INYAN KARA FORMATION OUTLINE

David W. Fischer, Fischer Oil and Gas, Inc.
James A. Sorensen, Energy & Environmental Research Center
Steven A. Smith, Energy & Environmental Research Center
Edward N. Steadman, Energy & Environmental Research Center
John A. Harju, Energy & Environmental Research Center

September 2005

EXECUTIVE SUMMARY

The Williston Basin is a relatively large, intracratonic basin with a thick sedimentary cover in excess of 16,000 ft. It 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 produce oil.

The basin has significant potential as a geological sink for sequestering carbon dioxide (CO_2). This topical report focuses on the general geological characteristics of formations in the Williston Basin that are relevant to potential sequestration in petroleum reservoirs and deep saline formations.

This report includes general information and maps on formation stratigraphy, lithology, depositional environment, hydrodynamic characteristics, and hydrocarbon occurrence. The Inyan Kara Formation in the Williston Basin has the potential to be a CO_2 sink through either enhanced oil recovery or saline formation storage.

ACKNOWLEDGMENTS

The Plains CO_2 Reduction (PCOR) Partnership is a collaborative effort of public and private sector stakeholders working toward a better understanding of the technical and economic feasibility of capturing and storing (sequestering) anthropogenic CO_2 emissions from stationary sources in the central interior of North America. It is one of seven regional partnerships funded by the U.S. Department of Energy's (DOE's) National Energy Technology Laboratory (NETL) Regional Carbon Sequestration Partnership (RCSP) Program. The Energy & Environmental Research Center (EERC) would like to thank the following partners who provided funding, data, guidance, and/or experience to support the PCOR Partnership:

- Alberta Department of Environment
- Alberta Energy and Utilities Board
- Alberta Energy Research Institute
- Amerada Hess Corporation
- Basin Electric Power Cooperative
- Bechtel Corporation
- Center for Energy and Economic Development (CEED)
- Chicago Climate Exchange
- Dakota Gasification Company
- Ducks Unlimited Canada
- Eagle Operating, Inc.
- Encore Acquisition Company
- Environment Canada
- Excelsior Energy Inc.
- Fischer Oil and Gas, Inc.
- Great Northern Power Development, LP
- Great River Energy

- Interstate Oil and Gas Compact Commission
- Kiewit Mining Group Inc.
- Lignite Energy Council
- Manitoba Hydro
- Minnesota Pollution Control Agency
- Minnesota Power
- Minnkota Power Cooperative, Inc.
- Montana–Dakota Utilities Co.
- Montana Department of Environmental Quality
- Montana Public Service Commission
- Murex Petroleum Corporation
- Nexant, Inc.
- North Dakota Department of Health
- North Dakota Geological Survey
- North Dakota Industrial Commission Lignite Research, Development and Marketing Program
- North Dakota Industrial Commission Oil and Gas Division
- North Dakota Natural Resources Trust
- North Dakota Petroleum Council
- North Dakota State University
- Otter Tail Power Company
- Petroleum Technology Research Centre
- Petroleum Technology Transfer Council
- Prairie Public Television
- Saskatchewan Industry and Resources
- SaskPower
- Tesoro Refinery (Mandan)
- University of Regina
- U.S. Department of Energy
- U.S. Geological Survey Northern Prairie Wildlife Research Center
- Western Governors' Association
- Xcel Energy

The EERC also acknowledges the following people who assisted in the review of this document:

Erin M. O'Leary, EERC
Stephanie L. Wolfe, EERC
Kim M. Dickman, EERC

BACKGROUND/INTRODUCTION

Formation outlines have been prepared as a supplement to the “Overview of Williston Basin Geology As It Relates to CO_2 Sequestration (Fischer et al., 2004). Although the stratigraphic discussion presented in the “Overview” is in a convenient format for discussing the general characteristics of the basin, it does not provide insight into the specific characteristics of every formation. A formation outline summarizes, in outline form, the current knowledge of the basic geology for each formation. If not specifically noted, the formation boundaries and names reflect terminology that is recognized in the North Dakota portion of the Williston Basin. The intended purpose of the formation outlines will provide a convenient basis and source of reference from which to build a knowledge base for more detailed future characterization. The development of sequestration volumes, estimates, and rankings are beyond the scope of the formation outlines prepared as part of the Phase I activities.

The Plains CO_2 Reduction (PCOR) Partnership believes these outlines are a necessary component in characterizing the sequestration potential of the basin. Although the stratigraphic discussion presented in the “Overview of Williston Basin Geology As It Relates to CO_2 Sequestration” is in a convenient format for discussing the general characteristics of the basin, it does not provide insight into the specific characteristics of every formation. In fact, each lithostratigraphic or geohydrologic unit discussed in that report can be further subdivided into individual formations. Formations may, in turn, be subdivided. Each subdivision may represent a sink, hereafter referred to as a “geological sequestration unit” (GSU) or a confining unit (aquitard). Some of the subdivisions may already be considered part of a large regional GSU or confining unit, while others may be localized and isolated. Many will represent a potential GSU within a regionally defined confining unit or a confining unit within a regionally defined sink.

Presently, the PCOR Partnership refers to CO_2 sequestration reservoirs as “sequestration units,” based on accepted legal terminology or protocol currently in use in the petroleum industry. CO_2 injection requires joint operating agreements that will necessitate the establishment of unitized lands for CO_2 sequestration, whether they are in petroleum reservoirs, coal beds, or subsurface formations or intervals containing brine.

