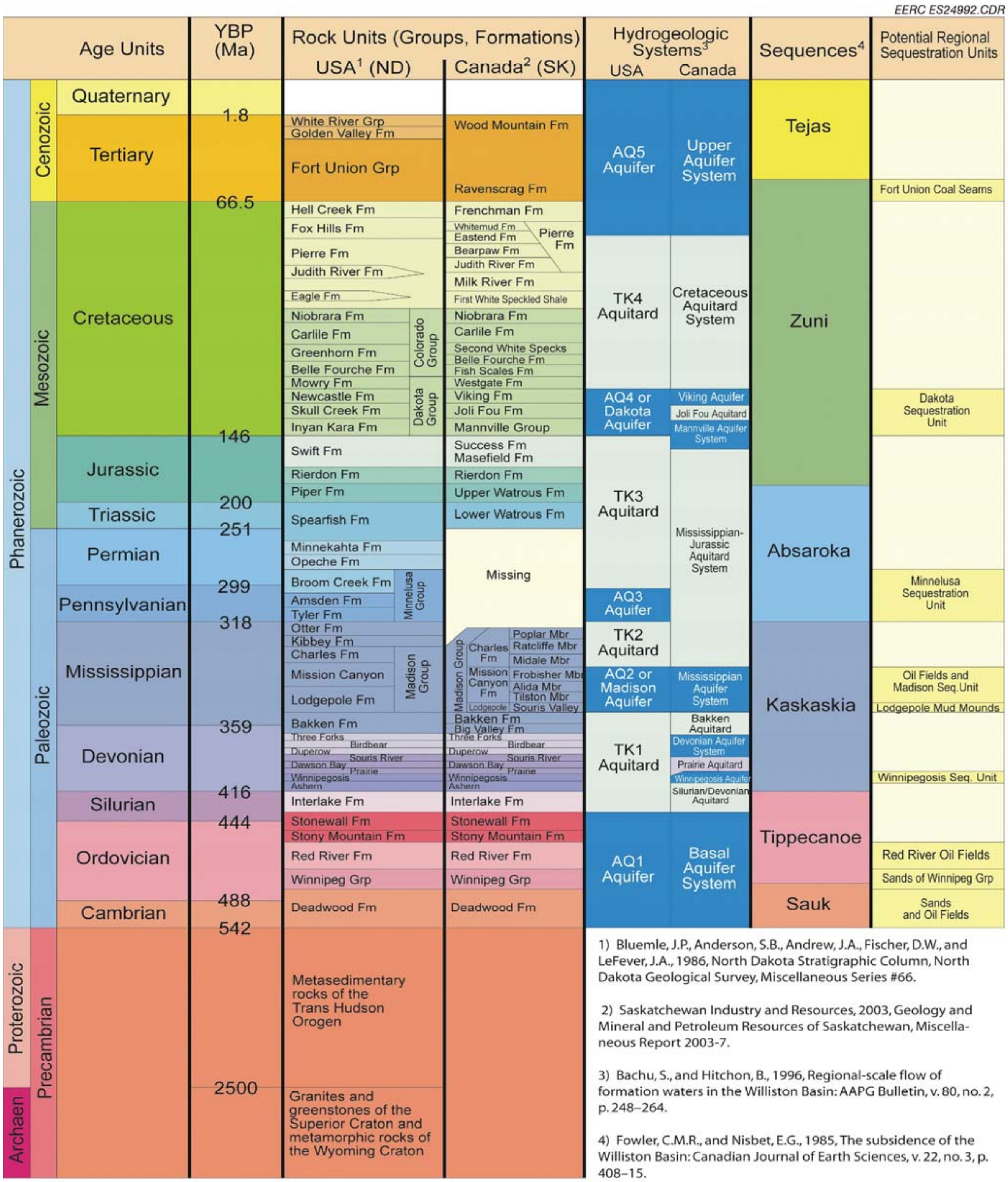


Figure 12. Geohydrologic nomenclature (modified from Bachu and Hitchon, 1996).

northern Great Plains region, which includes the Williston Basin (Figure 12). These aquifers are separated by four major confining units. Downey considers the Great Plains as one of the largest confining aquifer systems in the United States, with a flow system that extends more than 600 miles from the recharge areas to discharge areas in eastern Dakotas and Canada. Downey labels the aquifer units in ascending order from AQ1 through AQ5 and the confining units from TK1 through TK4.

