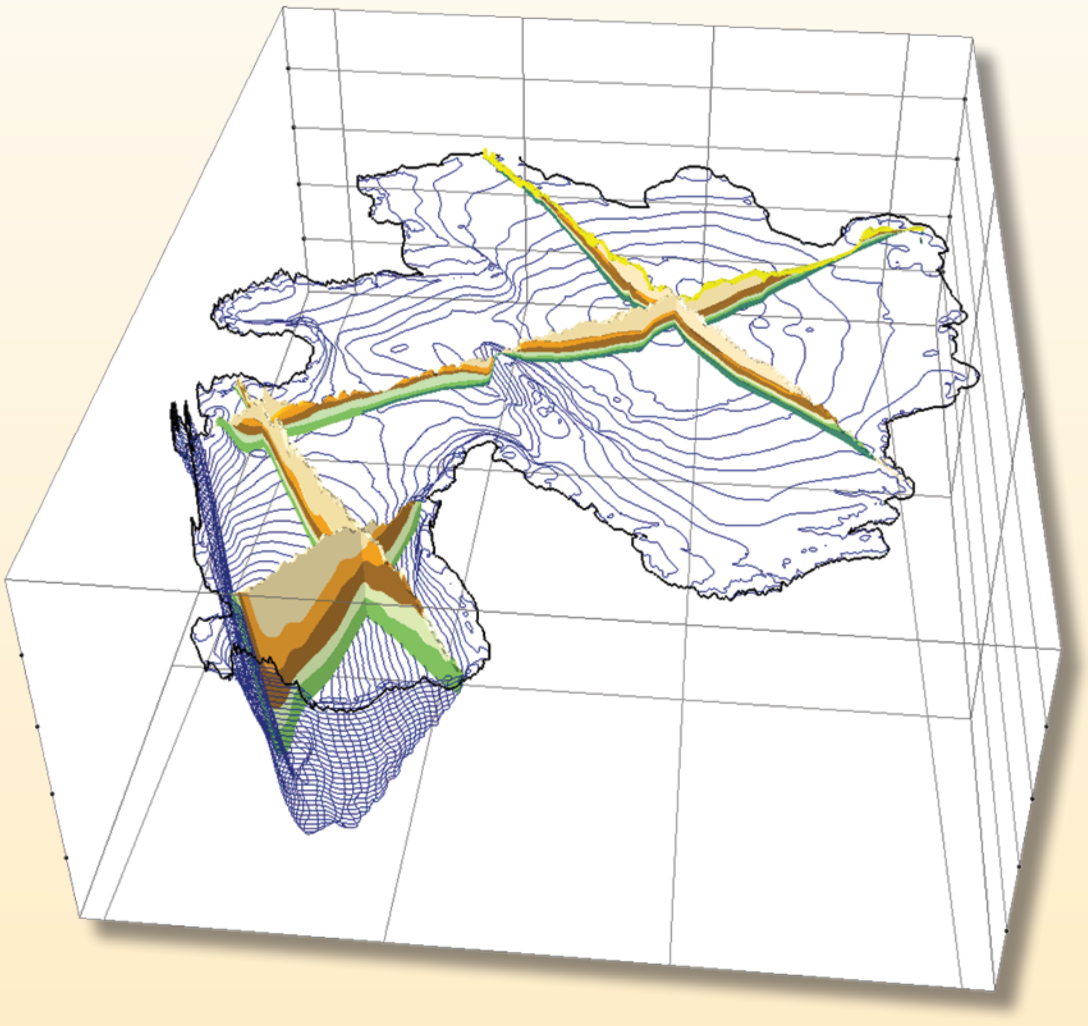
USGS
science for a changing world

Groundwater Resources Program

Hydrogeologic Framework of the Uppermost Principal Aquifer Systems in the Williston and Powder River Structural Basins, United States and Canada



Scientific Investigations Report 2014–5047
Version 1.1, December 2014

U.S. Department of the Interior
U.S. Geological Survey

Cover. Generalized cross sections showing the three-dimensional hydrogeologic framework from land surface to the top of basal confining unit in the Williston and Powder River structural basins.

Hydrogeologic Framework of the Uppermost Principal Aquifer Systems in the Williston and Powder River Structural Basins, United States and Canada

By Joanna N. Thamke, Gary D. LeCain, Derek W. Ryter, Roy Sando, and Andrew J. Long

Groundwater Resources Program

Scientific Investigations Report 2014–5047
Version 1.1, December 2014

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia
First release: 2014
Revised: December 2014 (ver. 1.1)

Suggested citation:
Thamke, J.N., LeCain, G.D., Ryter, D.W., Sando, Roy, and Long, A.J., 2014, Hydrogeologic framework of the uppermost principal aquifer systems in the Williston and Powder River structural basins, United States and Canada (ver. 1.1, December 2014): U.S. Geological Survey Scientific Investigations Report 2014–5047, 38 p., *http://dx.doi.org/10.3133/sir20145047*.

ISSN 2328-0328 (online)

Acknowledgments

The authors thank Kei Lo, Saskatchewan Government Water Security Agency, for providing water-level data and electronic versions of resistivity logs for thousands of water wells throughout southern Saskatchewan. The authors also thank Dan Kohlruss, Arden Marsh, Bill Slimmon, and Melinda Yurkowski (Saskatchewan Geological Survey, Ministry of the Economy) for providing their insight to bedrock geology in southern Saskatchewan and providing resistivity logs for hundreds of oil wells throughout southern Saskatchewan. Greg Keller (Manitoba Geological Survey; Manitoba Innovation, Energy and Mines) provided information regarding the bedrock geology in southwestern Manitoba. Robert Bergantino and Susan Vuke, Montana Bureau of Mines and Geology (MBMG), provided information about the bedrock geology in Montana. Fred Anderson, North Dakota Geological Survey, provided information about the bedrock geology in North Dakota. Special recognition goes to Jon Reiten and Kevin Chandler (MBMG); Alan Wanek and Kimberly Fischer (North Dakota State Water Commission); and Tom Wood, Mitch Plummer, and Luanjing Guo (Idaho National Laboratory), for their participation in bi-monthly technical conference calls to discuss the hydrogeologic framework of the principal aquifers in the Williston structural basin.

The work in this report was supported by the U.S. Geological Survey (USGS) Groundwater Resources Program. The authors gratefully acknowledge the insight and support provided by USGS leadership to develop the hydrogeologic framework for this large-scale groundwater availability study. Special thanks are extended to Kevin Chandler and Jon Reiten (MBMG) and Jonathan Gillip (USGS) for their insightful colleague reviews of this report. Finally, the work in this report is the product of a USGS team effort that included many individuals, specifically, Katherine Aurand, Jennifer Bednar, Kyle Davis, Jonathan McKaskey, and Joshua Valder (South Dakota Water Science Center), and Timothy Bartos and Diane Rauch (Wyoming-Montana Water Science Center).

Contents

Acknowledgments ... iii
Abstract ... 1
Introduction ... 2
  Purpose and Scope ... 2
  Previous Investigations ... 2
  Description of Study Area ... 4
Methods ... 6
  Hydrogeologic Units ... 6
  Hydraulic Characteristics ... 13
    Quantification of Hydraulic Conductivity and Transmissivity ... 13
    Qualification of Horizontal and Vertical Hydraulic Conductivity ... 14
  Potentiometric Surfaces ... 15
Hydrogeologic Framework ... 16
  Hydrogeologic Units ... 17
    Glacial Aquifer System ... 17
    Lower Tertiary Aquifer System ... 17
      Upper Fort Union Aquifer ... 17
      Middle Fort Union Hydrogeologic Unit ... 21
      Lower Fort Union Aquifer ... 22
    Upper Cretaceous Aquifer System ... 22
      Upper Hell Creek Hydrogeologic Unit ... 22
      Lower Hell Creek Aquifer ... 22
      Fox Hills Aquifer ... 23
    Basal Confining Unit ... 23
  Hydraulic Characteristics ... 23
    Hydraulic Conductivity ... 25
    Transmissivity ... 27
  Potentiometric Surfaces ... 27
    Williston Structural Basin ... 28
    Powder River Structural Basin ... 28
Summary ... 28
Selected References ... 29
Appendix 1. Interactive Maps ... 36
Appendix 2. Lithologic and Hydraulic Characteristics Determined from Well Logs at Selected Sites in the Williston Structural Basin ... 37
Appendix 3. Hydraulic Head Data in Selected Wells for the lower Tertiary and Upper Cretaceous Aquifers in the Williston Structural Basin ... 38

Figures

1. Map showing principal aquifers and structural basins of the Northern Great Plains......3
2. Map showing hydrogeologic units of the uppermost principal aquifer systems in the Williston and Powder River structural basins......5
3. Diagram showing lithostratigraphic and corresponding hydrogeologic units in the Williston structural basin and the Powder River structural basin......9
4. Index map showing sources of data used to determine the thickness of the glacial deposits in and near the Williston structural basin......12
5. Generalized cross sections showing the three-dimensional hydrogeologic framework from land surface to the top of basal confining unit in the Williston and Powder River structural basins......18
6. Maps showing thickness of glacial aquifer system in and near the Williston structural basin and combined lower Tertiary and Upper Cretaceous aquifer systems in the Williston and Powder River structural basins......19
7. Map showing altitude of the top of the basal confining unit in the Williston and Powder River structural basins......24

Appendix Figures

1–1. Interactive maps showing estimated horizontal hydraulic conductivity for the glacial, lower Tertiary, and Upper Cretaceous aquifer systems in the Williston and Powder River structural basins......36
1–2. Interactive maps showing potentiometric surfaces of the upper Fort Union aquifer, lower Fort Union aquifer, and the Upper Cretaceous aquifer systems in the Williston and Powder River structural basins......36

Tables

1. Digital download directory and file names of hydrogeologic framework of the uppermost principal aquifer systems in the Williston and Powder River structural basins......7
2. Sources of bedrock geologic data, Williston and Powder River structural basins......11
3. Summary of specific capacity tests for water wells in the Williston structural basin......14
4. Qualitative scale of horizontal-to-vertical hydraulic conductivity flow potential based on well logs in the Williston structural basin......15
5. Interpolated volumes, thicknesses, and horizontal hydraulic conductivity values of aquifer systems and hydrogeologic units in the Williston and Powder River structural basins......21
6. Horizontal and vertical hydraulic conductivity measured from borehole core samples for previous studies for the Williston structural basin in North Dakota......25
7. Ratios of horizontal to vertical hydaulic conductivity from borehole core samples composed of sandstone and shale in the United States and Canada......26

Appendix Tables

2–1. Table Lithologic and hydraulic characteristics determined from well logs at selected sites, North Dakota 37

2–2. Lithologic and hydraulic characteristics determined from well logs at selected sites, Montana....37

2–3. Lithologic and hydraulic characteristics determined from well logs at selected sites, South Dakota....37

2–4. Lithologic and hydraulic characteristics determined from well logs at selected sites, Saskatchewan 37

2–5. Statistical summary of the interpreted horizontal hydraulic conductivity values for the hydrogeologic units of the Williston structural basin....37

2–6. Summary of the horizontal-to-vertical conductivity ratings for the hydrogeologic units of the Williston structural basin 37

2–7. Statistical summary of the interpreted transmissivity values for the hydrogeologic units of the Williston structural basin 37

3–1. Hydraulic head data in selected wells for the lower Tertiary and Upper Cretaceous aquifers in the Williston structural basin....38

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Evapotranspiration	
inch per year (in/yr)	0.0254	meter per year (m/yr)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness ($[(ft^3/d)/ft^2]ft$). In this report, the mathematically reduced form, foot squared per day ($[ft^2/d]$), is used for convenience.

Abbreviations

<	less than
b	saturated thickness of aquifer
B.P.	years before present
CBNG	coalbed natural gas
GWIC	Groundwater Information Center
K	hydraulic conductivity
K_h	horizontal hydraulic conductivity
K_v	vertical hydraulic conductivity
LSA	land-surface altitude
MBMG	Montana Bureau of Mines and Geology
NDGS	North Dakota State Geological Survey
NDSWC	North Dakota State Water Commission
NED	National Elevation Dataset
NWIS	National Water Information System
T	transmissivity
USGS	U.S. Geological Survey

Hydrogeologic Framework of the Uppermost Principal Aquifer Systems in the Williston and Powder River Structural Basins, United States and Canada

By Joanna N. Thamke, Gary D. LeCain, Derek W. Ryter, Roy Sando, and Andrew J. Long

Abstract

The glacial, lower Tertiary, and Upper Cretaceous aquifer systems in the Williston and Powder River structural basins within the United States and Canada are the uppermost principal aquifer systems and most accessible sources of groundwater for these energy-producing basins. The glacial aquifer system covers the northeastern part of the Williston structural basin. The lower Tertiary and Upper Cretaceous aquifer systems are present in about 91,300 square miles (mi^2) of the Williston structural basin and about 25,500 mi^2 of the Powder River structural basin. Directly under these aquifer systems are 800 to more than 3,000 feet (ft) of relatively impermeable marine shale that serves as a basal confining unit. The aquifer systems in the Williston structural basin have a shallow (less than 2,900 ft deep), wide, and generally symmetrical bowl shape. The aquifer systems in the Powder River structural basin have a very deep (as much as 8,500 ft deep), narrow, and asymmetrical shape.

The Williston structural basin has been an important oil and natural gas producing region since the 1950s, and production has increased substantially since the mid-2000s due to improved drilling and hydraulic fracturing methods from deep formations, such as the Bakken and Three Forks Formations. These improved methods require considerable volumes of freshwater mostly from shallow aquifers or surface water. Coal, lignite, and coal-bed natural gas are additional sources of energy in both basins that can affect the quality and quantity of shallow aquifers through strip mining and groundwater depletion.

In 2011, the U.S. Geological Survey initiated a regional study of the glacial, lower Tertiary, and Upper Cretaceous aquifer systems in the Williston and Powder River structural basins with the goal to quantify groundwater availability. This report, together with a companion report of the conceptual flow model, provides an improved understanding of the groundwater flow systems and a basis for a numerical, regional groundwater-flow model.

This study combines the lithostratigraphic units of the glacial, lower Tertiary, and Upper Cretaceous aquifer systems in the United States and Canada into 7 regional hydrogeologic units—glacial deposits, 4 bedrock aquifers, and 2 bedrock confining units—using general hydraulic properties. The glacial deposits are composed of till and glacial outwash sands and gravels with areas of cobbles and boulders. The four bedrock aquifers are the upper Fort Union, lower Fort Union, lower Hell Creek, and Fox Hills aquifers and are contained primarily in sandstone layers. The two confining units are the middle Fort Union hydrogeologic unit (shale) and upper Hell Creek hydrogeologic unit (contains less sandstone than the underlying lower Hell Creek aquifer). Water from hydrogeologic units in these three aquifer systems is relatively fresh and potable, whereas withdrawals seldom occur from units below the basal confining unit because of great depths (greater than 800 ft) and poor water quality.

Analysis of about 300 electric (resistivity) and lithologic logs in the Williston structural basin and numerous existing publications for the Powder River structural basin were used to develop a three-dimensional hydrogeologic framework for both basins. Interpolated thicknesses of the glacial deposits, the lower Tertiary aquifer system, and the Upper Cretaceous aquifer system in the Williston structural basin are less than about 750; 2,250; and 1,050 ft, respectively. Interpolated thicknesses of the lower Tertiary aquifer system and the Upper Cretaceous aquifer system in the Powder River structural basin are less than about 7,180 and 5,070 ft, respectively. Interpolated horizontal hydraulic conductivity values for the Williston structural basin were as much as 25 feet per day (ft/d) in the glacial deposits and had smaller ranges in the lower Tertiary aquifer system (0.01–9.8 ft/d) and in the Upper Cretaceous aquifer system (0.06–5.5 ft/d). In the Powder River structural basin, the lower Tertiary aquifer system had a greater range of interpolated horizontal hydraulic conductivity values (0.10–11 ft/d) than the Upper Cretaceous aquifer system (0.02–5.7 ft/d). Transmissivity is greatest in the gravel zones of the glacial deposits (2,120 feet squared per day) and generally decreases with depth into the bedrock units.

Regionally, water in the lower Tertiary and Upper Cretaceous aquifer systems flows in a northerly or northeasterly direction from the Powder River structural basin to the Williston structural basin. Groundwater flow in the Williston

structural basin generally is easterly or northeasterly. Flow in the uppermost hydrogeologic units generally is more local and controlled by topography where unglaciated in the Williston structural basin than is flow in the glaciated part and in underlying aquifers. Groundwater flow in the Powder River structural basin generally is northerly with local variations greatest in the uppermost aquifers. Groundwater is confined, and flow is regional in the underlying aquifers.

Introduction

The Quaternary glacial aquifers, lower Tertiary bedrock aquifers, and Upper Cretaceous bedrock aquifers are the three uppermost principal aquifer systems of the Williston and Powder River structural basins (fig. 1) and much of the Northern Great Plains (Whitehead, 1996; Reilly and others, 2008). These basins are nationally important energy-producing areas that span Montana, North Dakota, South Dakota, and Wyoming in the United States and Manitoba and Saskatchewan in Canada. The Quaternary glacial aquifer system areal coverage is limited to the northeastern part of the Williston structural basin. The lower Tertiary and Upper Cretaceous aquifer systems are present in about 91,300 square miles (mi^2) of the Williston structural basin and about 25,500 mi^2 of the Powder River structural basin. The lower Tertiary and Upper Cretaceous aquifer systems overlie 800 to more than 3,000 feet (ft) of relatively impermeable Upper Cretaceous marine shale that serves as a basal confining unit (Anna, 1986; Downey, 1986; Downey and Dinwiddie, 1988).