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

- Injection into conventional GSUs may not require significant borehole stimulation because of inherent porosity and permeability; however, injection into unconventional GSUs will require significant stimulation, including fracture stimulation prior to injection, because of the lack of inherent permeability.

- For conventional reservoirs or GSUs, the presence of bounding or confining units will have to be well demonstrated and understood; these

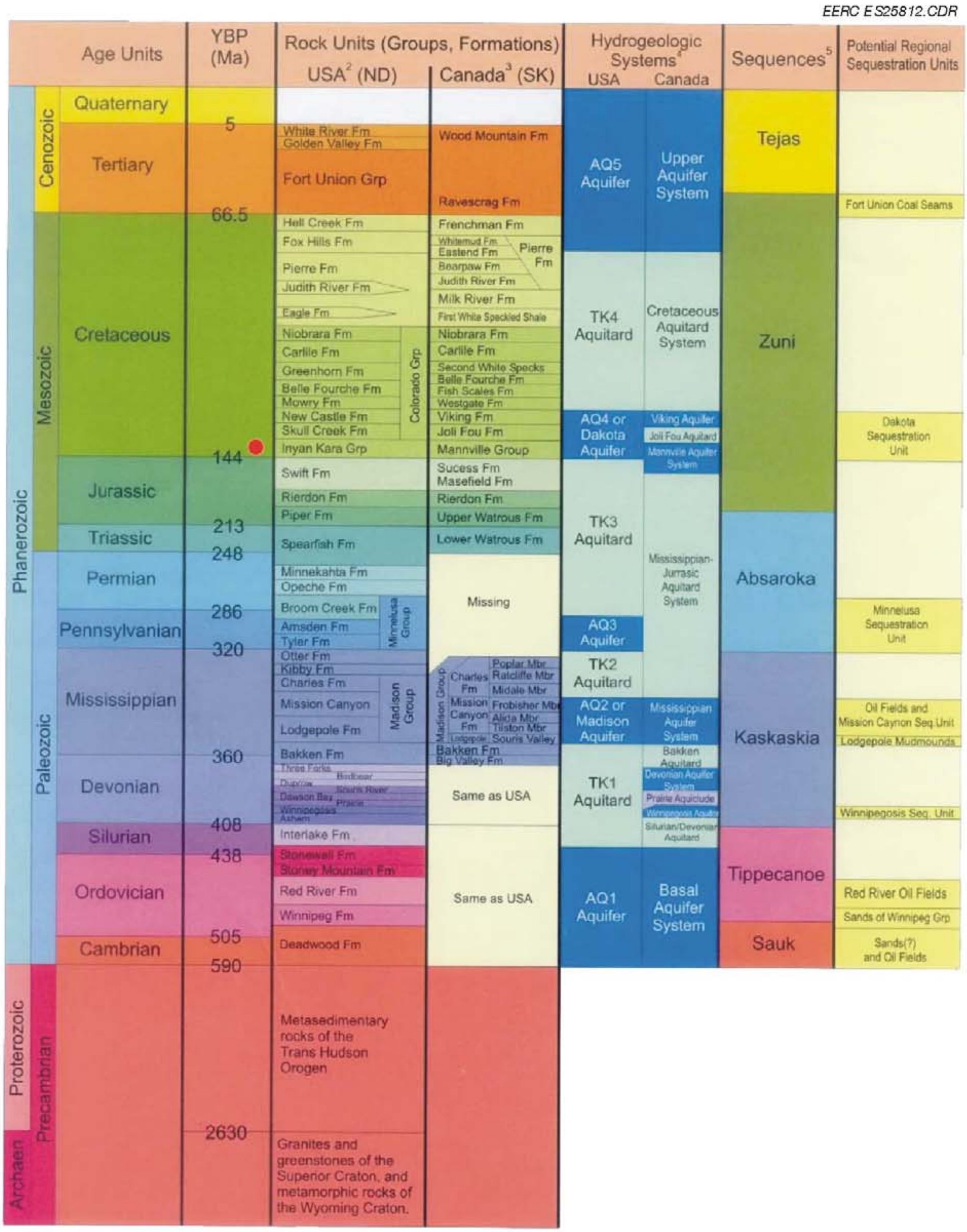


Figure 1. Williston Basin stratigraphic and hydrogeologic column.