Major aquifers within the Williston Basin crop out along the eastern flank of the Rocky Mountains and in the Black Hills of South Dakota. In general, groundwater flow in the basin is to the east and northeast (Figure 13). Flow direction in the AQ1 and AQ2 aquifers may be modified by an area of high-density brine in the central portion of the basin. (Downey, 1984, 1986; Downey et al., 1987). Downey considers three hypotheses regarding hydrologic flow in the brine area. The first is that the brine is static; second, that the brine area is static, with low but consistent flow velocities through it; and third, that the brine area is migrating with regional water flow to the northeast in an "attempt to adjust to changes to recharge and discharge associated with the end of Pleistocene glaciations (1987)." Downey believes that the second hypothesis seems to be the best fit to his digital simulation models (1987). Each hypothesis will have to be considered in modeling CO_2 sequestration in these aquifers.

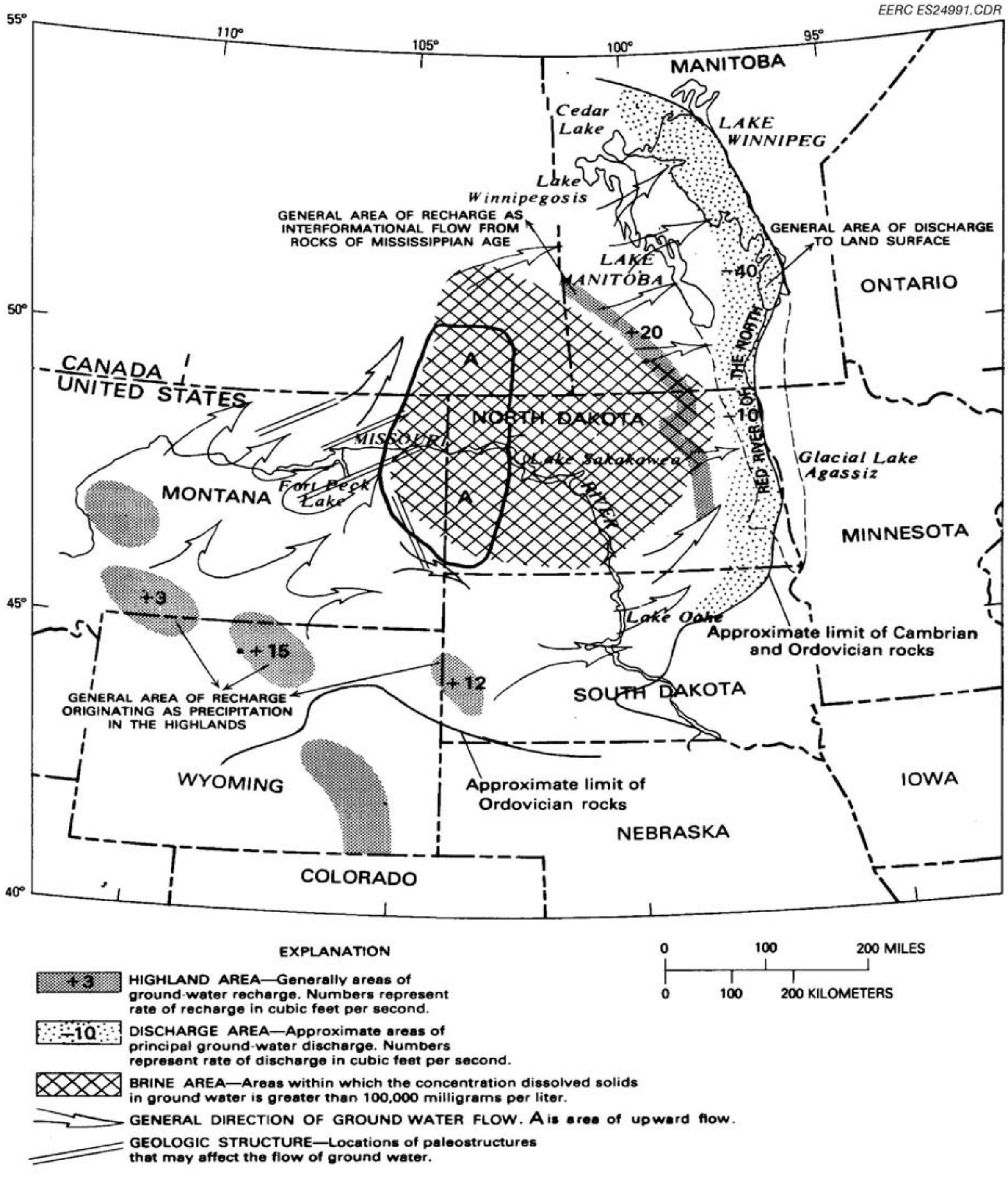
The possibility of vertical leakage through the confining units associated with the AQ1, AQ2, and AQ3 aquifers is recognized by Downey (1984, 1986; Downey et al., 1987). Vertical leakage occurs where confining beds are not locally present or the beds are extensively fractured. Detailed geochemical water facies mapping can be used to identify such areas. Leakage may also occur along regional zones of tectonic weakness or lineaments. Surface geochemical studies may help in identifying lineaments where leakage is occurring.