The Williston structural basin has been an important domestic oil and natural gas producing region since the 1950s (Anna and others, 2011). As demands for energy continue to increase (U.S. Energy Information Administration, 2013), oil and gas development in the basin has increased substantially since the mid-2000s, primarily because of recently improved precision horizontal drilling and hydraulic fracturing methods from previously inaccessible formations, such as the Bakken and Three Forks Formations (Gaswirth and others, 2013). These new methods require considerable volumes of freshwater, mostly from shallow aquifers or surface waters (Schuh, 2010). Additional potential sources of energy in the Williston structural basin include coal-bed natural gas (CBNG), coal, and lignite (Bluemle, 1998). The source rock for these potential energy resources is primarily the lower Tertiary and Upper Cretaceous lithostratigraphic units. Coal and lignite extraction commonly requires strip mining that removes large volumes of the host rock and has a high potential to affect shallow aquifers. CBNG development requires removal of substantial volumes of groundwater from coal beds to release stored gases and has the potential to affect aquifers.

Since the late 1880s, the Powder River structural basin has been an important mineral and energy-producing region to the Nation (Beikman, 1962; Flores and Bader, 1999). The Powder River structural basin is known primarily for oil, coal, and uranium production. Beginning in the late 1990s, widespread CBNG development has rapidly transformed the basin into a nationally important natural gas-producing region. Development of these energy resources can affect groundwater availability in the lower Tertiary and Upper Cretaceous aquifer systems in both the Williston and Powder River structural basins.

Because of the importance of water resources in these energy-rich basins, the U.S. Geological Survey (USGS) Groundwater Resources Program (*http://water.usgs.gov/ogw/gwrp/*) began a study in 2011 of the glacial, lower Tertiary, and Upper Cretaceous aquifer systems in the Williston and Powder River structural basins with a goal to quantify groundwater availability in the potable aquifers of both basins. The study approach included updating the regional hydrogeologic framework, estimating hydrologic budget components, and refining the conceptual model of groundwater flow for the glacial, lower Tertiary, and Upper Cretaceous aquifer systems in both basins. The information presented in this report, together with a description of the conceptual model of groundwater flow and estimation of water-budget components (Long and others, 2014), provides a more detailed understanding of the groundwater flow systems and provides the hydrogeologic framework for a numerical groundwater-flow model that could be used to simulate regional groundwater flow and test aquifer system responses to water-use and climate forecasts.

Purpose and Scope

This report describes the hydrogeologic framework of the three uppermost principal aquifer systems—the glacial, lower Tertiary, and the Upper Cretaceous—in the Williston and Powder River structural basins in the United States and Canada. The description of the hydrogeologic framework is based on historical and recent investigations. The scope of this report includes the regional geologic history, lithostratigraphy, hydrogeologic units, hydraulic characteristics, and potentiometric surfaces.

Previous Investigations

A general overview of the principal aquifers in the Williston and Powder River structural basins is provided by Whitehead (1996). A regional study during the 1980s by the USGS Regional Aquifer System Analysis program combined the glacial, lower Tertiary, and Upper Cretaceous aquifer systems into one aquifer layer for the Northern Great Plains, assessed the geohydrology of the bedrock aquifers (Downey, 1986), and developed a geologic framework (Anna, 1986) that served as a foundation for this study. More recently, Long and others (2014) described a conceptual groundwater-flow model of the uppermost principal aquifers in the Williston and Powder River structural basins that serves as a companion report to this report.

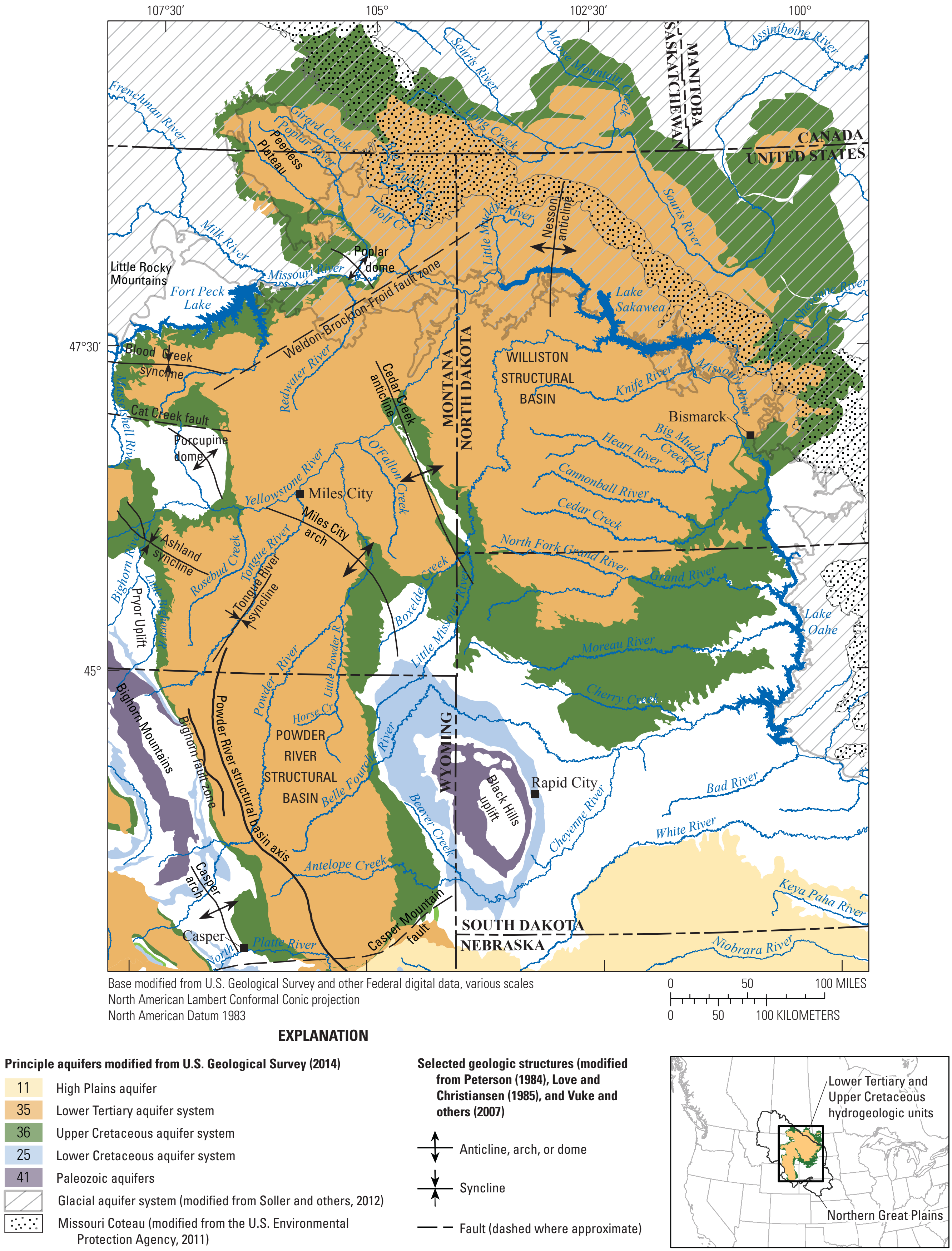


Figure 1. Principal aquifers and structural basins of the Northern Great Plains.

Numerous investigations provided hydrogeologic information for the glacial, lower Tertiary, and Upper Cretaceous aquifer systems in parts of the Williston and Powder River structural basins. Glacial extent and generalized thickness were mapped by Soller (1992) and Soller and others (2012). Detailed maps of depth to bedrock and glacial thickness for part of the glaciated area of the Williston structural basin were published by Kume and Hansen (1965), Klassen and others (1970), Armstrong (1971), Bluemle (1971, 1981, and 1984), Randich (1977), Carlson (1982), Bergantino (1984), Randich and Kuzniar (1984), Millard (1993), Simpson (1993), and Maathius and Simpson (2007a, 2007b). Bedrock geology was mapped at the State or Province level by Bluemle (1983), Love and Christiansen (1985), Macdonald and Slimmon (1999), Martin and others (2004), Vuke and others (2007), and Nicolas and others (2010). Stoner and Lewis (1980), Lewis and Hotchkiss (1981), and Ellis and Colton (1994) differentiated the Hell Creek Formation in the Powder River structural basin. Levings and others (1981) summarized an extensive literature search of all work related to geology and groundwater resources for the Montana part of the Northern Great Plains. Smith and others (2000) mapped potentiometric surfaces of the lower Tertiary and Upper Cretaceous aquifer systems for the Lower Yellowstone River area in the southwestern part of the Williston structural basin. During the 1960s through the 1980s, the North Dakota State Water Commission (NDSWC) and North Dakota State Geological Survey (NDGS) conducted detailed countywide geology and hydrology assessments across North Dakota (North Dakota State Water Commission, variously dated). Fischer (2013) included a detailed structure contour map of the basal confining unit in western North Dakota. Groundwater resource assessments were conducted throughout most of southern Saskatchewan during the 1990s through the 2000s (Millard, 1993; Simpson, 1993; Maathuis and Simpson, 2007a, 2007b). Hotchkiss and Levings (1986) mapped potentiometric surfaces and estimated thickness and transmissivity for the five hydrogeologic units of the Powder River structural basin.

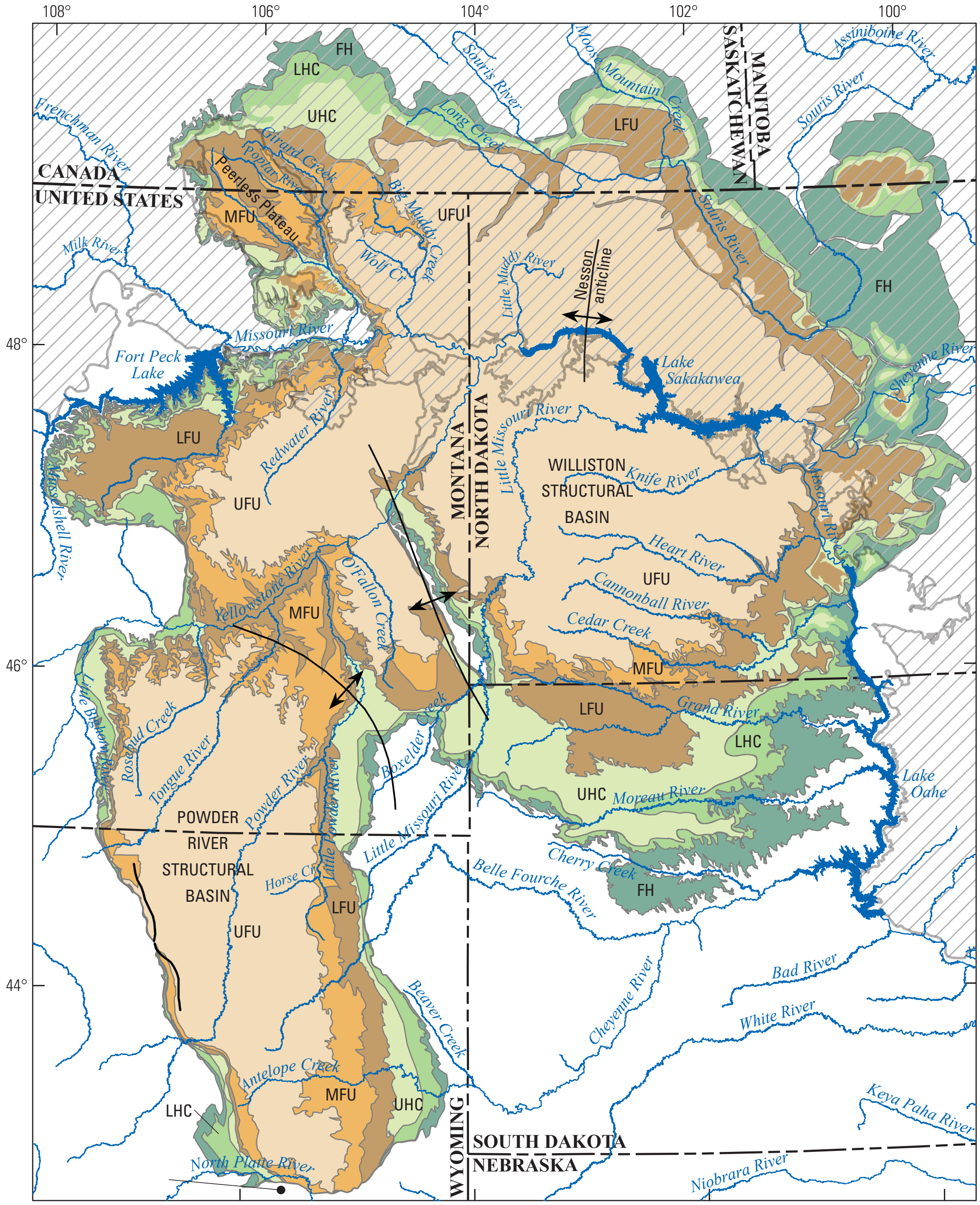
Description of Study Area

The study area is defined as the extent of the lower Tertiary and Upper Cretaceous aquifer systems in the Williston and Powder River structural basins (fig. 2). These aquifer systems underlie about 116,800 mi^2 (91,300 mi^2 in the Williston structural basin and about 25,500 mi^2 in the Powder River structural basin) in the United States and Canada. Topography in the study area is characterized by relatively low relief, except near large river channels, with a gently rolling land surface underlain mostly by sedimentary rocks composed primarily of sandstone, coal, and shale. Large river systems, such as the Missouri and Yellowstone Rivers, erode the relatively soft sedimentary rocks and create several hundred feet of local topographic relief.

The climate is semiarid, with monthly precipitation exceeding monthly potential evapotranspiration by 0 to 5 inches per year (in/yr) (Reilly and others, 2008). Within the Williston structural basin, precipitation ranges from 11.5 in/yr in the western part to 21.5 in/yr in the eastern part. In the Powder River structural basin, precipitation ranges from 11.5 in/yr in the western part to 18 in/yr in the eastern part (Long and others, 2014). Pasture and hayland (which includes rangeland) cover 70 percent of the study area (Multi-Resolution Land Characteristics Consortium, 2011). Population density is low, with the exception of a few towns, and is generally less than 10 people per square mile (U.S. Census Bureau, 2001; Statistics Canada, 2001).

Water resources are an important component of the energy resources in the Williston and Powder River structural basins. The lower Tertiary and Upper Cretaceous geologic units in the Williston and Powder River structural basins contain most of the Nation's reserves of coal/lignite and much of the CBNG (Bluemle, 1998). The overlying glacial deposits of the Williston structural basin also serve as a water supply for one of the Nation's most rapidly developing oil reserves, the Bakken and Three Forks Formations. Continued development in the region includes alternative energy, industry, irrigation, and growing demands for domestic and municipal water and depends on the quantity and quality of groundwater available from these shallow and accessible aquifers. Surface water is heavily appropriated in most of the area (Schuh, 2010), and the supply is not dependable due to variable streamflow in upper river reaches. The study area includes three of the Nation's largest surface-water reservoirs: Fort Peck Lake, Lake Sakakawea, and Lake Oahe, all located on the Missouri River (fig. 2).

Groundwater resources in the Williston and Powder River structural basins are present in the three uppermost principal aquifer systems. The glacial aquifer system contains the productive buried sand and gravel aquifers that are the source of water for thousands of shallow wells (Whitehead, 1996). The glacial aquifer system has a wide range of hydraulic conductivities and is characterized by disconnected local flow systems. The lower Tertiary and Upper Cretaceous aquifer systems are primarily under confined conditions, except along the basin margins and in the shallow aquifers located in the uppermost part of the lower Tertiary geologic units, where the lower Tertiary and Upper Cretaceous aquifer systems are characterized by local flow systems (Whitehead, 1996). In the areas where the lower Tertiary and Upper Cretaceous aquifer systems are overlain by the glacial aquifer system (fig. 2), water likely percolates downward through the glacial deposits to the bedrock aquifers. Most of the recharge to the lower Tertiary and Upper Cretaceous aquifer systems is from precipitation that falls directly on outcrop areas or from leakage from streams that cross aquifer boundaries (Whitehead, 1996). Discharge occurs in the form of base flow to streams and withdrawals for irrigation, public supply, and self-supplied industrial uses. Groundwater flow in the Powder River structural



Base modified from U.S. Geological Survey and other Federal digital data, various scales
North American Lambert Conformal Conic projection
North American Datum of 1983

EXPLANATION

Hydrogeologic units

Glacial aquifer system

Lower Tertiary aquifer system
- UFU — Upper Fort Union aquifer
- MFU — Middle Fort Union hydrogeologic unit
- LFU — Lower Fort Union aquifer

Upper Cretaceous aquifer system
- UHC — Upper Hell Creek hydrogeologic unit
- LHC — Lower Hell Creek aquifer
- FH — Fox Hills aquifer

Selected geologic structures modified from Peterson (1984), Love and Christiansen (1985), and Vuke and others (2007)

- Anticline or arch
- Fault

Figure 2. Hydrogeologic units of the uppermost principal aquifer systems in the Williston and Powder River structural basins.

basin generally is from south to north, where it flows into the adjoining Williston structural basin. Groundwater flow in the Williston structural basin generally is from west and southwest to the east and northeast, where the groundwater discharges to streams and springs.

Surface-water resources in the Williston and Powder River structural basins include rivers, streams, lakes, and wetlands. In the Williston structural basin, the Missouri River flows toward the east and southeast, with the Yellowstone and Little Missouri Rivers entering from the south (fig. 2). Several other tributaries in the southeastern part of the Williston structural basin flow easterly and enter the Missouri River from the west. Streams south of the Missouri Coteau (fig. 1) flow into the Missouri River from the north. Streams north of the Missouri Coteau generally flow southeasterly, except for parts of the Souris River, which flow northerly in southwestern Manitoba. Few streams cross the Missouri Coteau because of its nonintegrated drainage pattern (fig. 1) that is characterized by many small lakes and wetlands. The Tongue and Powder Rivers are large streams in the Powder River structural basin that originate within or near the Bighorn Mountains and flow northeasterly into the Williston structural basin; the Belle Fourche River flows northeasterly out of the Powder River structural basin and to the north of the Black Hills uplift; and Antelope Creek flows easterly out of the structural basin, where it joins the Cheyenne River near the southern Black Hills (fig. 2).