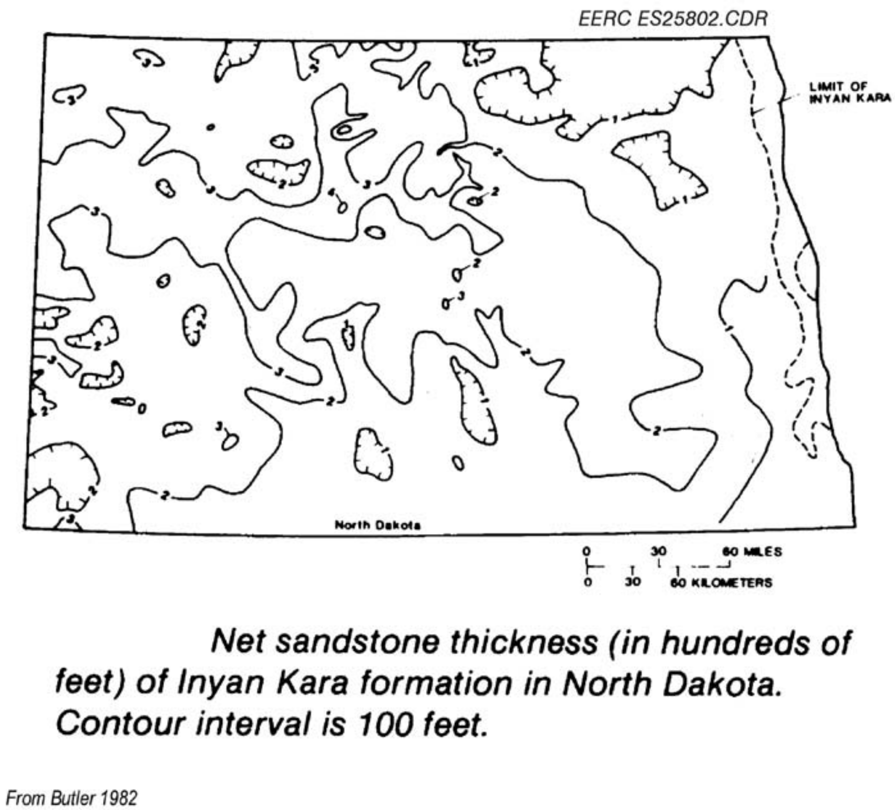


Figure 2. Inyan Kara net sand isopach in North Dakota.

units will be the trapping mechanism for injected fluids. Unconventional GSUs, because of the inherent lack of permeability, may be self-trapping.

- Conventional GSUs may not need expensive stimulation procedures and, therefore, would be less sensitive to economic constraints.
- Unconventional GSUs that have a component of organic-rich matrix materials need to be investigated as to the capacity, if any, to play a role in fixation of CO_2.

A distinction is also made between primary and secondary GSUs. A primary GSU is a regional GSU with lateral continuity and would likely be capable of sequestering a significant amount of CO_2. A primary GSU would be the main target in a regional sequestration unit. A secondary GSU is less continuous and perhaps isolated and capable of sequestering a relatively minor amount of CO_2. For instance, a secondary GSU would not necessarily be a “stand-alone” sequestration target, but it might be utilized for sequestration if a borehole were already in place.

The potential importance of thin or nonregional sinks cannot be overlooked once CO_2 has been captured. The major expenses involved in the postcapture phase of geologic sequestration are transportation and well costs. Smaller sinks that are stratigraphically proximal to a larger sink target represent a means to maximize the economic potential of injection programs by utilizing all available storage encountered in an individual borehole. In order for nonregional sinks to be utilized, detailed characterization and mapping of those units are necessary.

FORMATION NAME

Inyan Kara Formation Outline

The stratigraphy and nomenclature of the lower Cretaceous varies greatly throughout the PCOR Partnership region. In this document, Williston Basin statigraphic nomenclature will follow that recognized by the North Dakota Geological Survey as summarized in "North Dakota Stratigraphic Column" (Bluemle et al., 1986) and the "Williston Basin Stratigraphic Nomenclature Chart' (Bluemle et al., 1981).

Equivalents to the Inyan Kara Formation include the Fall River and Lakota sandstones (in ascending order) of the Inyan Kara Group in South Dakota (Schoon, 2005); the Manville group in southern Saskatchewan (Saskatchewan Industry and Resources, 2004); the Swan River in Manitoba (Rutulis, 1984); and the Lakota, Kootenai, Dakota, and Basal Colorado Silt (in ascending order) in Montana (Bluemle et al., 1981).

FORMATION AGE (LeRud, 1982)

Early Cretaceous
Aptian to Albian
Dakota Group

GEOLOGIC SEQUENCE

Zuni

HYDROSTATIGRAPHY

Downey et al. (1987): AQ4 aquifer Bachu and Hitchon (1996): Manville Aquifer system (Figure 1)

GEOGRAPHIC DISTRIBUTION (modified from LeRud, 1982)

Eastern Montana, North Dakota, South Dakota, southwestern Manitoba, southern Saskatchewan

THICKNESS

The Inyan Kara is in excess of 500 ft thick near the Basin center in North Dakota (Wartman, 1982). In southeastern Saskatchewan, the Inyan Kara (Manville) can be in excess of 400 ft (Hayes et al., 1994). Net sand thickness in the interval is variable (Butler, 1984; Rutulis, 1984; Case, 1984). In North Dakota (Figure 2), net sand thickness can be locally greater than 300 ft (Butler, 1984).

CONTACTS

The upper contact with the Skull Creek is conformable (LeFever and McCloskey, 1995; Leckie et al., 1994).

The lower contact of the Inyan Kara is unconformable. A major regional unconformity separates the Inyan Kara from underlying rocks. Throughout most of the basin, the Inyan Kara rests on Jurassic sediments (Wartman, 1982). In eastern North Dakota, they overlie progressively older Paleozoic rocks until the formation pinches out near the eastern border of the state.

LITHOLOGY

Clastic

SUBDIVISIONS

In a study of the Inyan Kara in North Dakota, Wartman (1982) informally subdivided the unit into three members. In ascending order, these members are the "A," the "B," and the "C" (Figure 3).