Other workers have also identified leakage through confining units, especially the TK4 system. Neuzil et al. (1984) studied the hydraulic conductivity of the TK4 shales and concluded that vertical leakage was occurring along fractures and that the average fracture spacing was on the order of 100 or 1000 m. Kolm and Peter (1982) note a relationship between leakage, fractures, and the occurrence of subsurface lineaments.

Downey (1987) presents a summary of his work in a figure showing generalized flow rates and directions for Paleozoic aquifer systems (Figure 13). A more detailed discussion of the geohydrology in the Williston Basin can be found in digital form through the U.S. Geological Survey (USGS) at http://capp.water.usgs.gov/gwa/ch_i/index.html.

In the Canadian portion of Williston Basin, Bachu and Hitchon (1996) recognize seven major aquifers with six confining units (Figure 12). Using formation water analysis and drill stem test data from oil wells, Bachu and Hitchon (1996) generated a series of hydrogeological regime maps for the Canadian portion of the Williston Basin.

In general, Bachu and Hitchon (1996) recognize flow patterns to the east and northeast, similar to those in Downey et al. (1987). Bachu and Hitchon (1996) classify aquifers and flow systems into three categories: open, semiopen, and closed.



Conceptual model of groundwater flow in the Paleozoic aquifers of the northern Great Plains.

Figure 13. Conceptual model of Paleozoic groundwater flow (Downey et al., 1987).

The Basal (Cambrian–Ordovician) and generally Devonian Aquifers are open systems, being exposed at the land surface in both recharge and discharge areas (southwest and northeast, respectively). The Mannville (Inyan Kara or Dakota) Aquifer is also open, although to a lesser extent. It is generally closed upstream at recharge, except for a small area in the south at the Black Hills uplift. Otherwise, the Mannville Aquifer is recharged in the west either directly by or through leakage from the Mississippian Aquifer. The Mannville Aquifer is open downstream in the northeast, where it discharges at the Manitoba Escarpment and toward the Canadian Shield. The Mississippian (Madison) and Pennsylvanian Aquifers are semi-open, because they are open only in exposed recharge areas in the west and southwest, but they do not crop out downstream and, thus, do not even discharge directly into other aquifer systems. Instead, they discharge into adjacent aquifers through the intervening confining aquitards. Finally, the Viking (Newcastle) Aquifer can generally be considered as a closed system, being confined by Cretaceous aquitards and basically not exposed to the land surface except for a small area at the Black Hills uplift. (Bachu and Hitchon, 1996).

Bachu and Hitchon (1996) suggest that the confining units may be more competent than Downey interpreted. They suggest that the Bakken confining unit and the Cretaceous confining unit are competent, as are the Permian–Jurassic and the Mississippian–Jurassic confining units, at least locally; they consider the Silurian–Devonian confining unit to be leaky.