Methods

This section describes the methods used to determine the areal extents, unit surfaces, and thicknesses of the hydrogeologic units that compose the glacial, lower Tertiary, and Upper Cretaceous aquifer systems in the Williston and Powder River structural basins. Methods used to determine hydraulic properties and potentiometric surfaces of the aquifers also are described in this section.

The extents, surfaces, thicknesses, and interpolated horizontal hydraulic conductivity for each hydrogeologic unit, and the potentiometric surfaces for the upper Fort Union aquifer, lower Fort Union aquifer, and Upper Cretaceous aquifer system are downloadable in grid ASCII format, shapefiles, or feature classes (table 1) at *http://pubs.er.usgs.gov/sir/2014/5047/downloads/ASCII_Files/*. Refer to the 'ASCII Files README' and 'Shapefiles and Feature Classes README' files at *http://pubs.er.usgs.gov/sir/2014/5047/downloads/Shapefiles_and_FeatureClasses/* for more information.

Hydrogeologic Units

The glacial, lower Tertiary, and Upper Cretaceous aquifer systems consist of seven hydrogeologic units (figs. 3*A*, *B*) that generally correspond to lithostratigraphic units in the United States and Canada. Five units are identified as aquifers: glacial, upper Fort Union, lower Fort Union, lower Hell Creek, and Fox Hills aquifers. Two units are identified as hydrogeologic units: middle Fort Union and upper Hell Creek hydrogeologic units. The units are identified as an aquifer if the unit is regionally productive or as a hydrogeologic unit if the unit contains confining properties. The glacial aquifer system is present in the northeastern part of the Williston structural basin and contained in the Quaternary glacial deposits, which are composed of till and glacial outwash sands and gravels with areas of cobbles and boulders.

The lower Tertiary aquifer system in the Williston structural basin is composed of lithostratigraphic units that include primarily the Golden Valley Formation; the Sentinel Butte, Tongue River, Lebo, Ludlow, Tullock, and Cannonball Members of the Fort Union Formation in the United States; and the Ravenscrag and Turtle Mountain Formations in Canada. The lower Tertiary aquifer system in the Powder River structural basin is composed of lithostratigraphic units that include the Wasatch Formation, and the Tongue River, Lebo, and Tullock Members of the Fort Union Formation.

The Upper Cretaceous aquifer system in the Williston structural basin is composed of lithostratigraphic units that include the Hell Creek and Fox Hills Formations in the United States, and the lower part of the Ravenscrag Formation; the Frenchman, Boissevain, and Eastend Formations; and the Coulter Member of the Pierre Formation in Canada (fig. 3). The basal confining unit in both basins is the equivalent shale formation among the Upper Cretaceous Lewis Shale, Bearpaw Shale, and Pierre Shale. These equivalent marine shale formations have been mapped in the study area and are identifiable on geophysical logs (Feltis and others, 1981; Lewis and Hotchkiss, 1981; Fischer, 2013).

The areal extents of the six bedrock hydrogeologic units (fig. 2) were simplified and modified from existing digital State and Province geologic maps (table 2). Polygons and erratic line segments less than about 1 mile (mi) in length from the existing digital geologic maps were removed for the map in figure 2. Discrepancies in hydrogeologic unit extents at political boundaries were merged by adjusting extents equally on either side of the political boundary or by using bedrock-surface maps to guide location of unit extents. The upper and lower Hell Creek Formation was undifferentiated in the geologic maps listed in table 2, so geologic maps by Stoner and Lewis (1980), Lewis and Hotchkiss (1981), and Ellis and Colton (1994) were used to screen digitize the aquifer differentiation in the Powder River structural basin on figure 2. The differentiation of the upper and lower Hell Creek Formation in the Williston structural basin was interpolated using methods described later in this section.

Surface altitudes and unit thicknesses were determined from a combination of existing publications and data for each of the seven hydrogeologic units. Land-surface altitude (LSA) was used as the top surface of the uppermost hydrogeologic unit. LSA data were obtained from the National Elevation Dataset (NED) (Gesch, 2007; Gesch and others, 2002) through

Table 1. Digital download directory and file names of hydrogeologic framework of the uppermost principal aquifer systems in the Williston and Powder River structural basins.

[U.S. Geological Survey Digital downloads available at *http://pubs.usgs.gov/sir/2014/5047/downloads/*]

Type of download	Folder	Theme	File name (alphabetical order within theme)
ASCII files	Powder_River_Basin	HydraulicConductivity	PRB_FoxHills_LowerHellCreek
			PRB_LowerFortUnion
			PRB_MiddleFortUnion
			PRB_UpperFortUnion
			PRB_UpperHellCreek
		Surfaces	PRB_BasalConfiningUnit
			PRB_FoxHills_LowerHellCreek
			PRB_LowerFortUnion
			PRB_MiddleFortUnion
			PRB_UpperFortUnion
			PRB_UpperHellCreek
		Thickness	PRB_FoxHills_LowerHellCreek
			PRB_LowerFortUnion
			PRB_MiddleFortUnion
			PRB_UpperFortUnion
			PRB_UpperHellCreek
	Williston_Basin	HydraulicConductivity	WB_FoxHills
			WB_GlacialDeposits
			WB_LowerFortUnion
			WB_LowerHellCreek
			WB_MiddleFortUnion
			WB_UpperFortUnion
			WB_UpperHellCreek
		Surfaces	WB_BasalConfiningUnit
			WB_FoxHills
			WB_LowerFortUnion
			WB_LowerHellCreek
			WB_MiddleFortUnion
			WB_UpperFortUnion
			WB_UpperHellCreek
		Thickness	WB_FoxHills
			WB_GlacialDeposits
			WB_LowerFortUnion
			WB_LowerHellCreek
			WB_MiddleFortUnion
			WB_UpperFortUnion
			WB_UpperHellCreek

Table 1. Digital download directory and file names of hydrogeologic framework of the uppermost principal aquifer systems in the Williston and Powder River structural basins.—Continued

[U.S. Geological Survey Digital downloads available at *http://pubs.usgs.gov/sir/2014/5047/downloads/*]

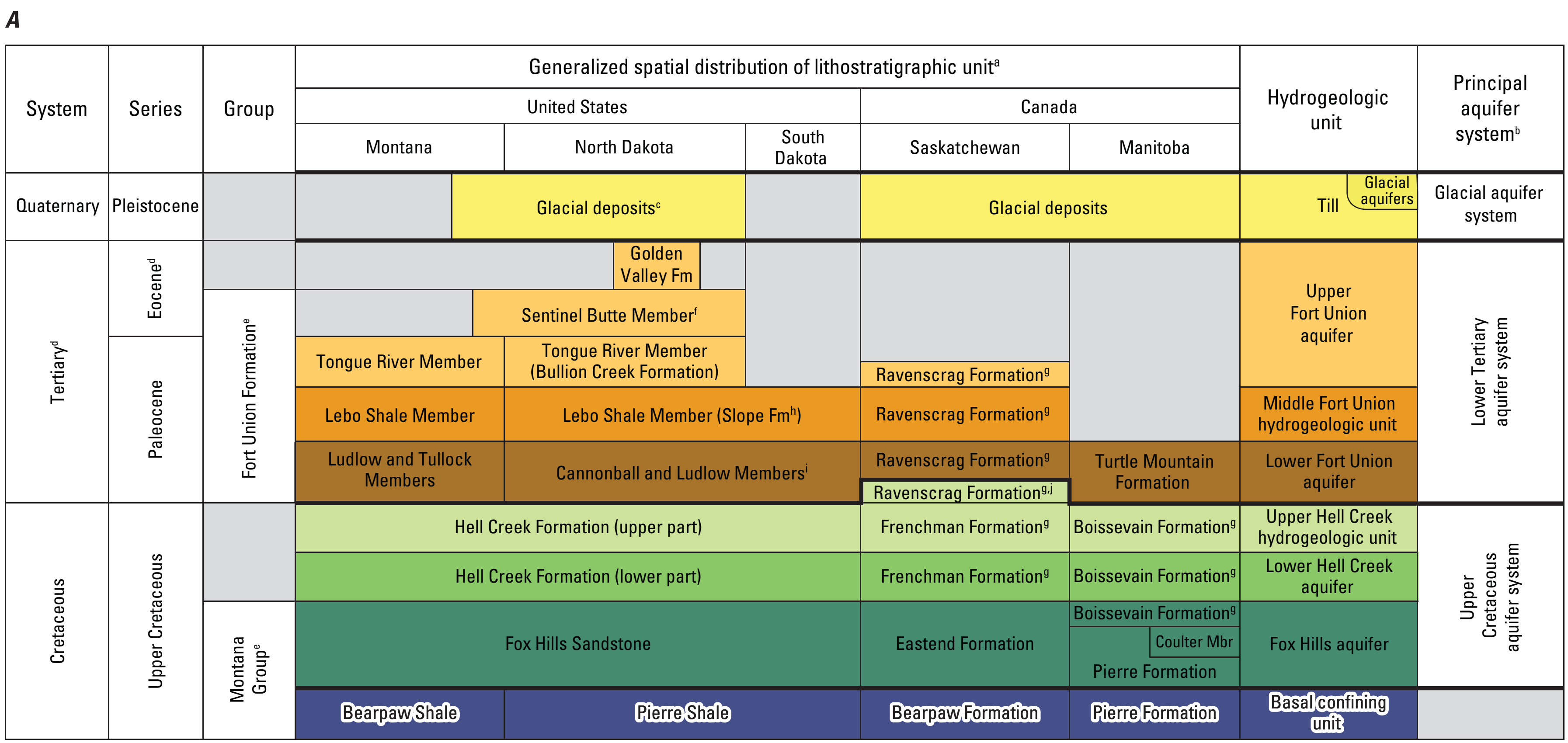
Type of download	Folder	Theme	File name (alphabetical order within theme)
Shapefiles_and_FeatureClasses	HydrogeologicUnitExtents	HydrogeologicUnitExtents.gdb	SouthernExtent_of_GlacialDeposits
			WBandPRB_FoxHills
			WBandPRB_LowerFortUnion
			WBandPRB_LowerHellCreek
			WBandPRB_MiddleFortUnion
			WBandPRB_UpperFortUnion
			WBandPRB_UpperHellCreek
	PotentiometricSurfaceContours	Powder_River_Basin	PRB_LowerFortUnionAquifer
			PRB_UpperCretaceous_Aquifer
			PRB_UpperFortUnionAquifer
		Williston_Basin	WB_LowerFortUnionAquifer
			WB_UpperCretaceousAquifer
			WB_UpperFortUnionAquifer

the USGS *The National Map* viewer and download platform (*http://nationalmap.gov/viewer.html*).

In the northeastern part of the Williston structural basin, the bedrock surface is overlain by glacial deposits, and the altitude of the top of the bedrock surface can be determined by subtracting the thickness of the glacial deposits from the LSA. Existing publications that mapped the top of the bedrock or thickness of glacial deposits (fig. 4) were compiled into one ArcGIS terrain model. The terrain model was compiled using the Delaunay triangulation method (Musin, 1997) that results in a geometrically smooth surface from multiple datasets at various spatial resolutions and allows the user to define the priorities of the data. In areas where previously published map extents overlapped, priority was given to the most recently published data. To allow seamless transitions from one data source to another, the contours were trimmed back 3 mi to smoothly interpolate the data across the seams as a triangulated surface. The surface was then converted to a raster with a spatial resolution of 0.6 mi. Areas where glacial deposits were relatively thin or where polygons and erratic line segments were less than about 1 mi were removed. Existing water-well data were compiled by Leslie Arihood and Randall Bayless (U.S. Geological Survey, written commun., 2013) into a single raster of glacial deposit thickness using methods described by Arihood (2009) and databases with lithologic data from (1) Groundwater Information Network for Manitoba and Saskatchewan (*http://www.gw-info.net/*), (2) Groundwater Information Center (GWIC) for Montana (http://*mbmggwic.mtech.edu/*), and (3) NDSWC (*http://www.swc.nd.gov/4dlink9/4dcgi/redirect/index.html*). Overall, the thickness of glacial deposits in the raster compiled from existing publications (fig. 4) and in the raster compiled from existing well data was similar. The largest absolute differences between the rasters was 613 ft near a single well point, and the mean difference between the rasters was 49 ft. Spatial distribution of the water-well data caused the primary differences between the two rasters and was particularly evident in areas with smaller drainage features; therefore, the raster compiled from existing well data, represented by source number 1 in figure 4, was used only in a small part of North Dakota where existing publications were not available digitally.

In both basins, the bottom of the Upper Cretaceous aquifer system (top surface of the basal confining unit) was developed as the initial hydrogeologic framework surface using the “Topo to Raster” tool in ArcMap 10.0. Hydrogeologic unit thickness rasters then were placed on the basal confining unit to build the hydrogeologic framework of units in the glacial, lower Tertiary, and Upper Cretaceous aquifer systems. In outcrop areas, the LSA was used as the surface of the hydrogeologic unit. To create a smooth transition from the subsurface LSA, the subsurface and land surface rasters were converted to 50-ft contours and interpolated together using the “Topo to Raster” tool.

In the Williston structural basin, top and bottom altitudes of the units were determined using a combination of electric (resistivity) and lithologic logs at about 300 sites (appendix 2). The electric log response was correlated to lithology, then that knowledge was applied to wells with electric logs but without lithologic logs to identify units. Electric logs were not available for the units in Manitoba. The altitudes of the hydrogeologic units for each site listed in tables 2–1 through 2–4 were used as anchor points in the hydrogeologic framework model to ensure the final bedrock unit surfaces agreed with the individual unit altitudes at each site. In addition to the anchor



[a] Spatial distribution of lithostratigraphic units from Bluemle (1983); Love and Christiansen (1985); Macdonald and Slimmon (1999); Martin and others (2004); Vuke and others (2007); Murphy and others (2009); and Nicolas and others (2010).

[b] Whitehead (1996).

[c] Generally located north of the Missouri River.

[d] Upper Tertiary units (Pliocene, Miocene, and Oligocene) exist only in a small part of study area and are not included in this study.

[e] This name applies only in the United States.

[f] Present in central part of Williston structural basin and a small contiguous area in Montana. Eocene Golden Valley Member also is present in local areas.

[g] Divided formation to correspond to hydrogeologic units in this regional study.

[h] Pinches out north of the Missouri River. Mapped as Tongue River Formation in South Dakota by Martin and others (2004).

[i] Cannonball Member present in the southern and eastern parts of the Williston structural basin. Slope Member is above the Cannonball Member in southern North Dakota. Ludlow Member is present in the southern part of North Dakota.

[j] Lower Ravenscrag Formation is part of the Upper Hell Creek hydrogeologic unit but is part of the Tertiary System.

EXPLANATION

Fm **Formation**

Mbr **Member**

Figure 3. Diagram showing lithostratigraphic and corresponding hydrogeologic units in *A*, the Williston structural basin and *B*, the Powder River structural basin.

B

<table>
<tr><th rowspan="2">System</th><th rowspan="2">Series</th><th rowspan="2">Group</th><th colspan="3">Generalized spatial distribution of lithostratigraphic unit[a]</th><th colspan="2">Hydrogeologic unit</th><th rowspan="2">Principal aquifer system[b]</th></tr>
<tr><th colspan="2">Wyoming</th><th>Montana</th><th>Names from previous studies[c]</th><th>Names used in this study</th></tr>
<tr><td rowspan="4">Tertiary[d]</td><td>Eocene[d]</td><td></td><td colspan="2">Wasatch Formation</td><td></td><td rowspan="2">Tongue River aquifer</td><td rowspan="2">Upper Fort Union aquifer</td><td rowspan="4">Lower Tertiary aquifer system</td></tr>
<tr><td rowspan="3">Paleocene</td><td rowspan="3">Fort Union Formation</td><td colspan="3">Tongue River Member</td></tr>
<tr><td colspan="3">Lebo Shale Member</td><td>Lebo confining unit</td><td>Middle Fort Union hydrogeologic unit</td></tr>
<tr><td colspan="3">Tullock Member</td><td>Tullock aquifer</td><td>Lower Fort Union aquifer</td></tr>
<tr><td rowspan="4">Cretaceous</td><td rowspan="4">Upper Cretaceous</td><td rowspan="2"></td><td colspan="2">Lance Formation (upper part)</td><td>Hell Creek Formation (upper part)</td><td>Upper Hell Creek confining unit</td><td>Upper Hell Creek hydrogeologic unit</td><td rowspan="3">Upper Cretaceous aquifer system</td></tr>
<tr><td colspan="2">Lance Formation (lower part)</td><td>Hell Creek Formation (lower part)</td><td>Fox Hills–Lower Hell Creek aquifer</td><td>Lower Hell Creek aquifer</td></tr>
<tr><td rowspan="2">Montana Group</td><td colspan="3">Fox Hills Sandstone</td><td>Fox Hills–Lower Hell Creek aquifer</td><td>Fox Hills aquifer</td></tr>
<tr><td>Pierre Shale</td><td>Lewis Shale</td><td>Bearpaw Shale</td><td>Basal confining unit</td><td>Basal confining unit</td><td></td></tr>
</table>

[a] Spatial distribution of lithostratigraphic units from Love and Christiansen (1985) and Vuke and others (2007).

[b] Whitehead (1996).

[c] From Lewis and Hotchkiss (1981) and Hotchkiss and Levings (1986).

[d] Upper Tertiary units (Pliocene, Miocene, and Oligocene) represent a small part of study area and are not included in this study.