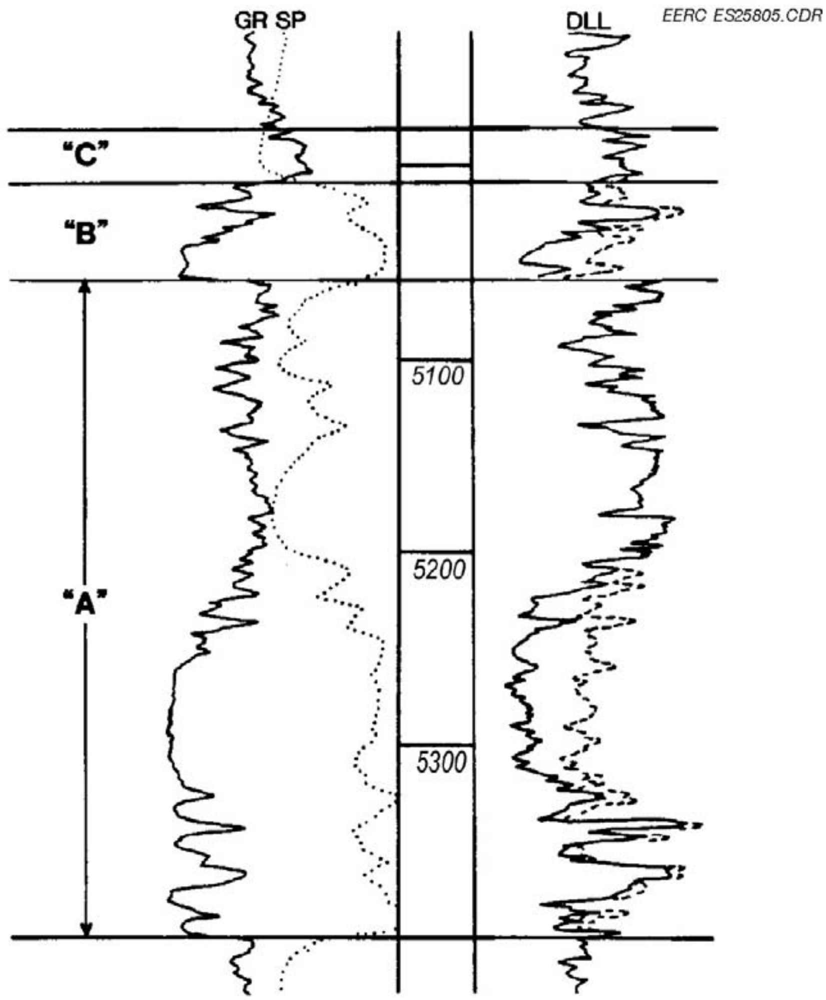


Figure 3. Well log of NDGS 6515, Twn. 156 N., Rng. 91 W., Sec. 17, showing members "A", "B" and "C" of the Inyan Kara formation (Wartman 1983). Log types: GR = Gamma-Ray, SP = Spontaneous Potential, DLL = Dual Laterolog (dashed line = shallow and solid line = deep).

From Wartman; 1982

Figure 3. Reference log with Inyan Kara Formation members.

LITHOFACIES

The lowermost member, the “A,” is the thickest, comprising over 90 percent of the total thickness. Wartman describes the “A” member as a series of discontinuous beds of fine- to coarse-grained sandstones, siltstones, and shales with some coals that were deposited in a fluvio-deltaic environment.

The middle “B” member sediments vary greatly in lateral distribution and consist of fine- to medium-grained sandstones, siltstones, and shales.

The “C” member is a highly continuous unit of fine- to medium-grained siltstone and clay laminae.

DEPOSITIONAL ENVIRONMENTS

Nonmarine to marine

DEPOSITIONAL MODEL (after Wartman, 1982)

- Member “A” was deposited in a fluvio-deltaic environment.
- Member “B” was deposited in a marginal marine setting.
- Member “C” was deposited in a shallow marine origin.

RESERVOIR CHARACTERISTICS

Porosity in the Inyan Kara can be significant. For example, north central North Dakota had a neutron density well log porosity in excess of 30 percent (Figure 4).

From Kelly (1968)

In eastern North Dakota: average porosity 42.7 percent, average permeability 235 meinzer units

From Butler (1984)

Porosity along flank of basin in North Dakota is 30–35.5 percent, dropping below 20.5 percent in the basin’s center.

HYDRODYNAMIC CHARACTERISTICS

From the U.S. Geological Survey Groundwater Atlas
Potentiometric map: Figure 5
Total dissolved solids: Figure 6

From Wartman (1982)

Transmissivity 200–77,000 ft^2/day
Hydraulic conductivity 20–30 ft/day: Figure 7

From Kelly (1968)

In eastern North Dakota: coefficient of storage 0.0004, transmissivity 50,000 gpd/ft, as low as 12,000 gpd/ft.

From Case (1984)

Estimated regional hydraulic conductivity in South Dakota is 1.2×10^{-5} ft/sec. Case also lists hydraulic conductivities from other sources; they range from $1.0–6.5 \times 10^{-5}$ ft/sec.

From Butler (1984)

Nodal hydraulic conductivity averages less than 40 ft/day. Transmissivities are from 200–77,000 ft^2/day.