LeFever (1998) presents a study of the hydrodynamic characteristics of waters from four oil-producing formations in the North Dakota portion of the Williston Basin: the Madison Group, the Duperow, Interlake, and Red River Formations. Data for his interpretation are taken from drill stem tests, original field pressures for older fields, and chemical analysis of drill stem test samples and produced waters.

LeFever (1998) concludes that "the Madison potentiometric surface shows steep slopes in the southwestern part of North Dakota, and has much lower slope and relief in the deeper part of the basin. Flow directions are north to north-northeast. For the Interlake and Red River Formations, the potentiometric surfaces are roughly similar. They show steeper slopes and northeast flow directions in the southwest, but have such little relief in the center of the basin that they appear to be nearly hydrostatic. The potentiometric surface of the Duperow Formation has no steep slopes and seems to be very close to hydrostatic. The surfaces calculated for all four units are at sufficiently different elevations to indicate hydrodynamic separation from one another."

A rise in the potentiometric surface in the Madison Group reservoir in the northeast producing portion of North Dakota has been interpreted to indicate freshwater influx from the northeast. Freshwater influx in the northeast does not fit any known hydrodynamic model, and some researchers speculate that this may represent waters introduced into the Madison through pressure maintenance from oil fields in Manitoba.

Deep Saline Formation

Based on the information reviewed to date, it appears that each of the major sequences present in the Williston Basin, with the exception of the Tejas, have formations containing brine that can serve as regional CO_2 sequestration reservoirs. In particular, some of the formations of the Madison Group and the Dakota Group appear to have the proper combination of thickness, areal extent, porosity, and seal competence to provide significant CO_2 sequestration capacity. It is believed that future evaluation of other, more detailed data sets may result in the identification of additional hydrostratigraphic units that are suitable for CO_2 sequestration.

PETROLEUM GEOLOGY

The Williston Basin is an oil-producing province. Oil was first discovered along the Cedar Creek Anticline in Montana in 1936. Subsequent oil discoveries were made in Saskatchewan in 1944, Manitoba in 1950, and North Dakota in 1951.

Prior to the discovery of oil, shallow Cretaceous-Age gas was produced in central South Dakota and south–central North Dakota during the late 1800s. This gas production was associated with artesian water flow and was used locally on farms, ranches, and by some municipalities. Gas production was also reported in the early 1900s in north-central North Dakota. This gas production was also associated with artesian water wells producing from glacial drift. The source of the drift gas is uncertain, but it may have migrated into the drift from underlying Cretaceous-Age sediments. Natural gas is still produced from Cretaceous-Age sediments along the Cedar Creek Anticline in Montana and North Dakota and from small structures in northwestern South Dakota. Additionally, shallow gas is produced along the basin margin and has been produced in Saskatchewan since the early 1900s (Shurr, 1999).

Oil currently is the most important hydrocarbon resource in the Williston Basin. Production is primarily from Paleozoic-Age rocks, principally carbonates. The earliest oil production was found in structurally controlled traps on the major structures in the central basin and along Paleozoic depositional and truncational edges. A significant number of traps in the Williston Basin are stratigraphic, with only a minor structural component.

Much of the natural gas production of the Williston Basin is associated with crude oil production. There is nonassociated gas produced from the deep Paleozoic reservoirs that are primarily Ordovician in age. Where present, gas production can be significant, with individual wells capable of producing well over 10 Bcf. Gas exploration and development remain in their infancy in the basin.

In a 1995 national assessment of U.S. oil and gas resources, the USGS identified six conventional oil and gas plays in the Williston Basin. Ranging in importance, these plays are as follows:

- Mississippian Madison
- Ordovician Red River
- Middle and Upper Devonian (pre-Bakken–post-Prairie salt)
- Pre-Prairie Middle Devonian and Silurian
- Post-Madison to Triassic clastic
- Pre-Red River

In that assessment, the USGS briefly defines the nature of the reservoirs—source rocks, migration, and trap—and reports on the exploration status and resource potential for each individual play. The USGS also recognizes and describes continuous-type unconventional plays in the basin. The USGS report is available at http://certmapper.cr.usgs.gov/data/noga95/prov31/text/prov31.pdf.