Figure 3. Diagram showing lithostratigraphic and corresponding hydrogeologic units in *A*, the Williston structural basin and *B*, the Powder River structural basin.—Continued

Table 2. Sources of bedrock geologic data, Williston and Powder River structural basins.

State/Province	Source	Scale
Manitoba	Nicolas and others, 2010	1:600,000
Montana	Vuke and others, 2007	1:500,000
North Dakota	Bluemle, 1983	1:670,000
Saskatchewan	Macdonald and Slimmon (compilers), 1999	1:1,000,000
South Dakota	Martin and others, 2004	1:500,000
Wyoming	Love and Christiansen, 1985	1:500,000

points, surface contours of the basal confining unit from Noble and others (1982) and Wanek (2009) were added to improve the detailed geometry of the basin. Priority was given to the anchor points because they received more individual scrutiny by the investigators than data from previous publications. The thicknesses of the overlying units in the Williston structural basin were calculated individually for each site with adequate log data and interpolated to thickness rasters.

In the Powder River structural basin, the surface of the top of the basal confining unit and thickness of overlying units were digitized from Lewis and Hotchkiss (1981). The thicknesses of the overlying units in the Powder River structural basin were calculated by interpolating the contours to thickness rasters.

For both basins, the digital hydrogeologic surface was constrained to the altitude of the land surface at 16-mi intervals along the outcrop area for each unit contact, thereby forcing the interpolated unit subsurfaces to pinch out at the basin boundaries; however, in areas along the unit erosional contacts that were within the basins, the thickness was allowed to interpolate through the edge of the unit because there would still be a unit thickness greater than zero at these locations. It is likely that at these locations the positive thickness would be exposed at the surface. Examples of this phenomenon include the sides of eroded streambeds or wind-eroded cliffs. After all of the surfaces had been built and stacked upon each other, the top of the uppermost unit was verified against the land surface. The areas where the uppermost unit differed from the land surface most commonly occurred where boreholes did not penetrate the entire thickness of the hydrogeologic unit or unit contacts were within cased portions of wells without logs. This discrepancy was resolved by calculation of the difference between the derived uppermost unit and the bedrock surface. The thickness of the missing or undocumented hydrogeologic units at this location was then derived using the following equation:

$$\mathrm{E}_{thick,i} - t_i\,(x) \qquad (1)$$

where

$E_{thick,i}$ is the interpolated thickness estimate for the hydrogeologic unit i,

t is the proportional thickness of i relative to the other hydrogeologic units that lack specified thicknesses at this location, and

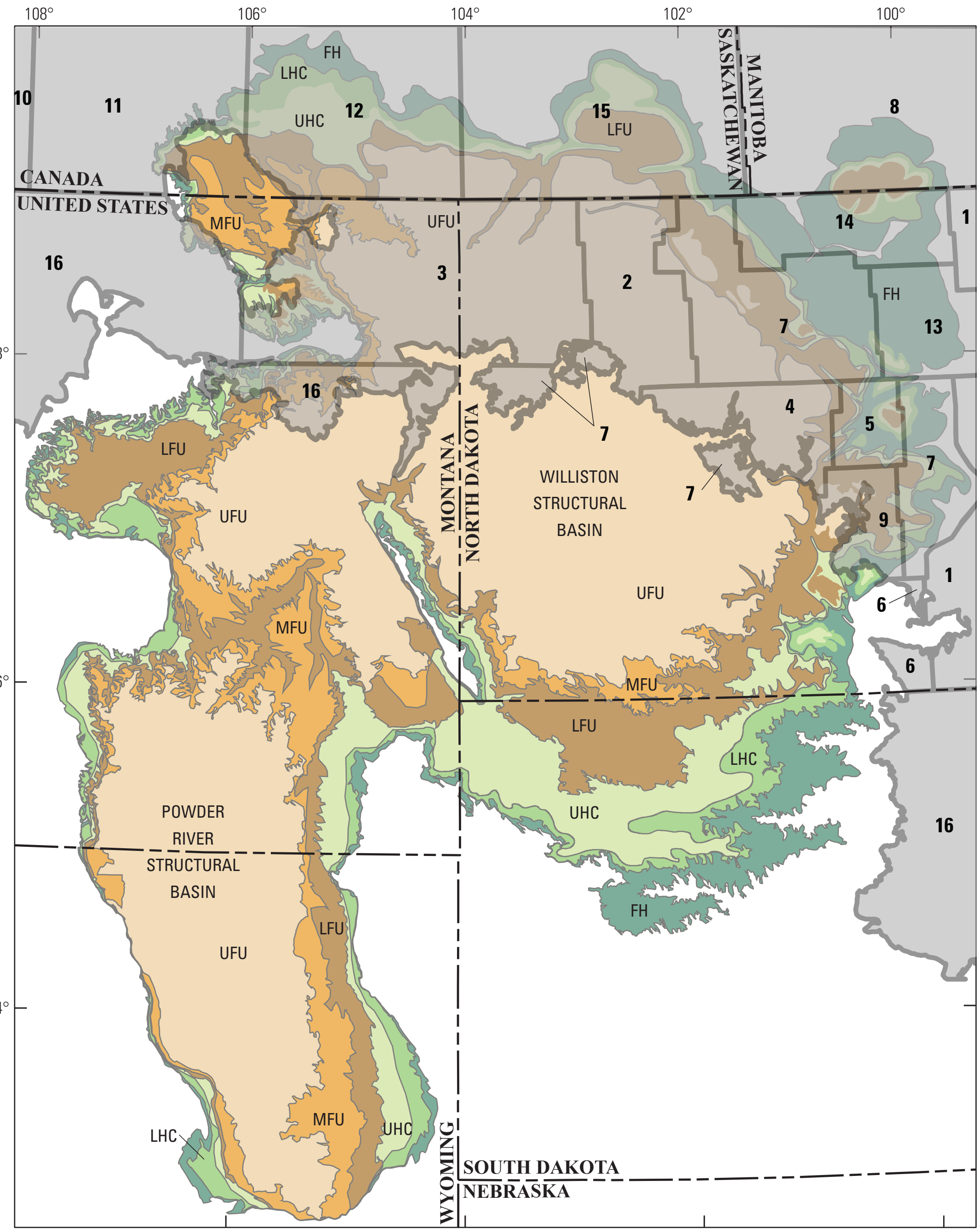
x is the difference, in feet, between the uppermost hydrogeologic unit surface and the interpolated bedrock surface.

The value t is calculated using the three nearest neighbors (data points) within 50 mi.

The contact between the upper Hell Creek and lower Hell Creek hydrogeologic units was mapped by Lewis and Hotchkiss (1981) in the Powder River structural basin. The contact between the upper Hell Creek and the lower Hell Creek hydrogeologic units had not been previously mapped in the Williston structural basin. During this study, this unit contact was estimated by calculating the regional surface trend (or slope and aspect) of the lower Hell Creek hydrogeologic unit at each well location near the edge of the basin and extrapolating the slope to the bedrock surface. The spatial trend of the lower Hell Creek hydrogeologic unit surface was calculated using a localized first-order polynomial interpolation (Fan and Gijbels, 1996) provided in the ArcMap "Kernel Interpolation with Barriers" tool. After the spatial trends were calculated, the slope and aspect of the surface was calculated at well locations near the edge of the previously mapped Hell Creek and Fox Hills contact. Vectors were created, using the slope and aspect values, and extrapolated at the well locations to the outer edge of the basin. Surface altitude contact points were created where these vectors intersected the bedrock surface. Based on the contact points, along with the bedrock topography and boundaries of the lower Hell Creek and Fox Hills Formations, the lower Hell Creek geohydrologic unit extent and surface were estimated for the Williston structural basin.

Canadian lithostratigraphic units were modified to correspond with the United States lithostratigraphic units and assigned to the six bedrock hydrogeologic units identified in this study (fig. 3). To ensure lithostratigraphic consistency in the hydrogeologic units across the international border, the method described above for estimating contact points at the bedrock surface also was implemented to assist in estimating the boundaries for the contacts between the hydrogeologic units in the lower Tertiary and Upper Cretaceous aquifer systems in Saskatchewan and Manitoba.

Upon completion of the determination of each hydrogeologic unit surface within the Williston and Powder River structural basins, the surface then was mosaicked across the basin boundary by overlapping the raster datasets near the Miles City arch to ensure consistency of the contours between the structural basins. The hydrologic unit surfaces within the Williston and Powder River structural basins generally were



EXPLANATION

Hydrogeologic units

- Glacial aquifer system
- UFU Upper Fort Union aquifer
- MFU Middle Fort Union hydrogeologic unit
- LFU Lower Fort Union aquifer
- UHC Upper Hell Creek hydrogeologic unit
- LHC Lower Hell Creek aquifer
- FH Fox Hills aquifer

Sources of data:

1. Leslie Arihood and Randall Bayless, U.S. Geological Survey, written commun., 2013
2. Armstrong, 1971
3. Bergantino, 1984
4. Bluemle, 1971
5. Bluemle, 1981
6. Bluemle, 1984
7. Carlson, 1982
8. Klassen and others, 1970
9. Kume and Hansen, 1965
10. Maathuis and Simpson, 2007a
11. Maathuis and Simpson, 2007b
12. Millard, 1993
13. Randich, 1977
14. Randich and Kuzniar, 1984
15. Simpson, 1993
16. Soller and others, 2012

Figure 4. Sources of data used to determine the thickness of the glacial deposits in and near the Williston structural basin.

in close agreement at the boundary. In the overlap areas where small discrepancies (less than 100 ft) were identified, the Williston structural basin surface data were retained because these data underwent a higher degree of scrutiny.

Hydraulic Characteristics

Methods for quantifying hydraulic characteristics of hydraulic conductivity and transmissivity are described in this section. Additional methods for qualification of horizontal and vertical hydraulic conductivity also are described.

Quantification of Hydraulic Conductivity and Transmissivity

The hydraulic conductivity and transmissivity values of the hydrogeologic units in the Williston structural basin were estimated using a combination of borehole electric (resistivity) logs from oil and gas wells and lithologic logs from nearby water wells and mean hydraulic conductivity values derived from water-well specific capacity tests. The resistivity logs were used to identify the hydrogeologic units (fig. 3*A*) and to quantify the vertical detailed lithology (thickness of sand, coal, gravel, silt, and shale) in the oil and gas exploration boreholes. The relatively higher resistivity of sand and gravel compared to the other lithologies provided a basis for identification of the higher transmissivity layers. Oil and gas boreholes are often cased at shallow depths (200 to 500 ft), so resistivity logs for the shallow intervals of the geologic column at these sites are limited. Lithologic logs from nearby water wells were used to calculate the hydraulic conductivities for the shallow depths. Lithologic logs also were used to estimate the thickness of sand and gravel layers embedded in the glacial deposits and therefore were used to estimate hydraulic conductivity. The hydraulic conductivity values derived from lithologic logs are identified in tables 2–1 through 2–4 in appendix 2. Based on the resistivity or lithologic logs, the borehole lithology was documented, and the percentages of sand, coal, gravel, silt, and shale were estimated for each hydrogeologic unit based on standard geophysical methods (Jorgensen, 1989). After the percentage of sand, coal, gravel, silt, and shale of a selected unit was determined, these values were multiplied by the respective mean hydraulic conductivity values that were obtained from the water-well specific capacity tests to provide a calculated hydraulic conductivity value for the hydrogeologic unit, as described further in the following paragraphs. The calculated hydraulic conductivity value was then multiplied by the hydrogeologic unit thickness to provide an estimated transmissivity value. The transmissivity values for the lithologic characteristics (sand, coal, gravel, silt, and shale) were then added together to provide a bulk transmissivity value for the hydrogeologic units. A summary of the lithology and hydraulic characteristics determined from well logs, including top and bottom altitudes of each unit; percentages of lithologic characteristics; calculated transmissivity and hydraulic conductivity values; and qualitative anisotropy values, are provided in tables 2–1 through 2–4 of appendix 2. Because of the large areal extent of the Williston structural basin, 1,000-mi^2 grid cells were used to ensure spatial distribution of at least one representative borehole and associated unit thicknesses and transmissivity values within each of the grid cells. More than 300 borehole resistivity logs from throughout the Williston structural basin were collected and analyzed. Resistivity logs were obtained from the NDGS and NDSWC County Groundwater Reports; the Montana Bureau of Mines and Geology (MBMG) GWIC; the USGS Oil and Gas Geophysical Logs microfiche database located in office files in Denver, Colorado; the Saskatchewan Water Security Agency; and the Saskatchewan Ministry of the Economy, Petroleum and Natural Gas Division.

The mean hydraulic conductivity values for the hydrogeologic units were based on the analysis of water-well specific capacity tests conducted on water wells located throughout the North Dakota portion of the Williston structural basin. The water-well specific capacity data are documented in the drill logs filed with the NDSWC and can be accessed by entering the township and range of interest (*http://www.swc.nd.gov/*). The specific capacity tests can be converted to an estimate of the test interval (screen or perforated pipe length) transmissivity using equation 2 (Theis and others, 1963):

$$T = \frac{Q}{s}\left[k - 264\log\left(5{*}S{*}10^{3}\right) + 264\ log\ t\right] \qquad (2)$$

where

- T is transmissivity, in feet squared per day;
- Q is pump rate, in gallons per minute;
- s is drawdown, in feet;
- k is 2,477;
- S is storativity, dimensionless; and
- t is time, in days.

The method for a confined aquifer is from Theis and others (1963) and assumes a storativity of 0.0001. The unit "*k*" also is dependent on the well radius; because most water wells have a diameter of 6 to 8 inches; a well radius of 0.25 ft was assumed and therefore *k* is 2,477. Sensitivity analysis found that changing the well radius from 0.25 to 0.5 and 1.0 ft resulted in a change of the transmissivity value of less than 15 percent, and changes of the storativity values by orders of magnitude affected the transmissivity value even less. Calculation of the hydraulic conductivity value is from equation 3:

$$K = \frac{T}{b} \qquad (3)$$

where

- K is hydraulic conductivity, in feet per day;
- T is transmissivity, in feet squared per day; and
- b is saturated thickness of aquifer, in feet.

The saturated thickness of the aquifer (*b*) at each site was based on the well screen or perforated pipe length as determined from the drill logs. Reliable estimates of the well screen or perforated pipe length from the drill logs can be challenging. The drill logs usually document screen interval length or perforated pipe length; however, an inspection of the geology reported on the log may show that the screen length does not match the length of the water yielding layer; for example, a 10-ft screen interval may include a 5-ft thick sand layer and a 5-ft thick clay layer. In this example, the saturated thickness (*b*) value can be adjusted to 5 ft because most of the flow likely is coming from the sand layer and not from the clay layer.

A review of the NDSWC database provided areal and vertical coverage of the Williston structural basin. Analysis of 75 water-well specific-capacity tests provided mean hydraulic conductivity values for the sand, coal, gravel, silt, and shale layers of the seven hydrogeologic units (table 3).

The mean hydraulic conductivity values ranged from 1.1 feet per day (ft/d) for the Fox Hills Sandstone to 25.5 ft/d for gravel deposits (table 3). The mean hydraulic conductivity values are geometric mean values with the exception of an arithmetic value for the Fox Hills Sandstone; hydraulic conductivity values are generally assumed to have a log-normal distribution, but the five values for the Fox Hills Sandstone indicated a normal distribution. These mean hydraulic conductivity values were used in conjunction with the lithologic percentages (sand, coal, gravel, silt, and shale) to calculate the hydraulic conductivity and transmissivity values for the hydrogeologic units as presented in tables 2–1 through 2–4 in appendix 2 for the Williston structural basin.

Transmissivities and interlayer thicknesses of the hydrogeologic units in the Powder River structural basin were published by Hotchkiss and Levings (1986). The transmissivity and interlayer thickness contour maps were digitized and converted to rasters during this study. The upper Fort Union aquifer is primarily unconfined in the Powder River structural basin, and the difference between the water table and the base of the unit was used to represent the saturated thickness of the aquifer. Because the lower Fort Union aquifer and Upper Cretaceous aquifers are primarily under confined conditions in the Powder River structural basin, fully saturated conditions were applied, and the interlayer thicknesses were used to represent the saturated thickness of the aquifer. Hydraulic conductivity (*K*) values of the hydrogeologic units in the Powder River structural basin were determined by dividing the transmissivity (*T*) raster by the interlayer thickness (saturated thickness) (*b*) raster (equation 3).

Qualification of Horizontal and Vertical Hydraulic Conductivity

The Fox Hills, Hell Creek, and Fort Union Formations and their associated hydrogeologic units are composed of alternating layers of sand/sandstone, silt/shale, clay/claystone, coal, and lignite. The fluctuating depositional environments during the Late Cretaceous and early Tertiary time periods resulted in alternating layers and abrupt facies changes (Flores, 1992) that substantially affected the hydraulic characteristics of the hydrogeologic units. In theory, the ratio of horizontal-to-vertical hydraulic conductivity of an individual hydrogeologic unit is controlled by two factors: (1) the number of facies changes, and (2) the difference in hydraulic conductivity values between the facies. Water flowing in a sand layer that is confined between clay layers will be dominated by horizontal flow; the clay layers limit the vertical flow. For a given vertical section of borehole, the greater the number of facies changes and the larger the difference in hydraulic characteristics between the facies, the greater the probability that flow will be limited to directions parallel to the bedding planes.

Quantification of hydraulic conductivities for horizontal and vertical components is difficult; however, borehole resistivity logs provide a qualitative evaluation of the relative ratio of horizontal-to-vertical hydraulic conductivity. Because the resistivity logs document the number of facies changes, and the abruptness (measured as the difference in resistivity values

Table 3. Summary of specific capacity tests for water wells in the Williston structural basin.