HYDROCARBON PRODUCTION

There is currently no oil or natural gas production from the Inyan Kara in the North Dakota or Montana portion of the Williston Basin. Some shallow natural gas may have been produced from the Inyan Kara in central South Dakota. The Inyan Kara (Manville Group/Canada) produces natural gas, heavy oil, and coal in Canada.

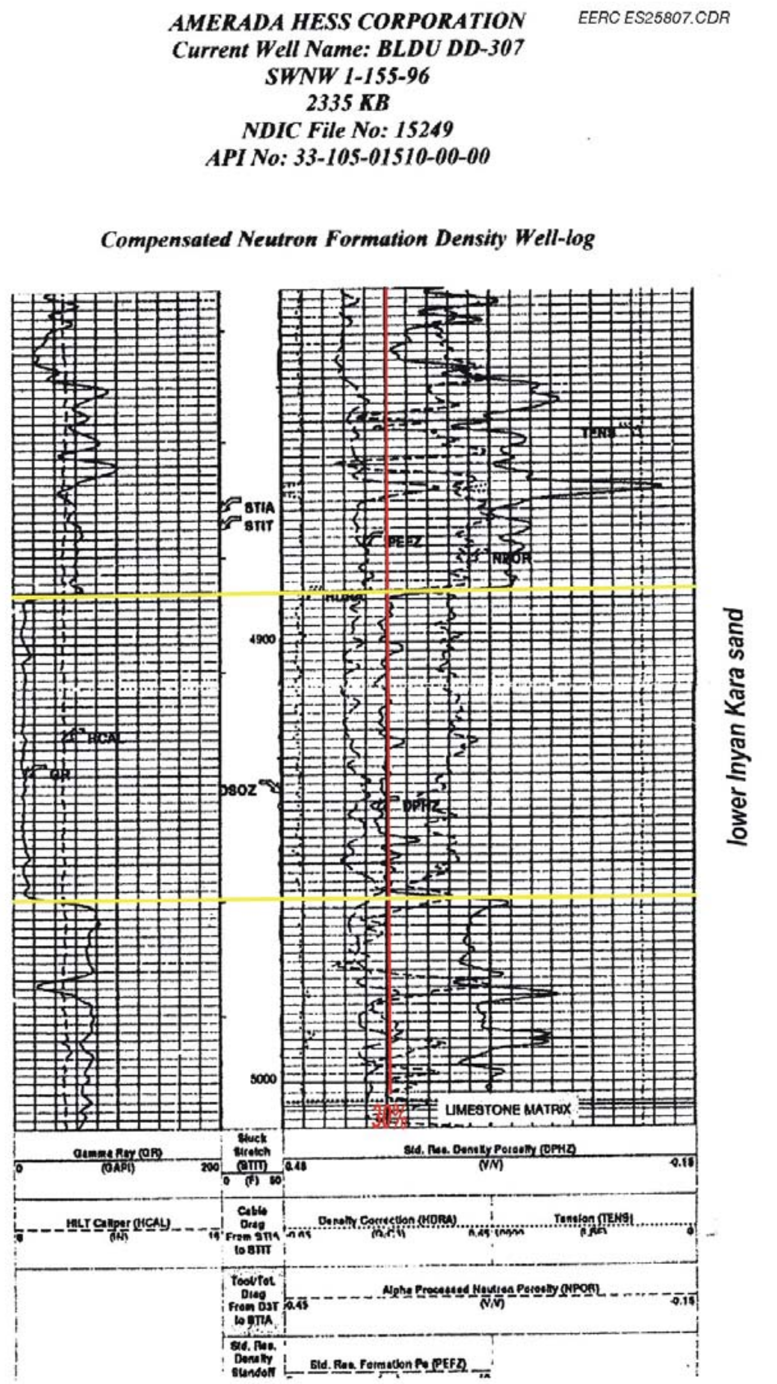


Figure 4. Inyan Kara Formation example log.