Informational outlines for selected formations have been developed which discuss their basic geology and reservoir characteristics and their potential value for CO_2 sequestration. These outlines will be completed and published separately.

With nearly 1100 fields spread out over North Dakota, South Dakota, Montana, Manitoba, and Saskatchewan, it is apparent that petroleum reservoirs represent tremendous opportunities for geological sequestration of CO_2 throughout the Williston Basin. CO_2-flood enhanced oil recovery (EOR) is the most economically viable means of geologically sequestering CO_2. The Weyburn Field of Saskatchewan is the site of one of the largest and most studied CO_2-flood EOR projects in the world. General reservoir data provided by the states and provinces suggest that several other fields in the basin are also technically suitable for CO_2-flood EOR. Beyond EOR, many depleted petroleum reservoirs in the basin are also technically suitable for CO_2 sequestration, although a carbon credit trading system or other economic incentive will be necessary to make such sequestration economically viable.

SUMMARY

In general, the lithostratigraphy and hydrostratigraphy of the Williston Basin is understood. Locally, sequestration can begin as EOR projects and in abandoned oil and gas fields. The geology of those fields is understood, and the presence of trap is demonstrated by their existence.

Regionally, it would appear that there is significant sequestration potential in the basin, but there are some concerns that need to be more clearly addressed. A uniform geological framework with common lithostratigraphy and hydrostratigraphy will have to be finalized and accepted throughout the basin and across all political boundaries. Additional geological data will have to be collected before sequestration can occur regionally. Most importantly, porosity data will need to be generated throughout the basin. A detailed log top base will need to be generated for at least the zones that are considered primary sequestration candidates. These data may be best generated by the creation of digitized well logs in log ASCII standard (LAS) format. Additional hydrodynamic work will be needed to better model intra- and inter-formational fluid flow.

The competency of regional traps will need to be understood and proven. At present, the use of geochemical surveys is being reviewed as a method to identify lineaments that may be leaking. The use of remote sensing techniques is also being considered to identify lineaments that may have surface expression.

Anthropogenic activity, notably the disposal of oil field brines, may affect regional groundwater flow. Sequestration models will have to consider this possible effect.

CONCLUSIONS

In the Williston Basin, sequestration in localized stratigraphic units has significant potential and can be implemented with our current geological, geohydrological, and geotechnical capabilities. CO_2 is being used for EOR projects and will continue to be used. Sequestration in abandoned oil fields and locally and in stratagraphically isolated horizons is also possible.

Additional work is required before sequestration can begin on a regional basis. A more thorough understanding of formational hydrodynamics is needed; moreover, trap competency on a large scale needs to be demonstrated. Additional geological data will need to be collected and/or generated, including detailed formation tops and porosity data.

REFERENCES

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.

Benn; A.A., and Rostron, B.J., 1998, Regional hydrochemistry of Cambrian to Devonian Aquifers in the Williston Basin, Canada–U.S.A., *in* Christopher, J.E., Gilboy, C.F., Paterson, D.F., Bend, S.L., eds., Eighth international Williston Basin Symposium, Saskatchewan Geological Society Special Publication, 13, p. 238–246.

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.

Brown, D.L., and Brown, D.L., 1987, Wrench-style deformation and paleostructural influence on sedimentation in and around a cratonic basin, *in* Longman, M.W., ed., Williston Basin: Anatomy of a cratonic oil province: Rocky Mountain Association of Geologists, p. 57–70.

Carlson, C.G., 1960, Stratigraphy of the Winnipeg and Deadwood Formations in North Dakota: North Dakota Geological Survey Bulletin 35, p. 145.

Chimney, P.J., Treska, C.E., and Wolosin, C.A., 1992, Richardton/Taylor Fields–U.S.A., American Association of Petroleum Geologists Treatise of Petroleum Geology, Stratigraphic Traps III, p. 421–445.

Clement, J.H., 1987, Cedar Creek: A significant paleotectonic feature of the Williston Basin, *in* Longman, M.W., ed., Williston Basin: Anatomy of a cratonic oil province: Rocky Mountain Association of Geologists, p. 323–336.