[≤, less than or equal to; >, greater than]

Geology	Depth (feet)	Number of tests	Range of hydraulic conductivity (feet/day)	Mean hydraulic conductivity (feet/day)
Sand	≤100	12	2.4–27.6	8.1
Sand	>100	38	0.1–13.9	2.0
Sand of the Fox Hills Sandstone	680–1,836	5	0.8–1.8	1.1
Coal	≤100	11	1.6–108.6	17.2
Coal	>100	5	0.9–10.6	3.6
Gravel	12–140	4	11.0–41.7	25.5
Silt/shale	None available	None available	Assumed zero	Assumed zero

between facies) of these changes, the resistivity logs can be used as a qualitative estimate of the horizontal-to-vertical ratio. The thickness of the Late Cretaceous and early Tertiary sand, silt, and clay layers varies from a few feet to greater than 100 ft. The degree of resistivity change between layers varies from small, as between a sand layer and a sandy silt layer, to large, as between a sand layer and a clay layer. For example, a given 100-ft section of the Hell Creek Formation may be composed of a 50-ft thick sand layer overlain by a 50-ft thick sandy silt layer or composed of 10 or 12 alternating layers of sand and clay. The former will have a substantially larger vertical flow component compared to the latter. Based on resistivity logs, a qualitative scale of the horizontal-to-vertical flow potential (anisotropy) was developed. The scale is shown in table 4 and is based on (1) the number of facies changes and (2) the degree of resistivity change between facies. The qualitative values assigned to the lithologic layers are referred to as anisotropy in tables 2–1 through 2–4 in appendix 2.

Potentiometric Surfaces

Existing databases and publications were used to develop or digitize potentiometric surfaces in the Williston and Powder River structural basins. Potentiometric surfaces for the Williston structural basin were developed during this study using existing data for the upper Fort Union aquifer, the lower Fort Union aquifer, and the hydraulically connected lower Hell Creek and Fox Hills aquifers. Water-level altitudes (hydraulic heads) for the period preceding the year 2000 were used to represent the period prior to substantial water use from energy development in the Williston structural basin. Potentiometric surfaces for the Powder River structural basin were estimated by Hotchkiss and Levings (1986) for the upper Fort Union, middle Fort Union, lower Fort Union, and the hydraulically connected lower Hell Creek and Fox Hills aquifers. The potentiometric surfaces were digitized for this study, and 100-ft contours were interpolated between the original 200-ft contours.

In the Williston structural basin, hydraulic head and well LSA data were compiled from five existing databases: (1) the USGS National Water Information System (NWIS; U.S. Geological Survey, 2013), (2) the NDSWC Ground and Surface Water database (North Dakota Information Technology Department, 2012), (3) the MBMG GWIC database (Montana Bureau of Mines and Geology, 2011), (4) the South Dakota Department of Environment and Natural Resources Observation Wells database (South Dakota Department of Environment and Natural Resources, 2011), and (5) the Saskatchewan Water Security Agency (Kei Lo, written commun., 2011). Data were provided by each of these sources through their Web sites, file transfer protocol downloads, or direct transfer from the source. Hydraulic head data were primarily from water-supply wells or observation wells. In many cases, particularly in the part of the basin extending into Saskatchewan, only one measurement was available per well, which was usually associated with the initial development of the well. None of the selected Saskatchewan wells had more than one measurement, and none of the wells in Manitoba had sufficient information (Groundwater Information Network, 2011). Hydraulic head in many wells in Montana, North Dakota, and South Dakota were measured periodically, and several were continuously measured with pressure transducers. At sites with multiple measurements, the mean of measurements prior to the year 2000 at each site was calculated. Trends in hydraulic head at 74 wells in Montana with at least quarterly measurements were calculated; the mean standard deviation for depth to water was 3.05 ft, and the mean range between minimum and maximum depths to water was 15.5 ft. Consistent temporal or seasonal trends in data from these sites were not observed, and trends were relatively steady, so all hydraulic head data prior to 2000 were used to represent the predevelopment period. A relational database was built to link the selected wells to the hydraulic head data. The LSA at each well was supplied and in some cases an accuracy rating of both the location and altitude based on the methods used to obtain the data also was supplied. The data structure of each original data source was mapped to a common schema that was used to store all the data with a new unique number for each well and another unique number for each measurement. Measurements were linked to the well table using the unique site number. The original index for each site and measurement and the data source were maintained in the relational database so that the relational database could be checked against the original databases.

Selected wells were evaluated in several different ways before hydraulic heads were processed. First, only the wells located within the lateral and vertical extents of the hydrogeologic unit were included. Second, wells had to be confirmed to be completed in one of the hydrogeologic units being mapped; this could be indicated by the NWIS aquifer code or a code

Table 4. Qualitative scale of horizontal-to-vertical hydraulic conductivity flow potential based on well logs in the Williston structural basin.

Qualitative value (anisotropy)	Number of facies changes	Degree of resistivity change
1	Interval composed of a single facies or two similar facies	Small resistivity change between facies.
2	Facies changes, on average, every 20 to 30 feet	Moderate resistivity change between facies.
3	Facies changes, on average, every 10 to 20 feet	Moderate resistivity changes between facies.
4	Facies changes greater than every 10 feet	Large resistivity changes between facies.

or aquifer name assigned by a State or Provincial agency. If a well did not have an aquifer designation but did have a well or screen depth and valid LSA, the aquifer could be determined by comparing the well to the altitudes of the top and bottom of the hydrogeologic unit. If no well depth or aquifer information was available, the well data were not used. The well had to have at least one reported measurement before January 1, 2000, to represent predevelopment conditions.

Selected wells also required a LSA so that the hydraulic head could be calculated. The validity of the LSA was tested by comparing the reported altitude to the altitude provided by a 32.8-ft (10-meter) USGS NED (Gesch and others, 2002; Gesch, 2007) at the reported well location. The LSA also was compared with the minimum, maximum, and mean altitudes of NED cells within a 0.5-mi radius of the reported location. If a well had a LSA more than 100-ft different from the NED altitude or was outside the minimum and maximum NED altitude range, the well was assumed to have either an erroneous location or LSA and was not used. During the preparation of the potentiometric surface maps and review of water levels at nearby data points, the relative differences between the reported LSA and the NED also were used as a qualitative screening of wells.

Other reasons for excluding wells included questionable hydraulic heads, the relative hydraulic head or quality of site data compared to nearby wells, duplicate sites reported both by NWIS and a State agency, wells that are part of a set of nested wells, wells that were open to multiple hydrogeologic units, and wells with a questionable hydrogeologic unit. Questionable readings were evaluated by comparing the hydraulic head to those around it, or if the aquifer is unconfined at the location, by comparing the hydraulic head to the NED altitude at streams. For example, if numerous wells with similar, good quality hydraulic heads surrounded a data point with a differing hydraulic head, the inconsistent point was investigated and potentially excluded. Several wells had been assigned to the Fort Union Formation without identifying if the well was completed in the upper, middle, or lower part of the formation and thus required assignment to the upper or lower Fort Union aquifer based on the well depth and the estimated altitude of the hydrogeologic unit surfaces at the well location. If it was not clear which unit the well was completed in, the well was excluded.

Potentiometric surfaces were contoured using the mean hydraulic heads for the selected wells listed in table 3–1 of appendix 3 as well as other conditions such as the altitude of surface water, the LSA, and the hydrogeologic unit extent. In areas where the potentiometric surface was assumed to be unconfined, the hydraulic head could not exceed the LSA. Generally, the deeper hydrogeologic units are overlain by shallower units in the middle of the basins and exposed at the basin margins. The upper Fort Union aquifer is assumed to be unconfined throughout the study area except where confined by more than 25 ft of overlying Quaternary glacial deposits in the northeastern part of the Williston structural basin. Potentiometric contours in the unconfined parts of the upper Fort Union aquifer represent the water table. As a regional map, the scale was not adequate to differentiate perched water or confined conditions created by local confining beds. Where overlain by the upper Fort Union aquifer or the middle Fort Union hydrogeologic unit, the lower Fort Union aquifer was assumed to be confined unless measured water levels showed that it is hydraulically connected to the upper Fort Union aquifer. Where the hydraulically connected lower Hell Creek and Fox Hills aquifers are exposed at the surface by erosion, these two aquifers are assumed to be unconfined; where they are covered by the upper Hell Creek unit, they are assumed to be confined.

For the lower Yellowstone River Basin groundwater study, Smith and others (2000) mapped the potentiometric surfaces of the upper Fort Union aquifer, lower Fort Union aquifer, and Fox Hills aquifer, although the their methods used for delineating the hydrogeologic units were different than those used for this study. The potentiometric contours for the lower Fort Union aquifer and Fox Hills aquifer in some areas of the lower Yellowstone River Basin of this study and of Smith and others (2000) are similar, but potentiometric contours for the upper Fort Union aquifer vary substantially between the two studies. This may be because this study used all wells with hydraulic heads attributed to the upper Fort Union aquifer, whereas Smith and others (2000) used only wells that penetrated less than 200 ft below the land surface.

The potentiometric-surface maps for this study are highly generalized regional-scale maps that represent the mean potentiometric surface prior to the year 2000 and do not resolve local conditions. Hydraulic heads may have changed substantially since the last measurements used in this study, and because of the limited accuracy of available measurements, hydraulic head values are not expected to be more accurate than 10 percent of saturated thickness.

Hydrogeologic Framework

The hydrogeologic framework of the uppermost aquifer systems (glacial, lower Tertiary, and Upper Cretaceous) in the Williston and Powder River structural basins consists of lithostratigraphic units that have been combined into seven hydrogeologic units for this study that include the United States and Canada. The only previous regional assessment that included both structural basins represented these seven hydrogeologic units as one aquifer and was limited to the United States (Downey and Dinwiddie, 1988).

The Williston structural basin aquifer systems have a very shallow (less than 2,900 ft deep), wide, and generally symmetrical bowl shape (fig. 5) that is irregular only near the Poplar dome and at the Nesson and Cedar Creek anticlines (fig. 1). The Powder River structural basin aquifer systems have a very deep (as deep as 8,500 ft), narrow, and asymmetrical shape (fig. 5), with the deepest part of the basin near the western margin. The Powder River structural basin is bounded by the Bighorn Mountains on the west and the Black Hills on the east. The greatest thickness of the glacial, lower Tertiary, and Upper Cretaceous aquifer systems combined is about 2,900 ft in the center of the Williston structural basin and about 8,500 ft near the western margin of the Powder River structural basin (figs. 6*A*, *B*).

The boundary between the Williston and Powder River structural basins is defined in this study by the Miles City arch (fig. 1) that forms a subtle rise in the hydrogeologic units between the two basins (figs. 5, 6*B*). The Pierre Shale (Formation), Bearpaw Shale (Formation), and Lewis Shale of the basal confining unit (figs. 3*A*, *B*) consist of 800 to more than 3,000 ft of bentonitic marine shale with low hydraulic conductivity and is assumed to hydraulically separate groundwater flow in the lower Tertiary and Upper Cretaceous aquifer systems from the deeper geologic units. The basal confining unit also surrounds the lower Tertiary and Upper Cretaceous aquifer systems at the land surface, except where the Bighorn Mountains are adjacent to the Powder River structural basin (fig. 1).

Hydrogeologic Units

Seven hydrogeologic units have been identified as the primary units in the glacial, lower Tertiary, and Upper Cretaceous aquifer systems (figs. 3*A*, *B*). Thickness rasters for each of the hydrogeologic units were used to determine the volume for each aquifer system. The glacial aquifer system consists of glacial deposits that form multiple local and disconnected aquifers in the Williston structural basin with a volume of 150 trillion cubic feet (ft^3) (table 5). The lower Tertiary aquifer system has a volume of 1,002 trillion ft^3 in the Williston structural basin and 1,381 trillion ft^3 in the Powder River structural basin (table 4) and consists of the upper Fort Union aquifer, the middle Fort Union hydrogeologic unit, and the lower Fort Union aquifer. The Upper Cretaceous aquifer system has a volume of 1,005 trillion ft^3 in the Williston structural basin and 938 trillion ft^3 in the Powder River structural basin (table 5) and consists of the upper Hell Creek hydrogeologic unit, the lower Hell Creek aquifer, and the Fox Hills aquifer. Water from these units is relatively fresh and potable, and withdrawals seldom occur from units below the basal confining unit (Long and others, 2014) because of great depths (greater than 800 ft) and poor water quality.

Glacial Aquifer System

The glacial aquifer system is present in the northeastern part of the Williston structural basin and overlies the lower Tertiary and Upper Cretaceous aquifer systems in this area (fig. 1). Near the southern glacial margin, the till cover is patchy, and bedrock exposures are common (Soller, 1992). As such, the southern extent of the glacial aquifer system was defined for this investigation to encompass most of the glacial deposition, but may exclude locally present and incongruous deposits. Because these thin and local deposits are excluded, the extent of the glacial aquifer system mapped for this investigation is slightly smaller, but typically within 40 miles, of the glacial extent mapped by Soller (1992) and Fullerton and others (2004) that includes thin and local deposits. Numerous advances and retreats of continental ice sheets occurred in this area, and the present-day topography is predominantly the result of glacial deposits of Late Wisconsinan age till and reworked till (Fullerton and others, 2004). The southern extent of the two Late Wisconsinan glacial advances are marked by the present day Missouri River channel [20,000 years before present (B.P.)] and the Missouri Coteau (fig. 1), which is a plateau with numerous small wetlands, ponds, and lakes (14,000 B.P.). The interpolated thickness for the glacial aquifer system can be as much as 756 ft (table 5), but the mean thickness is 138 ft (Soller and others, 2012). A small area (approximately 2,800 mi^2) on the Saskatchewan/Montana border has no glacial deposits (fig. 6*A*).

The glacial aquifer system consists of till, sand, gravel, silt, and clay. Till is an unstratified mixture of clay, silt, sand, pebbles, cobbles, and boulders deposited by glaciers. The coarse-grained material is composed of local sandstone and shale but also contains granitic, metamorphic, and basic igneous rocks from northern Canada (Bluemle, 1982). The sand and gravel include river, stream, and outwash deposits of reworked till. The deposits are moderately well sorted and cross-bedded and are usually associated with a gentler topography, as found on the Coteau Slope (between the Missouri Coteau and the Missouri River). The silt and clay consist of fine-grained materials deposited at the bottom of lakes and ponds. These lacustrine deposits generally are flat and smooth; however, it is common for the lacustrine deposits to be reworked by strong winds into extensive dune fields.

Lower Tertiary Aquifer System

The term ‘lower Tertiary’ is not a formally-recognized USGS geologic name, therefore, ‘lower’ is not capitalized. The lower Tertiary aquifer system consists of the upper and lower Fort Union aquifers, which are separated by the middle Fort Union hydrogeologic unit. These three hydrogeologic units and the lithostratigraphic units that compose them are described in the following subsections.

Upper Fort Union Aquifer

The upper Fort Union aquifer consists of the Sentinel Butte and Tongue River Members of the Fort Union Formation in Montana; the Golden Valley Formation, Sentinel Butte Member, and Bullion Creek Formation in North Dakota; and the uppermost part of the Ravenscrag Formation in Saskatchewan in the Williston structural basin; and the Wasatch Formation and Tongue River Member in Montana and Wyoming in the Powder River structural basin (figs. 3*A*, *B*). The upper Fort Union aquifer is not present in South Dakota or Manitoba. The term Bullion Creek Formation is commonly used in North

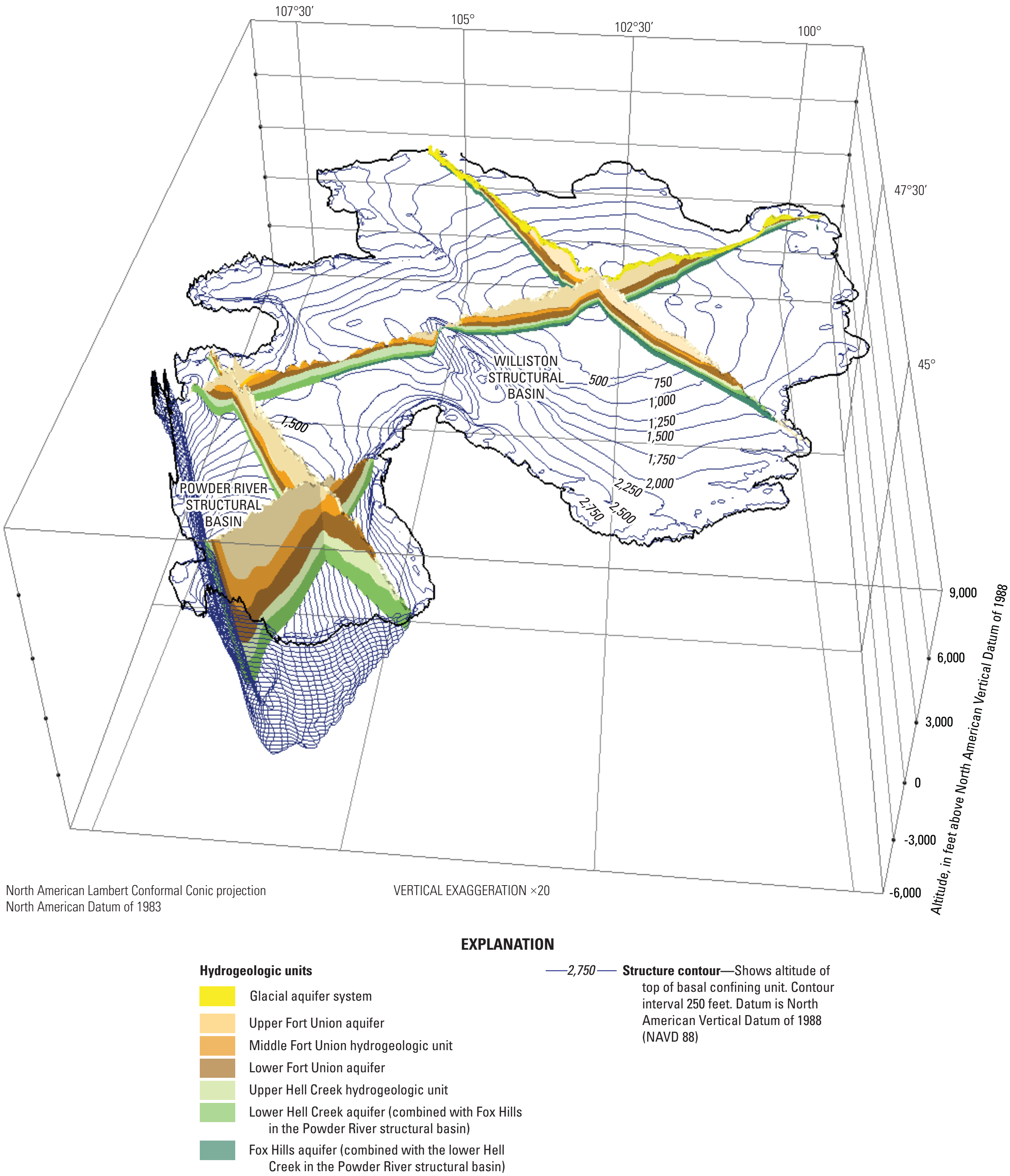


Figure 5. Generalized cross sections showing the three-dimensional hydrogeologic framework from land surface to the top of basal confining unit in the Williston and Powder River structural basins.