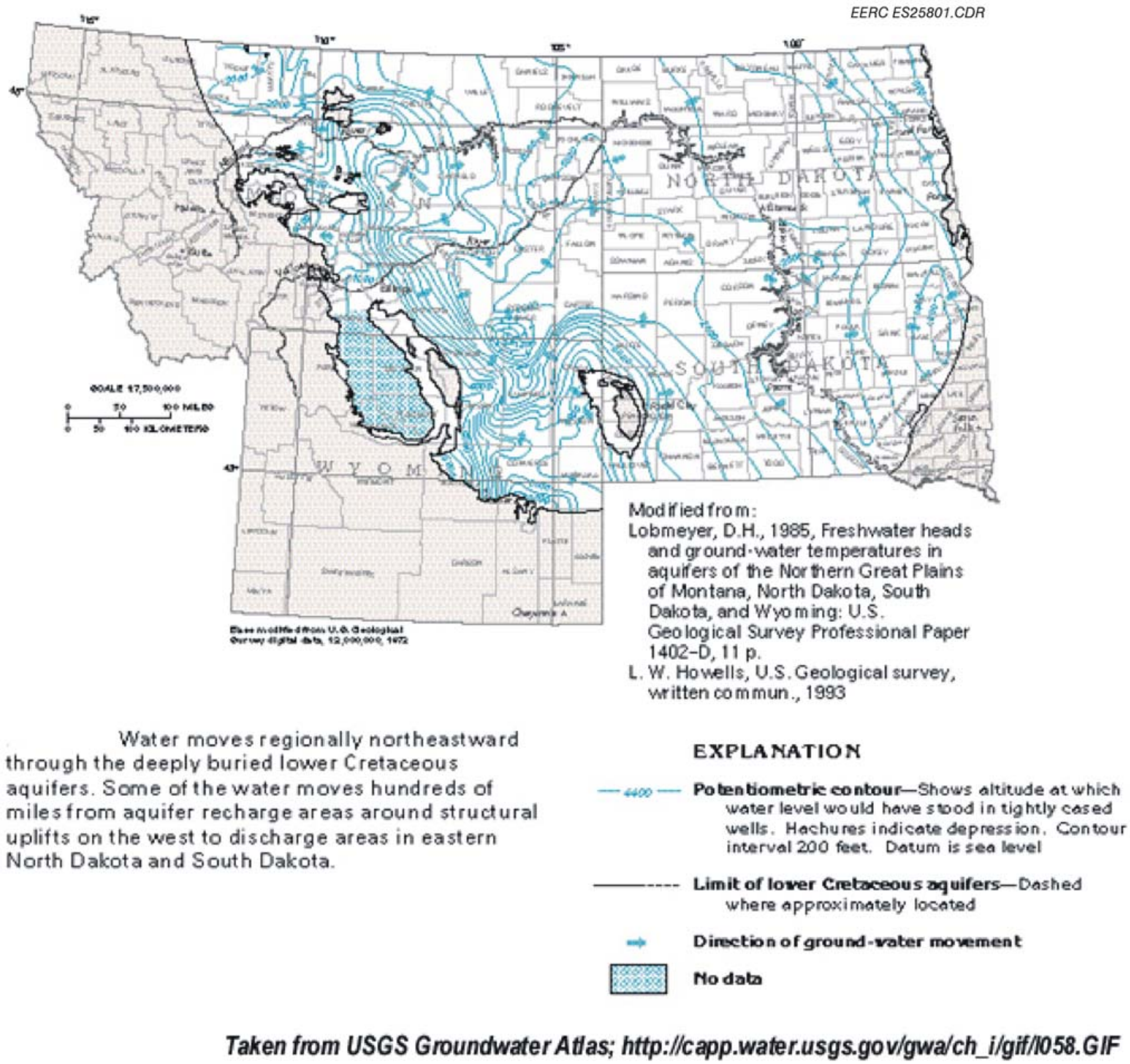


Figure 5. Potentiometric map of the lower Cretaceous formations including the Inyan Kara Formation.