Downey, J.S., Busby, J.F., and Dinwiddie, G.A., 1987, Regional aquifers and petroleum in the Williston Basin region of the United States, *in* Peterson, J.A., Kent, D.M., Anderson, S.B., Pilatzke, R.H., and Longman, M.W., eds., Williston Basin: Anatomy of a cratonic oil province, Rocky Mountain Association of Geologists, p. 299–312.

Downey, J.S., 1986, Geohydrology of bedrock aquifers in the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming, U.S. Geological Survey Professional Paper 1402-E, p. E1–E87.

Downey, J.S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota, and Wyoming, U.S. Geological Survey Professional Paper 1273-G, p. G1–G47.

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. 408–415.

Gerhard, L.C., Anderson, S.B., LeFever, J.A., and Carlson, C.G., 1982, Geological development, origin, and energy mineral resources of the Williston Basin, North Dakota: North Dakota Geological Survey Miscellaneous Series 63, p. 31.

Gerhard, L.C., Anderson, S.B., and LeFever, J.A., 1987, Structural history of the Nesson Anticline, North Dakota, *in* Peterson, J.A., Kent, D.M., Anderson, S.B., Pilatzke, R.H., and Longman, M.W., eds., Williston Basin: anatomy of a cratonic oil province, Rocky Mountain Association of Geologists, Denver, CO, p. 337–354.

Green, A.G., Weber, W., and Hajnal, Z., 1985, Evolution of proterozoic terranes beneath the Williston Basin: Geology, v. 13, p. 624–628.

Heck, T.J., LeFever, R., Fischer, D.W., and LeFever, J., 2004, *in* Overview of the petroleum geology of the North Dakota

Williston Basin, www.state.nd.us/ndgs/resources/wbpetroleum_h.htm (accessed August 2004).

Kolm, K.E., and Peter, K.D., 1982, A possible relation between lineaments and leakage through confining layers in South Dakota, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota Aquifer, National Water Well Association, Worthington, Ohio.

LeFever, R.D., Thompson, S.C., and Anderson, S.B., 1987, Earliest Paleozoic history of the Williston Basin in North Dakota, *in* Carlson, C.G., and Christopher, J.E., Fifth International Williston Basin Symposium Volume: Saskatchewan Geological Society Special Publication 9, p. 22–37.

LeFever, R.D., 1998, Hydrodynamics of formation waters in the North Dakota Williston Basin, *in* Christopher, J.E., Gilboy, C.F., Paterson, D.F., and Bend, S.L., eds., Eighth International Williston Basin Symposium: Saskatchewan Geological Society Special Publication 13, p. 229–237.

Lochman-Balk, C., 1972, Cambrian system, *in* Geologic atlas of the Rocky Mountain region, U.S.A.: Rocky Mountain Association of Geologists, p. 60–76.

NDGS Web site. www.state.nd.us/ndgs (accessed Oct 2004).

Neuzil, C.E., Bredehoeft, J.D, Wolff, R.G., 1984, Leakage and fracture permeability in the Cretaceous shales confining the Dakota Aquifer in South Dakota, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota Aquifer, National Water Well Association, Worthington, Ohio.

Peterson, J.A., and MacCary, L.M. 1987, Regional stratigraphy and general petroleum geology, Williston Basin, United States and adjacent area, *in* Peterson, J.A., Kent, D.M., Anderson, S.B., Pilatzke, R.H., and Longman, M., eds., Williston Basin anatomy of a cratonic oil province, Rocky Mountain Association of Geologists, p. 9–44.

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

Shurr, G.W., 1999, Shallow gas play around the margins of the Williston Basin, *in* Christopher, J.E., Gilboy, C.F., Paterson, D.F., and Bend, S.L., eds., Eighth International Williston Basin Symposium: Saskatchewan Geological Society Special Publication 13, p. 129–139.

Sloss, L.L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, p. 93–114.

White, C.M., Strazisar, B.R., Granite, E.J., Hoffman, J.S., Pennline, H.W., 2003, Separation and capture of CO_2 from larger stationary sources and sequestration in geological formations–coalbeds and deep saline aquifer, *in* Air & Waste Management Association, v. 53, p. 645–715, 2003.

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