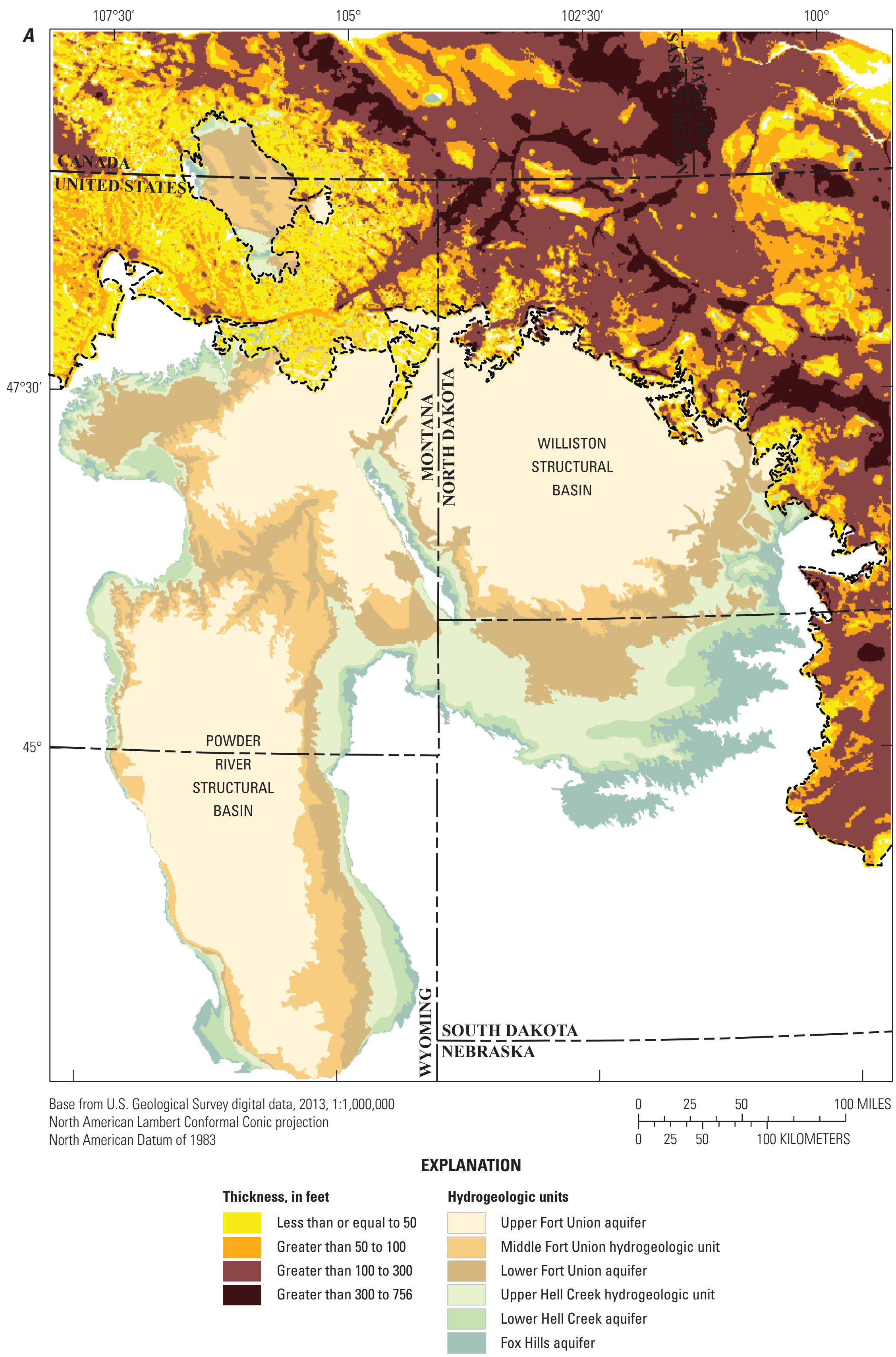


Figure 6. Thickness of *A*, glacial aquifer system in and near the Williston structural basin and *B*, combined lower Tertiary and Upper Cretaceous aquifer systems in the Williston and Powder River structural basins.

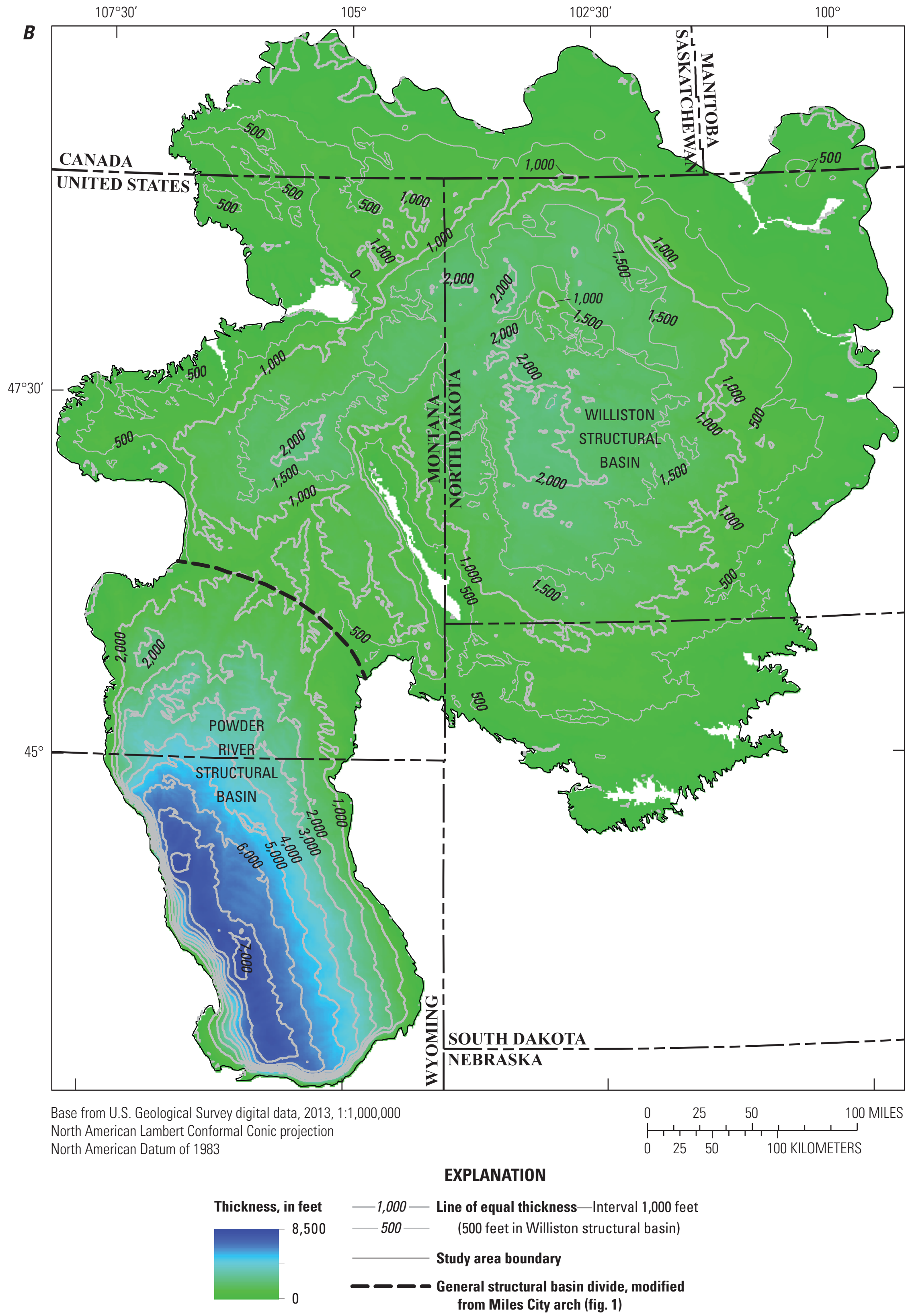


Figure 6. Thickness of *A*, glacial aquifer system in and near the Williston structural basin and *B*, combined lower Tertiary and Upper Cretaceous aquifer systems in the Williston and Powder River structural basins.—Continued

Table 5. Interpolated volumes, thicknesses, and horizontal hydraulic conductivity values of aquifer systems and hydrogeologic units in the Williston and Powder River structural basins.

[ft³, cubic feet; K_h, horizontal hydraulic conductivity; ft/d, feet per day; —, no data or not applicable; HU, hydrogeologic unit]

Hydrogeologic unit or aquifer system	Williston structural basin			Powder River structural basin		
	Volume, in trillion ft³	Thickness, in feet	K_h, in ft/d	Volume, in trillion ft³	Thickness, in feet	K_h, in ft/d
Glacial aquifer system	150	0–756	0.01–24	—	—	—
Lower Tertiary aquifer system	1,002	0–2,246	—	1,381	0–7,180	—
Upper Fort Union aquifer	549	0–1,917	0.14–9.8	562	0–4,458	0.23–11
Middle Fort Union HU	145	0–520	0.01–7.8	378	0–3,643	0.10–7.1
Lower Fort Union aquifer	307	0–668	0.14–5.5	440	0–2,913	0.26–6.4
Upper Cretaceous aquifer system	1,005	0–1,047	—	938	0–5,070	—
Upper Hell Creek HU	337	0–738	0.10–5.5	355	0–3,002	0.03–5.7
Lower Hell Creek aquifer	296	0–548	0.10–1.7	583	0–3,274	0.02–1.4
Fox Hills aquifer	372	0–422	0.06–1.0			

Dakota (Clayton and others, 1977); however, the USGS GEOLEX database (*http://ngmdb.usgs.gov/Geolex/geolex_home.html*) uses the term Tongue River Member in Montana and North Dakota. The upper Fort Union aquifer is present near land surface over much of the south-central part of the Williston structural basin and much of the central part of the Powder River structural basin (figs. 2 and 5).

The upper Fort Union aquifer is composed of thick massive crossbedded, light-yellow to light-yellow-gray sandstone, sandy mudstone, gray shale, carbonaceous shale, and thick coal-beds that can burn where exposed resulting in fractured clinker (McLellan, 1992). It is generally light-colored compared to the underlying gray middle Fort Union hydrogeologic unit. The upper Fort Union aquifer was deposited in the flood basin and swamps of a large alluvial plain that drained the newly formed Rocky Mountains. The maximum measured thickness of the upper Fort Union aquifer, determined from resistivity logs, is 1,160 ft in the Williston structural basin. The maximum interpolated thickness of the upper Fort Union aquifer is 1,917 ft in the Williston structural basin and substantially larger than the measured thickness because it includes topographically high areas with larger thickness, whereas the logged wells were not located in topographically high areas. The maximum interpolated thickness of the upper Fort Union aquifer is 4,458 ft in the Powder River structural basin (fig. 5; table 5).

Middle Fort Union Hydrogeologic Unit

The middle Fort Union hydrogeologic unit consists of the Lebo Shale Member of the Fort Union Formation in Montana and Wyoming, the Slope Formation in North and South Dakota, and part of the Ravenscrag Formation in Saskatchewan (figs. 3*A*, *B*). The middle Fort Union hydrogeologic unit is not present in Manitoba. The term Slope Formation is commonly used in North Dakota (Clayton and others, 1977); however, the USGS GEOLEX database (*http://ngmdb.usgs.gov/Geolex/geolex_home.html*) uses the term Lebo Shale Member in Montana and North Dakota. The middle Fort Union hydrogeologic unit is present throughout the central part of the Williston structural basin, thins towards the northeast, and pinches out along the northeast one-third of the basin (figs. 2 and 5). The middle Fort Union hydrogeologic unit is present throughout the central part of the Powder River structural basin.

The middle Fort Union hydrogeologic unit is composed of alternating beds of sandstone, siltstone, mudstone, claystone, and lignite in North Dakota (Murphy, 2001) and dark grey shale in Montana (Diemer and others, 1992) and contrasts with the light-colored upper Fort Union aquifer above and the light-colored lower Fort Union aquifer below. The Lebo Shale Member and Slope Formation in the Williston structural basin are the same age as the Lebo Shale Member in the Powder River Basin in Wyoming and, therefore, all three are sometimes considered equivalent. Although deposition in both basins was because of erosion of the newly formed mountains (Rocky Mountains in the Williston structural basin and Bighorn Mountains in the Powder River structural basin), the depositional environments were different. The Montana and North Dakota deposits formed in the flood basin and swamps of a large alluvial plain, whereas the Wyoming deposits are lacustrine and formed in a large freshwater lake (McLellan, 1992). The maximum measured thickness of the middle Fort Union hydrogeologic unit, determined from resistivity logs, is 400 ft in the Williston structural basin. The maximum interpolated thickness of the middle Fort Union hydrogeologic unit is 520 ft in the Williston structural basin and 3,643 ft in the Powder River structural basin (fig. 5; table 5).

Lower Fort Union Aquifer

The lower Fort Union aquifer is present throughout much of the Williston and Powder River structural basins (figs. 2 and 5). The lower Fort Union aquifer consists of the Ludlow and Tullock Members of the Fort Union Formation in Montana, the Cannonball and Ludlow Members in North and South Dakota, the lower part of the Ravenscrag Formation in Saskatchewan, and the Turtle Mountain Formation in Manitoba in the Williston structural basin; and the Tullock Member in Montana and Wyoming in the Powder River structural basin (fig. 3). The Ludlow Formation is difficult to differentiate from the overlying Lebo Shale Member and Slope Formation and is difficult to correlate regionally, particularly in southeastern Montana and near the Cedar Creek anticline (Ellis and Colton, 1994). This difficulty can occur when attempting to regionally correlate geologic units that are based on different time periods and geographic areas. Northern Montana stratigraphy was used to guide differentiation and correlation of these lithostratigraphic units (fig. 3*A*).

The lower Fort Union aquifer is composed of continental, marine, nonlignite, and clastic deposits dominated by yellow-weathering sandstones and light gray-weathering sandy mudstones (Cvancara, 1976a) and interfingers with alternating brown and gray beds of sandstone, siltstone, claystone, mudstone, and lignite (Murphy, 2001; Rigby and Rigby, 1990). The maximum measured thickness of the lower Fort Union aquifer, determined from resistivity logs, is 670 ft in the Williston structural basin. The maximum interpolated thickness of the lower Fort Union aquifer is 668 ft in the Williston structural basin and 2,913 ft in the Powder River structural basin (fig. 5; table 5).

Upper Cretaceous Aquifer System

The term ‘Upper Cretaceous’ is a formally recognized USGS geologic name, therefore, ‘Upper’ is capitalized. The Upper Cretaceous aquifer system consists of the upper Hell Creek hydrogeologic unit, the lower Hell Creek aquifer, and the Fox Hills aquifer. The Hell Creek Formation is divided into informal upper and lower units based on a moderately persistent coal seam (Rigby and Rigby, 1990). These hydrogeologic units and the lithostratigraphic units that compose them are described in the following subsections.

Upper Hell Creek Hydrogeologic Unit

The upper Hell Creek hydrogeologic unit consists of the upper part of the Hell Creek Formation in Montana, North Dakota, and South Dakota and the upper parts of the Lance, Frenchman, and Boissevain Formations in Wyoming, Saskatchewan, and Manitoba, respectively (figs. 3*A*, *B*). The upper Hell Creek hydrogeologic unit is present throughout much of the Williston and Powder River structural basins and is the uppermost unit that is not eroded near the structural basin divide (figs. 2 and 5).