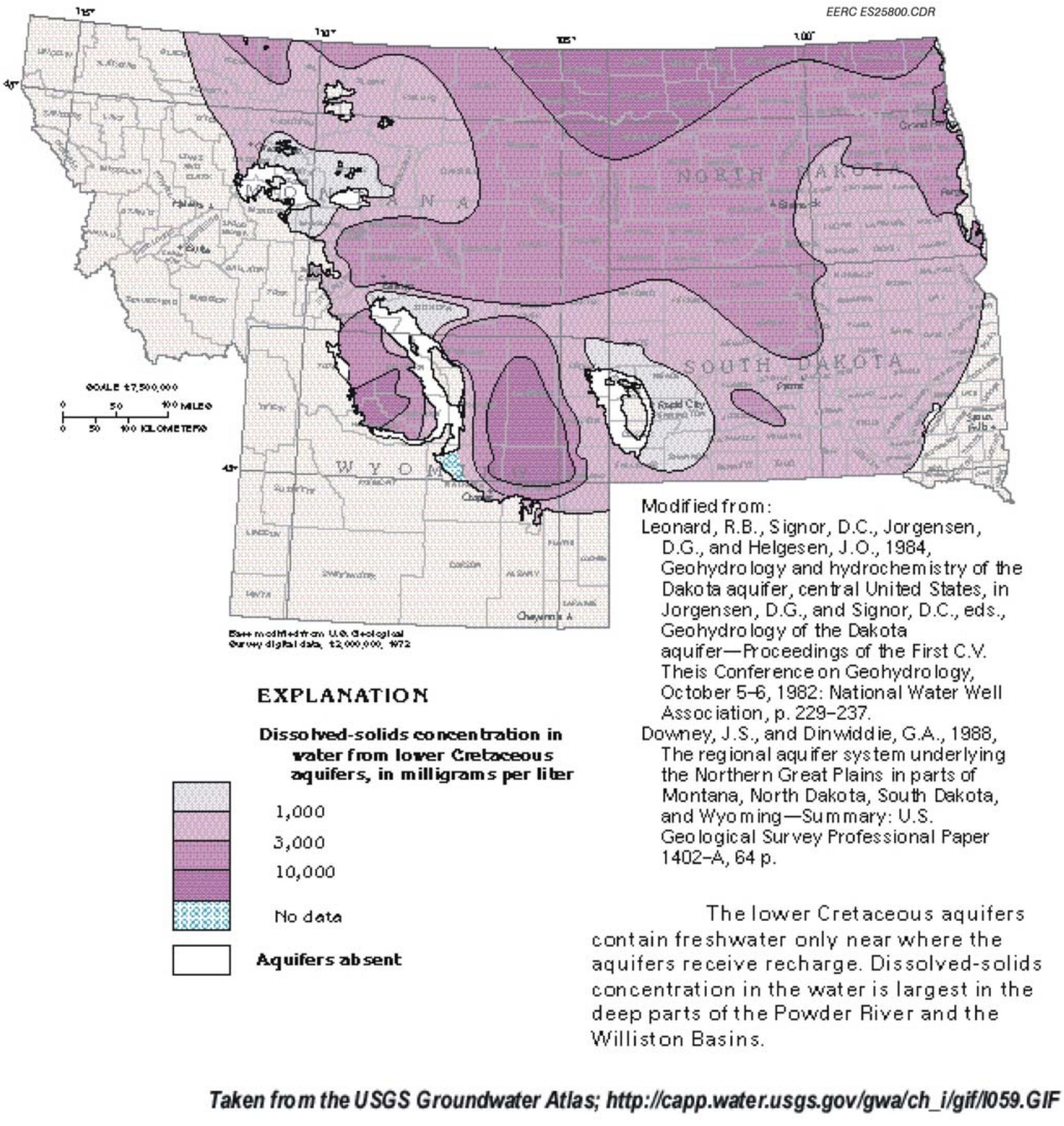
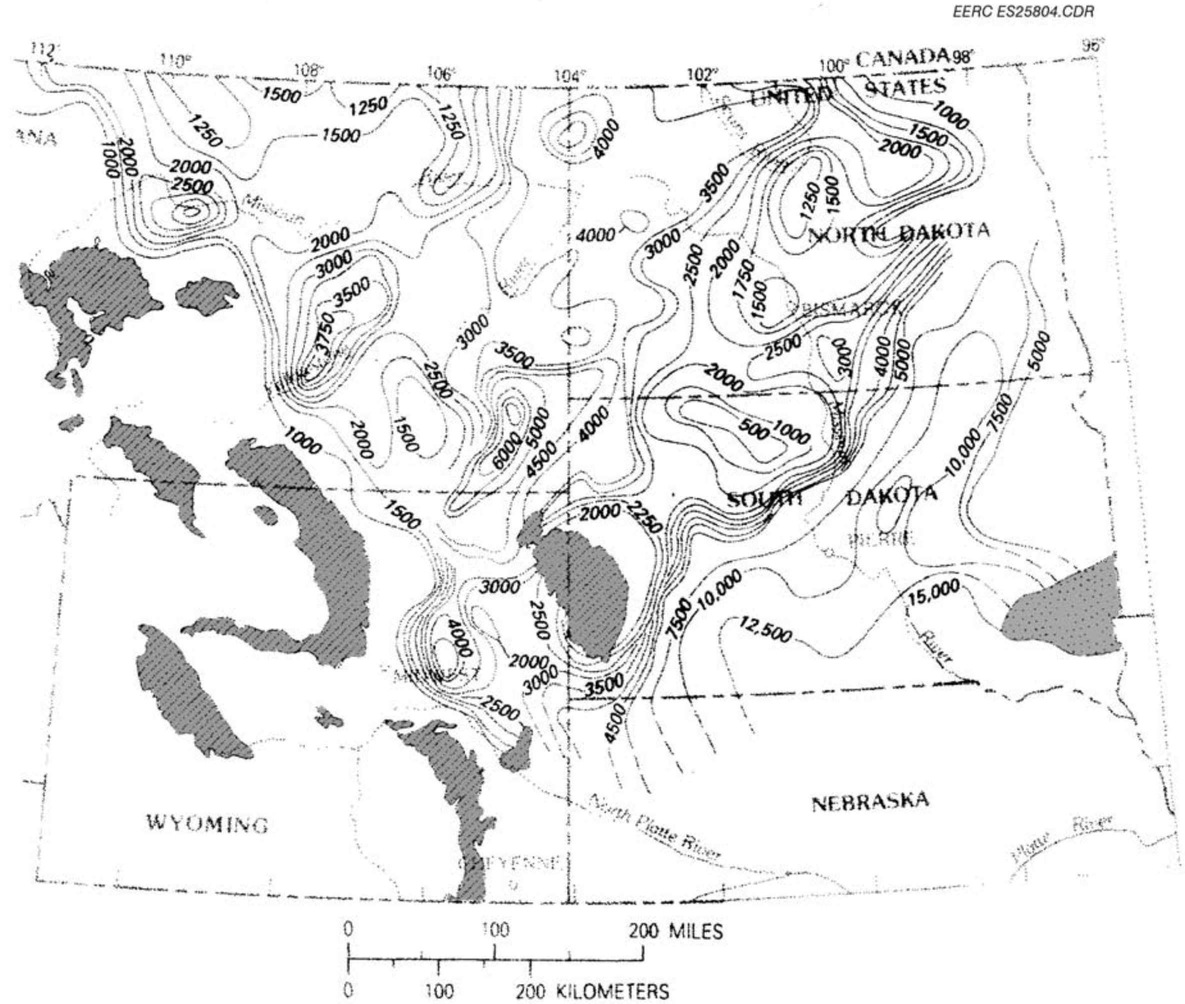


Figure 6. Map of total dissolved solids concentrations from lower Cretaceous formations including the Inyan Kara Formation.