The upper Hell Creek hydrogeologic unit consists of alternating layers of gray and brown mudstone, siltstone, sandstone, and sparse lignite beds and generally is defined where the relative percentage of sandstone is generally smaller than that of the lower Hell Creek aquifer. The upper Hell Creek hydrogeologic unit was deposited by meandering channels with point bars and channel plugs (Flores, 1992). Identification of the lower contact is based on a change in the relative sand content between the upper and lower Hell Creek hydrogeologic units as identified in the resistivity logs. In areas where a resistivity log indicated no substantial difference in sand content, the lower contact was selected at the midpoint of the entire Hell Creek Formation. Identification of the upper contact of the Hell Creek Formation can be difficult because the official contact is defined as the Cretaceous/Tertiary contact and not an abrupt change in the depositional environment; this can be a problem in trying to correlate geologic units across State and Provincial boundaries. Comparison of the geologic contacts based on oil and gas borehole resistivity logs from northeastern Montana to the cross sections based on resistivity logs from oil and gas wells in southern Saskatchewan indicates that the Montana and North Dakota interpretations tend to extend the Hell Creek Formation upward into the Saskatchewan Ravenscrag Formation (fig. 3*A*). In addition, comparison of the Saskatchewan geologic map (Macdonald and Slimmon, 1999) to the Montana and North Dakota geologic maps (Vuke and others, 2007 and Bluemle, 1983) indicates that the Canadian Tertiary/Cretaceous contact is approximately equivalent to the Montana and North Dakota upper/lower Hell Creek Formation contact. To maintain consistency, the resistivity logs for Saskatchewan oil and gas wells were interpreted using the criteria developed for Montana and North Dakota. The maximum measured thickness of the upper Hell Creek hydrogeologic unit, determined from resistivity logs, is 560 ft in the Williston structural basin. The maximum interpolated thickness of the upper Hell Creek hydrogeologic unit is 738 ft in the Williston structural basin and 3,002 ft in the Powder River structural basin (fig. 5; table 5).

Lower Hell Creek Aquifer

The lower Hell Creek aquifer consists of the lower part of the Hell Creek Formation in Montana, North Dakota, and South Dakota and the lower parts of the Lance, Frenchman, and Boissevain Formations in Wyoming, Saskatchewan, and Manitoba, respectively (figs. 3*A*, *B*). The lower Hell Creek aquifer is present throughout much of the Williston and Powder River structural basins (figs. 2 and 5).

The lower Hell Creek aquifer consists of alternating layers of gray and brown mudstone, siltstone, sandstone, and sparse lignite beds. From a hydrogeologic perspective, the lower Hell Creek aquifer is defined as the lower part of the Hell Creek Formation where the relative percentage of sandstone generally is larger than the upper part. The aquifer is the basal portion of a Late Cretaceous, continental clastic wedge that extends from the Rocky Mountains to the central plains

(Murphy, 2001) and was deposited in the swamps and flood plains on or near a deltaic front adjacent to the Late Cretaceous inland sea. The lower Hell Creek aquifer is dominated by channel deposits and erosional surfaces (Flores, 1992). In Montana and western North Dakota, the bottom and top of the Hell Creek Formation sometimes are identified by coal zones (Diemer and others, 1992) however, in many areas these coal zones are sparse or absent, and in much of North Dakota, the Hell Creek Formation is defined as extending from above the uppermost sandstone member (Colgate Member) of the Fox Hills Sandstone upwards to the first substantial coal seam. Identification of the top surface of the lower Hell Creek aquifer was based on a change in the relative content of sandstone between the top of the lower Hell Creek aquifer and the bottom of the upper Hell Creek hydrogeologic unit as identified in borehole resistivity logs. In the Powder River structural basin, the outcrop contact between the upper and lower Hell Creek units was mapped by Stoner and Lewis (1980) and Lewis and Hotchkiss (1981), and the outcrop contact between the lower Hell Creek and Fox Hills Formations has been mapped for State geology maps (Love and Christiansen, 1985; Vuke and others, 2007). The subsurface contact between the hydraulically connected lower Hell Creek aquifer and underlying Fox Hills aquifer, however, has not been previously mapped; therefore, the lower Hell Creek and Fox Hills aquifers were combined in figure 5 for the Powder River structural basin. The maximum measured thickness of the lower Hell Creek aquifer, determined from resistivity logs, is 350 ft. The maximum interpolated thickness of the lower Hell Creek aquifer is 548 ft in the Williston structural basin, and the combined thickness of the lower Hell Creek and Fox Hills aquifers is 3,274 ft in the Powder River structural basin (fig. 5; table 5).

Fox Hills Aquifer

The Fox Hills aquifer consists of the Fox Hills Sandstone in Montana, Wyoming, North Dakota, and South Dakota; the Eastend Formation in Saskatchewan; and the lower Boissevain Formation/Coulter Member of the Pierre Formation in Manitoba (figs. 3*A*, *B*). The Fox Hills aquifer is the deepest hydrogeologic unit of the Upper Cretaceous aquifer system and is present throughout all of the Williston and Powder River structural basins.

The Fox Hills aquifer consists of mudstones, siltstones, and sandstones deposited in a shore and nearshore environment during the final stage of the Late Cretaceous inland sea (Murphy, 2001). Depositional environments probably included tidal channel, bay, estuary, and various environments associated with a delta plain (Cvancara, 1976b). In the Williston structural basin, geologic cross sections obtained from the Saskatchewan Geological Survey indicate that the interpretation of the oil and gas borehole geophysics logs combined the sandstones of the Eastend and lower Frenchman Formations as a single unit. A review of the Manitoba geologic maps indicated that the basal sandstone of the Boissevain Formation is equivalent to the upper one-third of the Fox Hills Sandstone, and the Coulter Member of the Pierre Shale is equivalent to the middle one-third of the Fox Hills Sandstone. To maintain consistency with the geologic interpretations for Montana and North Dakota, the oil and gas geophysical logs for Saskatchewan were interpreted with the same criteria used in Montana and North Dakota. In the Powder River structural basin, the subsurface contact between the hydraulically connected lower Hell Creek and Fox Hills aquifers has not been previously mapped; therefore, the lower Hell Creek and Fox Hills aquifers were combined in figure 5. The maximum measured thickness of the Fox Hills aquifer, determined from resistivity logs, is 422 ft in the Williston structural basin. The maximum interpolated thickness of the Fox Hills aquifer is also 422 ft in the Williston structural basin, and the combined thickness of the lower Hell Creek and Fox Hills aquifers is 3,274 ft in the Powder River structural basin (fig. 5; table 5).

Basal Confining Unit

The basal confining unit is composed of the Bearpaw Shale in Montana; the Pierre Shale and Lewis Shale in Wyoming, North Dakota, and South Dakota; the Bearpaw Formation in Saskatchewan; and the Pierre Formation in Manitoba (figs. 3*A*, *B*). The basal confining unit underlies the entire Upper Cretaceous aquifer system in the Williston and Powder River structural basins (figs. 6 and 7).

The basal confining unit consists of dark clay shale with many calcareous concretions. The basal confining unit was deposited at the bottom of a large inland sea during the Late Cretaceous. Deposition consisted of alternating periods of transgressions and regressions that resulted in a vertical sequence of shales, siltstones, and, to a lesser degree, sandstones (Tourtelot, 1962; Murphy, 2001). Because the depositional environment of the basal confining unit alternated between transgression and regression, the unit has been divided into several members with different names at different locations. Carlson (1979) states that the contact with the overlying Fox Hills Sandstone is transitional from a silty shale to a silty sandstone in North Dakota. Tourtelot (1962, p. 7) states that the last regression of the Cretaceous sea left a marine regressive sandstone sequence; this agrees with the review of the borehole resistivity and geologic logs that commonly showed a 50- to 100-ft thick transition zone where the basal confining unit changed from hard black shale to softer gray shale with increased sand content. The thickness of the basal confining unit is 800 to more than 3,000 ft (Downey, 1986; Anna, 1986; and Downey and Dinwiddie, 1988).

Hydraulic Characteristics

Hydraulic characteristics of hydraulic conductivity and transmissivity are described in this section of the report. For hydraulic conductivity, horizontal and vertical components were determined.

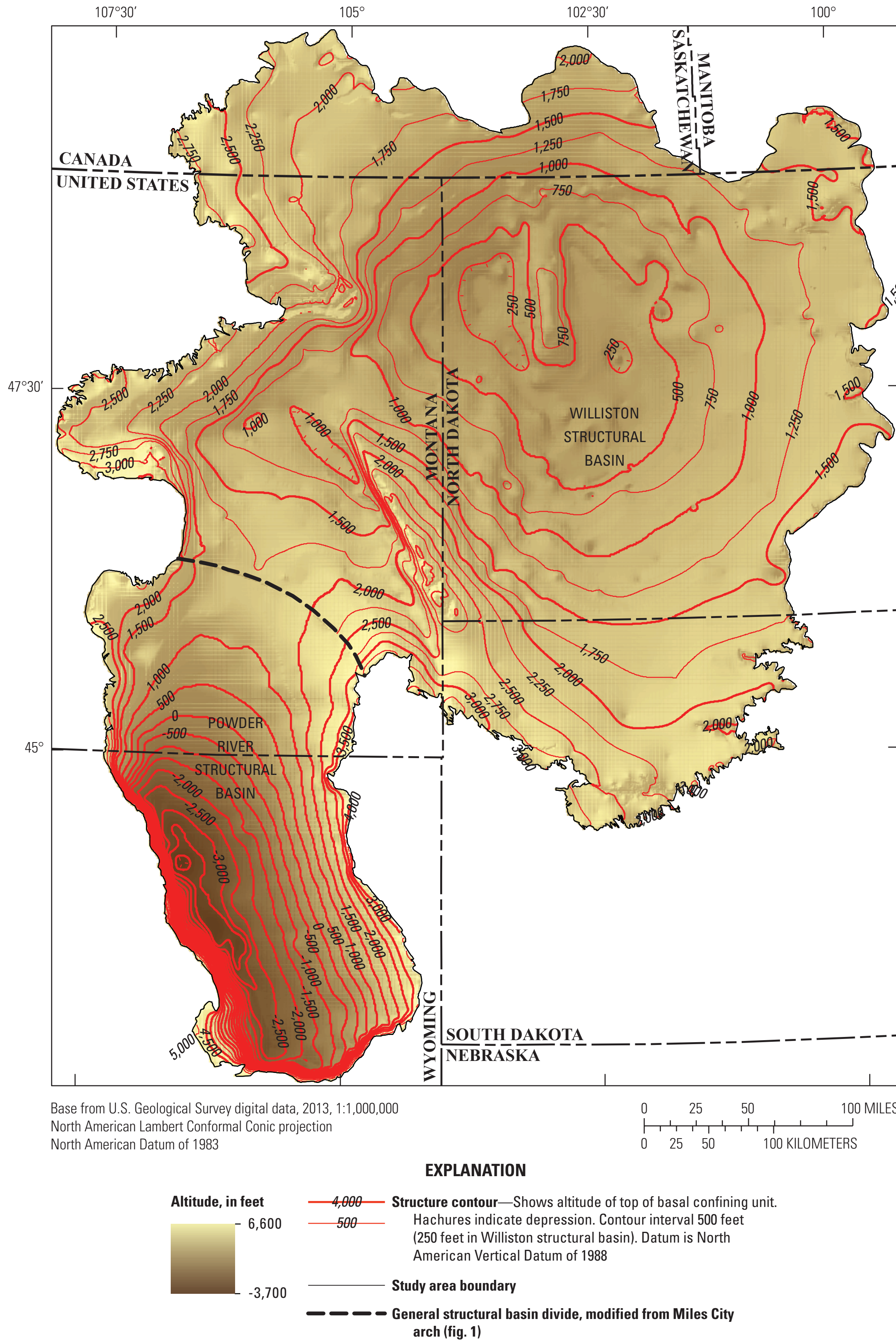


Figure 7. Altitude of the top of the basal confining unit in the Williston and Powder River structural basins.

Hydraulic Conductivity

Horizontal and vertical hydraulic conductivity values (K_h and K_v, respectively) were measured from borehole core samples of bedrock formations during previous studies in the Williston structural basin in North Dakota (North Dakota State Water Commission, variously dated). These values ranged from 0.00059 to 16.7 ft/d for K_h and from 0.0000023 to 2.31 ft/d for K_v (table 6) and were used as a comparison for values determined during this study. The ratio K_h/K_v affects the rate of vertical groundwater flow in relation to horizontal flow and, therefore, is an important parameter in characterizing groundwater flow. This ratio, which commonly is greater than unity (K_h is greater than K_v) for stratified aquifers, ranged from 0.92 to 22,600 for core samples from within the study area (table 6) and from 0.08 to 300 for several previous studies elsewhere in the United States and Canada (table 7). Aquifers with ratios greater than unity typically are dominated by horizontal groundwater flow. Dominantly horizontal flow also is a result of confining units that overlie or underlie an aquifer or a result of multiple confining layers within the aquifer.

Horizontal hydraulic conductivity values were interpreted in this study from resistivity and lithologic logs (appendix 2), and these values were spatially interpolated for hydrogeologic units of the glacial, lower Tertiary, and Upper Cretaceous aquifer systems throughout the Williston structural basin (fig. 1–1 in appendix 1, table 5). The range of horizontal hydraulic conductivity values for each hydrogeologic unit that were interpreted from logs and that were interpolated spatially are similar. The greatest range of hydraulic conductivity values is in the glacial deposits where interpreted values range from less than 0.01 ft/d in the high-clay content zones (till) to about 25 ft/d in the gravel zones (table 2–5) and interpolated values range from 0.01-24 ft/d (table 5). Some areas of gravel can have much larger hydraulic conductivity than 25 ft/d (Kevin Chandler, Montana Bureau of Mines and Geology, written commun., 2013). The arithmetic mean of horizontal hydraulic conductivity decreases with hydrogeologic unit depth, (table 2–5), which is possibly associated with overburden pressure and the subsequent closing of secondary fractures at greater depths. With the exceptions of the lower Hell Creek and Fox Hills aquifers, the geometric mean values are substantially smaller than the arithmetic mean values, likely because of log-normal population distribution. The areal distribution of interpolated horizontal hydraulic conductivity values in the Williston structural basin in the upper, middle, and lower Fort

Table 6. Horizontal and vertical hydraulic conductivity measured from borehole core samples for previous studies for the Williston structural basin in North Dakota.

[K_h, horizontal hydraulic conductivity; ft/d, feet per day; *n*, number; K_v, vertical hydraulic conductivity. Data summarized from Ackerman, 1977; Anna, 1980; Croft, 1974; Croft, 1985; Klausing, 1976; and Randich, 1975]

Formation/member	Mean				
	K_h (ft/d)	*n*	K_v (ft/d)	*n*	Ratio (K_h/K_v)
Sentinel Butte	16.7	5	0.0235	7	711
Tongue River	1.43	18	1.04	6	1.37
Lebo Shale	0.02	1	—	—	—
Cannonball	2.12	3	2.31	10	0.92
Cannonball-Ludlow	0.22	4	—	—	—
Upper Ludlow	0.70	1	—	—	—
Ludlow	0.0046	1	—	—	—
Middle Ludlow	1.30	1	—	—	—
Lower Fort Union Formation	5.78	13	—	—	—
Lower Ludlow	0.64	6	—	—	—
Lower Ludlow and Upper Hell Creek	0.87	3	—	—	—
Hell Creek	0.410	27	0.192	20	2.14
Hell Creek, same core	0.00059	1	0.000049	1	12.04
Basal Hell Creek and Fox Hills	1.65	6	—	—	—
Hell Creek and Fox Hills undifferentiated	10.48	30	—	—	—
Fox Hills	1.12	47	0.117	8	9.60
Pierre Shale	0.052	2	0.0000023	1	22,600
Total		**169**		**53**	

Table 7. Ratios of horizontal to vertical hydraulic conductivity from borehole core samples composed of sandstone and shale in the United States and Canada.

[K_h, horizontal hydraulic conductivity; K_v, vertical hydraulic conductivity; —, not applicable]

K_h/K_v	Study location	Source
	Shale	
10–20	South Dakota	Powertech (USA) Inc, 2009.
0.86	Wisconsin	Eaton and others, 2000.
0.08–300	Wisconsin	Hart and others, 2006.
10[a]	—	Domenico and Schwartz, 1990.
	Sandstone	
1.5	Illinois	Piersol and others, 1940.
2.4–4.5	South Dakota	Powertech (USA) Inc, 2009.
0.6–35	East Yorkshire, United Kingdom	Pokar and others, 2006.
2[a]	—	Domenico and Schwartz, 1990.

[a]Calculated by dividing the range midpoint of K_h by that of K_v.

Union hydrogeologic units (fig. 1–1) indicates larger values in the south and west and smaller values in the northeast, probably associated with the formation geomorphology that resulted in finer deposits (lower hydraulic conductivity) in the eastern part of the basin. The larger hydraulic conductivity values located at the edges are because of the shallowing of the unit and the larger hydraulic conductivity values assigned to sand and sandstone located within 100 ft of the land surface (table 3). The upper Fort Union aquifer has the greatest range of hydraulic conductivity values (0.14–9.8 ft/d) of the hydrogeologic units composing the lower Tertiary and Upper Cretaceous aquifer systems (table 5, fig. 1–1). The larger hydraulic conductivity values are because the Tongue River Member, Bullion Creek Formation, and Sentinel Butte Member, that make up the upper Fort Union hydrogeologic unit, contain a higher percentage of sand and sandstone than the deeper units. The hydraulic conductivity values of the upper Hell Creek hydrogeologic unit cover a wide range of values (fig. 1–1). The areal distribution in the upper Hell Creek hydrogeologic unit in the Williston structural basin indicates smaller hydraulic conductivity values in the northeast and southwest and a central area of larger values extending from the northwest to the southeast. The southeastern zone of larger hydraulic conductivity values is associated with the shallowing of the hydrogeologic unit and the larger hydraulic conductivity values assigned to sand and sandstone located within 100 ft of the land surface. The areal distribution of the hydraulic conductivity throughout the Williston structural basin in the lower Hell Creek and Fox Hills aquifers is generally consistent (fig. 1–1). The consistency may be associated with the relatively thick (30–50 ft) extensive sandstone layers that make up the lower Hell Creek and Fox Hills aquifers. The hydraulic conductivity values in the Fox Hills aquifer decrease towards the north, whereas the areal distribution of values in the lower Hell Creek aquifer is more random (fig. 1–1).