EXPLANATION

JURASSIC AND TRIASSIC OR OLDER ROCKS EXPOSED AT THE SURFACE

APPROXIMATE AREA WHERE LOWER CRETACEOUS ROCKS ARE MISSING IN THE SUBSURFACE

—1000— LINE OF EQUAL TRANSMISSIVITY—Interval, in square feet per day, is variable. Dashed where inferred

Transmissivity distribution used in the Lower Cretaceous aquifer simulations.

From: USGS PP 1402E

Figure 7. Transmissivity distribution in the lower cretaceous formation including the Inyan Kara Formation.

SINK POTENTIAL

The Inyan Kara is a potentially important regional sink. The quartz arenites that can comprise a significant part of the section are both porous and permeable.

REFERENCES

Bachu, S., and Hitchon, B., 1996, Regional-scale flow of formation waters in the Williston Basin, AAPG Bulletin, v. 80, n. 2, p. 248–264.

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 No. 66, 3 sheets.

Bluemle, J.P., Anderson, S.B., and Carlson, C.G., 1981, Williston Basin stratigraphic nomenclature chart: North Dakota Geological Survey Miscellaneous Series No. 61, 1 sheet.

Butler, R.D., 1984, Hydrogeology of Dakota Aquifer system, Williston Basin, North Dakota, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota Aquifier, National Water Well Association, C.V. Thesis Conference on Geohydrology, 1st, Lincoln, Nebraska, October 5–6, 1982, Proceedings: p. 14–23.

Case, H.L., III, 1984, Hydrology of Inyan Kara and Dakota-Newcastle aquifer system, South Dakota, in Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota Aquifier, National Water Well Association, C.V. Thesis Conference on Geohydrology, 1st, Lincoln, Nebraska, October 5–6, 1982, Proceedings: p. 147–165.

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, Denver, Colorado, p. 299–312.

Fischer, D.W., LeFever, J.A., LeFever, R.D., Anderson, S.B.; Helms, L.D., Sorensen, J.A., Smith, S.A., Peck, W.D., Steadman, E.N., and Harju, J.A., 2004, Overview of Williston Basin geology as it relates to CO_2 sequestration: Plains CO_2 Reduction (PCOR) Partnership Topical Report for U.S. Department of Energy and multiclients, Grand Forks, North Dakota, Energy & Environmental Research Center, October 2004.

Hayes B.J.R., Christopher, J.E., Rosenthal, L., Los, G., McKercher, B., Minken, D., Tremblay, Y.A., and Fennell, J., 1994, Chapter 19: Cretaceous Mannville Group, *in* Geological Atlas of the Western Canada Sedimentary Basin: Mossop, G.D., and Shetson, I. comps., Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary, Alberta, www.ags.gov.ab.ca/publications/ATLAS_WWW/ATLAS.shtml (accessed July 2005).

Kelly, T.E., 1968, Notes on the geohydrology of the Dakota Sandstone, eastern North Dakota: U.S. Geological Survey Professional Paper 600-C, p. C185–C191.

Leckie, D.A., Bhattacharya J.P., Bloch, J. Gilboy, C.F., and Norris, B., 1994, Chapter 20: Cretaceous Colorado/Alberta Group, *in* Geological Atlas of the Western Canada Sedimentary Basin: Mossop, G.D., and Shetson, I., comps., Canadian Society of Petroleum Geologists and Alberta Research Council, Calgary, Alberta, www.ags.gov.ab.ca/publications/ATLAS_WWW/ATLAS.shtml (accessed July 2005).

LeFever, R.D., and McCloskey, G.G., 1995, Depositional history of the Newcastle Formation (lower Cretaceous), Williston Basin, North Dakota, South Dakota and eastern Montana, in Hunter, L.D.V., and Schalla, R.A., eds., Seventh International Williston Basin Symposium, Billings, Montana, Montana Geological Society, Proceedings: p. 411–416.

LeRud, J., 1982, Lexicon of stratigraphic names of North Dakota, North Dakota Geological Survey Report of Investigations No. 71, p. 139.

Rutulis, M., 1984, Dakota aquifer system in Manitoba, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota Aquifier, National Water Well Association, C.V. Thesis Conference on Geohydrology, 1st, Lincoln, Nebraska, October 5–6, 1982, Proceedings: p. 178–185.

Saskatchewan Industry and Resources, 2004, Stratigraphic correlation chart, www.ir.gov.sk.ca/Default.aspx?DN=3966,3625,3384,2936 (accessed April 2005).

Schoon, R.A., 2005, http://jurassic2.sdgs.usd.edu/pubs/pdf/EM-06%20-%2011X17%20inches.pdf.

Wartman, B.L., 1982, Geology and hydrology of the Inyan Kara Formation (Lower Cretaceous), North Dakota, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota Aquifer Symposium, October 5–6, 1982, National Water Well Association, Lincoln, Nebraska, Proceedings: p. 22–26.

For more information on this topic, contact:

David W. Fischer, Fischer Oil and Gas, Inc.
(701) 746-8509; fischerd@gfwireless.com

James A. Sorensen, EERC Senior Research Manager
(701) 777-5287; jsorensen@undeerc.org

Edward N. Steadman, EERC Senior Research Advisor
(701) 777-5279; esteadman@undeerc.org

John A. Harju, EERC Associate Director for Research
(701) 777-5157; jharju@undeerc.org

Visit the PCOR Partnership Web site at www.undeerc.org/PCOR.

Sponsored in Part by the U.S. Department of Energy