Horizontal hydraulic conductivity throughout the Powder River structural basin in the upper Fort Union aquifer is generally larger than the underlying middle Fort Union hydrogeologic unit (fig. 1–1). The middle Fort Union hydrogeologic unit has smaller hydraulic conductivity values than the aquifers that are above and below this unit, except in small areas within the northern part of the Powder River structural basin (fig. 1–1). Hydraulic conductivity in the lower Fort Union aquifer generally is larger than the underlying upper Hell Creek hydrogeologic unit, with smaller values along the basin margins (fig. 1–1). Hydraulic conductivity in the upper Hell Creek hydrogeologic unit generally is smaller than the hydraulic conductivity in the combined lower Hell Creek and Fox Hills aquifers, with slightly larger values in the thickest part of the hydrogeologic unit along the basin axis (fig. 1–1). Hydraulic conductivity in the lower Hell Creek and Fox Hills aquifers is fairly consistent, with lower values along the basin margins (fig. 1–1).

Resistivity logs were evaluated using a qualitative rating scale to obtain an estimate of horizontal-to-vertical hydraulic conductivity flow potential (anisotropy) throughout the Williston structural basin (table 2–6). The rating number ranges from 1 to 4 (table 4) and provides a qualitative assessment of the density and facies variability of the stratigraphic layers in a hydrogeologic unit as described previously in the "Qualification of Horizontal and Vertical Hydraulic Conductivity" section. A rating number of 1 indicates few stratigraphic layers, minimal facies changes, and therefore a high probability for vertical flow. A rating number of 4 indicates numerous stratigraphic layers, maximum facies changes, and a very low probability for vertical flow. Most of the glacial deposits and the Fox Hills aquifer (57 and 58 percent, respectively) were rated 2, indicating a moderate potential for vertical flow (table 2–6). The ratings of 1 and 2 for the glacial deposits and Fox Hills Sandstone were assigned because these units contain thick layers of gravel, sand, and sandstone with minimal facies changes. The Fort Union and Hell Creek units were mostly divided between ratings of 2 and 3, indicating moderate to a low potential for vertical flow. The lower Hell Creek aquifer has a slightly higher potential for vertical flow compared to the upper Fort Union aquifer (51 percent compared to 38 percent, respectively, were rated 2), probably because some the lower part of the Hell Creek Formation contains thick sandstones. Between 6 and 14 percent of the Fort Union and Hell Creek units, respectively, were rated 4, and therefore have a very low (near zero) potential for vertical flow.

Transmissivity

Because the transmissivity values are the product of the hydraulic conductivity and the unit thickness, quantification of the hydrogeologic unit thicknesses is required. The hydrogeologic unit thicknesses were determined by subtracting the altitude of the bottom of the unit from the altitude of the top of the unit (tables 2–1 through 2–4). The thickness of the glacial deposits is generally greatest (greater than 300 ft) in the northern part of the Williston structural basin (northern North Dakota and Canada) (fig. 6*A*). The glacial deposits thin to the south and west and are very thin or absent south of the Missouri River. The maximum thickness of the glacial deposits, documented in the borehole resistivity logs, is 638 ft in northwestern North Dakota. The maximum thickness of the upper Fort Union aquifer, documented in the borehole resistivity logs, is 1,160 ft in east-central Montana. The thickness of the upper Fort Union aquifer is greatest (1,000–1,160 ft) in the central part of the Williston structural basin, near the Montana/North Dakota border, and thins at the edges where erosion has removed most of the unit. The maximum thickness of the middle Fort Union hydrogeologic unit, documented in the borehole resistivity logs, is 400 ft in east-central Montana. The thickness of the middle Fort Union hydrogeologic unit is greatest (350–400 ft) in the western part of the Williston structural basin, eastern Montana, and thins to the northeast and at the edges where the unit shallows and intersects the bedrock surface. The maximum thickness of the lower Fort Union aquifer, documented in the borehole resistivity logs, is 670 ft in north-central North Dakota. The thickness of the lower Fort Union aquifer is greatest (600–670 ft) in the central part of the Williston structural basin, near the Montana/North Dakota border, and in the southeast part near the North Dakota/South Dakota border. The lower Fort Union aquifer thins to the west and at the edges where it shallows and intersects the bedrock surface. Near the North Dakota/South Dakota border, the increased thickness of the lower Fort Union aquifer is because of the presence of the Cannonball Member, which was deposited during an early Paleocene marine transgression that spread from the southeast to the northwest. The maximum thickness of the upper Hell Creek hydrogeologic unit, documented in the borehole resistivity logs, is 560 ft in east-central Montana. The thickness of the upper Hell Creek hydrogeologic unit is greatest (450–560 ft) in the southwestern part of the Williston structural basin, in Montana, and thins to the northeast and at the edges where the unit shallows and intersects the bedrock surface. The maximum thickness of the lower Hell Creek aquifer, documented in the borehole resistivity logs, is 350 ft in east-central Montana. The thickness of the lower Hell Creek aquifer is greatest (300–350 ft) in the southern part of the Williston structural basin, in Montana and South Dakota, and thins to the north and at the edges where the unit shallows and intersects the bedrock surface. The maximum thickness of the Fox Hills aquifer, documented in the borehole resistivity logs, is 422 ft in west-central North Dakota. The thickness of the Fox Hills aquifer is greatest in the east-central part of the Williston structural basin (approximately 400 ft) and thins to the west and at the edges where the unit shallows and intersects the bedrock surface.

Transmissivity values (tables 2–1 through 2–4) determined from resistivity logs in the Williston structural basin are statistically summarized in table 2–7 for each of the hydrogeologic units. The arithmetic means of transmissivity values range from 73.0 feet squared per day (ft^2/d) in the Fox Hills aquifer to 322.2 ft^2/d in the upper Fort Union aquifer. The greatest range in transmissivity values is in the glacial deposits where values range from <0.1 ft^2/d in the high-clay content till to 2,120 ft^2/d in the gravel zones. Similar to the hydraulic conductivity values, the Tertiary and Cretaceous hydrogeologic units indicate decreased transmissivity with increased depth, possibly associated with overburden pressure and the subsequent closing of secondary fractures. The geometric means of transmissivity values are smaller than the arithmetic means indicating that the population distributions may be log-normal.

Potentiometric Surfaces

In the Williston structural basin, potentiometric surface maps representing predevelopment (prior to 2000) conditions were developed using data from several databases. In the Powder River structural basin, potentiometric surfaces were digitized using maps from Hotchkiss and Levings (1986). These surfaces are shown for the upper Fort Union and lower Fort Union aquifers and the Upper Cretaceous aquifer system in figure 1–2 (located in appendix 1), an interactive figure containing multiple layers that can be viewed in different combinations to aid interpretation.

Williston Structural Basin

South of the glacial aquifer system where the upper Fort Union aquifer is unconfined, the potentiometric surface is topographically controlled and generally follows the orientation of land-surface slopes, resulting in groundwater flow from topographically high areas toward stream valleys (fig. 1–2). Because of this topographic control, groundwater-flow directions in the unconfined upper Fort Union aquifer are highly variable. The upper Fort Union aquifer generally has lower hydraulic gradients (as indicated by wide spaces between potentiometric contours) and less topographic control where overlain by the glacial aquifer system than elsewhere.

The general topographic control of the potentiometric surface for the upper Fort Union aquifer is similar in most areas of the lower Fort Union aquifer, except with less relief and lower hydraulic gradients (fig. 1–2), which likely results from hydraulic connection between the two aquifers. Horizontal groundwater-flow directions in the upper and lower Fort Union aquifers inferred from potentiometric maps (fig. 1–2) generally are similar (Long and others, 2014), except in the area east of the Little Missouri River and south of Lake Sakakawea (select Hydrography layer in fig. 1–2), where groundwater-flow directions are variable and topographically controlled in the upper Fort Union aquifer but primarily are towards the northeast in the lower Fort Union aquifer. These areas with differences in groundwater-flow directions between the upper and lower Fort Union aquifers indicate the areas with the weakest hydraulic connection between these two aquifers in the Williston structural basin. The confining properties of the middle Fort Union hydrogeologic unit, which does not exist in the northeastern part of the Williston structural basin (fig. 2), are spatially variable.

Groundwater flow in the Upper Cretaceous aquifer system generally is easterly or northeasterly in the Williston structural basin (Long and others, 2014), with lower hydraulic gradients than in the upper and lower Fort Union aquifers (fig. 1–2). Interpretation of potentiometric surface maps (fig. 1–2) indicates that where unconfined, groundwater in the Upper Cretaceous aquifer system flows toward several streams in the southeastern part of the Williston structural basin. Where confined, groundwater flows toward the Souris, Yellowstone, and Little Missouri Rivers and the upper part of the Missouri River.

Powder River Structural Basin

Groundwater flow in the lower Tertiary and Upper Cretaceous aquifer systems in the Powder River structural basin generally is northerly, except at the far southern end, where flow is toward the east and discharges to Antelope Creek, as indicated by potentiometric-surface gradients (fig. 1–2). Locally in the upper Fort Union aquifer, groundwater flows toward and discharges into streams, primarily the Powder and Tongue Rivers, and is topographically controlled (fig. 1–2). The difference in potentiometric surfaces between the upper and lower Fort Union aquifers is greater in the Powder River structural basin than in the Williston structural basin, indicating that the greatest hydraulic separation between the two aquifers occurs in the Powder River structural basin. These two aquifers are separated by the middle Fort Union hydrogeologic unit, which is described as a confining unit in the Powder River structural basin (Lewis and Hotchkiss, 1981; Hotchkiss and Levings, 1986).

Potentiometric surfaces for the lower Fort Union aquifer and Upper Cretaceous aquifer system are similar in the central part of the Powder River structural basin, with generally higher hydraulic head in the Upper Cretaceous aquifer system than in the lower Fort Union aquifer in the southern part of the structural basin (fig. 1–2). In the northern part of the structural basin, groundwater in the lower Fort Union aquifer flows toward the Tongue and Powder Rivers (fig. 1–2), which is more subtle in the Upper Cretaceous aquifer system (fig. 1–2).

Summary

The glacial, lower Tertiary, and Upper Cretaceous aquifer systems in the Williston and Powder River structural basins within the United States and Canada are the uppermost principal aquifer systems and most accessible sources of groundwater in two important energy-producing regions. The glacial aquifer system covers the northeastern part of the Williston structural basin. The lower Tertiary and Upper Cretaceous aquifer systems are present in about 91,300 square miles (mi^{2}) of the Williston structural basin and about 25,500 (mi^{2}) of the Powder River structural basin. Directly under these aquifer systems are 800 to more than 3,000 feet (ft) of relatively impermeable marine shale that serves as a basal confining unit. The uppermost principal aquifer systems in the Williston structural basin have a very shallow (less than 2,900 ft deep), wide, and generally symmetrical bowl shape. The uppermost principal aquifer systems in the Powder River structural basin have a very deep (as much as 8,500 ft deep), narrow, and asymmetrical shape.

The Williston structural basin has been an important domestic oil and natural gas producing region since the 1950s. Oil and natural gas development in the basin has increased substantially since the mid-2000s, primarily because of recently improved drilling and hydraulic fracturing methods from deep formations, such as the Bakken and Three Forks Formations. These improved methods require considerable volumes of freshwater derived mostly from shallow aquifers or surface water. Additionally, development of coal, lignite, and coal-bed natural gas resources in the Williston and Powder River structural basins could affect the shallow aquifers by strip mining and groundwater depletion.

Because of the importance of water resources in these energy-rich basins, the U.S. Geological Survey Groundwater Resources Program began a regional study in 2011 of the glacial, lower Tertiary, and Upper Cretaceous aquifer systems in the Williston and Powder River structural basins with the goal to quantify groundwater availability. The information presented in this report, together with a description of the conceptual flow model in a companion report, provides a more detailed understanding of the groundwater-flow systems and provides the hydrogeologic framework for a numerical groundwater-flow model that could be used to simulate regional groundwater flow and test aquifer system responses to water-use and climate forecasts.

This study combined the lithostratigraphic units of the glacial, lower Tertiary, and Upper Cretaceous aquifer systems into 7 hydrogeologic units—glacial deposits, 4 bedrock aquifer units, and 2 bedrock confining units—on the basis of general hydraulic properties. The glacial deposits are composed of till and glacial outwash sands and gravels with areas of cobbles and boulders. The four bedrock aquifer units are the upper Fort Union, lower Fort Union, lower Hell Creek, and Fox Hills aquifers and are composed primarily of sandstone. The units with confining properties are the middle Fort Union hydrogeologic unit (shale) and upper Hell Creek hydrogeologic unit (less sandstone than the underlying lower Hell Creek aquifer). Water from these units is relatively fresh and potable, and withdrawals seldom occur from units underneath the basal confining unit. Data and information from about 300 electric (resistivity) and lithologic logs were compiled to determine thickness, hydraulic conductivity, and transmissivity for the hydrogeologic units in the Williston structural basin. The data were interpolated spatially to develop a three-dimensional hydrogeologic framework. Previous publications provided thickness and transmissivity for the hydrogeologic units in the Powder River structural basin. This information was digitally mapped and interpolated to provide the spatial distribution of hydraulic conductivity in the Powder River structural basin.

Interpolated thicknesses of the glacial deposits, the lower Tertiary aquifer system, and the Upper Cretaceous aquifer system in the Williston structural basin are less than about 750; 2,250; and 1,050 ft, respectively. Interpolated thicknesses of the lower Tertiary aquifer system and the Upper Cretaceous aquifer system in the Powder River structural basin are less than about 7,180 and 5,070 ft, respectively. Interpolated horizontal hydraulic conductivity values for the Williston structural basin were as much as 25 feet per day (ft/d) in the glacial deposits and had smaller ranges in the lower Tertiary aquifer system (0.01–9.8 ft/d) and in the Upper Cretaceous aquifer system (0.06–5.5 ft/d). In the Powder River structural basin, the lower Tertiary aquifer system had a greater range of horizontal hydraulic conductivity values (0.10–11 ft/d) than the Upper Cretaceous aquifer system (0.02–5.7 ft/d). Transmissivity is greatest in the gravel zones of the glacial deposits (2,120 feet squared per day) and generally decreases with depth into the bedrock units.

Regionally, groundwater flows in a northerly or northeasterly direction from the Powder River structural basin to the Williston structural basin. The upper Fort Union aquifer is generally unconfined, and flow is local and generally controlled by topography in both basins, except where covered by glacial deposits in the northern part of the Williston structural basin. Flow directions in the lower Fort Union aquifer are less localized than in the upper Fort Union aquifer; however, topographic controls still exist in eastern Montana. Groundwater in the Upper Cretaceous aquifer system generally has lower hydraulic gradients than in the Fort Union aquifers, and flow is regional.

Selected References

Ackerman, D.J., 1977, Ground-water basic data for Morton County, North Dakota: U.S. Geological Survey for North Dakota State Water Commission County Ground-Water Studies 27, part II and North Dakota Geological Survey Bulletin 72, part II, 592 p. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubContentPDF/PB-305/Morton_Part_2.pdf*.]

Anna, L.O., 1980, Ground-water data for Billings, Golden Valley and Slope Counties, North Dakota: U.S. Geological Survey for North Dakota State Water Commission County Ground-Water Studies 29, part II and North Dakota Geological Survey Bulletin 76, part II, 241 p. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubContentPDF/PB-174/PartII_Ground.pdf*.]

Anna, L.O., 1986, Geologic framework of the ground-water system in Jurassic and Cretaceous rocks in the Northern Great Plains, in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402–B, 18 pls. [Also available at *http://pubs.er.usgs.gov/publication/pp1402B*.]

Anna, L.O., Pollastro, Richard, and Gaswirth, S.B., 2011, Williston Basin Province—Stratigraphic and structural framework to a geologic assessment of undiscovered oil and gas resources, chap. 2 *of* Assessment of undiscovered oil and gas resources of the Williston Basin Province of North Dakota, Montana, and South Dakota, 2010: U.S. Geological Survey Digital Data Series 69–W, 17 p., 1 CD-ROM. [Also available at *http://pubs.er.usgs.gov/publication/ds69W*.]

Arihood, Leslie, 2009, Processing, analysis, and general evaluation of well-driller logs for estimating hydrogeologic parameters of the glacial sediments in a ground-water flow model of the Lake Michigan Basin: U.S. Geological Survey Scientific Investigations Report 2008–5184, 26 p. [Also available at *http://pubs.usgs.gov/sir/2008/5184/*.]

Armstrong, C.A., 1971, Ground-water resources of Burke and Montrail Counties: North Dakota Geological Survey Bulletin 55, part III, and North Dakota State Water Commission County Ground Water Studies 14, part III, 86 p. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubContentPDF/PB-187/*.]

Beikman, H.M., 1962, Geology of the Powder River Basin, Wyoming and Montana, with reference to subsurface disposal of radioactive wastes: U.S. Geological Survey Trace Elements Investigations Report 823 (Open-File Report 62–7), 84 p. [Also available at*http://pubs.er.usgs.gov/publication/ofr627*.]

Bergantino, R.N., 1984, Topographic map of the bedrock surface, northeastern Montana, northwestern North Dakota, and southeastern Saskatchewan: Montana Bureau of Mines and Geology Open-File Report 151, 1 sheet, 1:250,000.

Bluemle, J.P., 1971, Geology of McLean County, North Dakota: North Dakota Geological Survey Bulletin 60, part I, and North Dakota State Water Commission County Ground Water Studies 19, part I, 65 p. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubContentPDF/PB-291/*.]

Bluemle, J.P., 1981, Geology of Sheridan County, North Dakota: North Dakota Geological Survey Bulletin 75, part I, and North Dakota State Water Commission County Groundwater Studies 32, part I, 59 p. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubContentPDF/PB-341*.]

Bluemle, J.P., 1982, Geology of McHenry County, North Dakota: North Dakota Geological Survey Bulletin 74, part 1, 50 p. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubContentPDF/PB-273/*.]

Bluemle, J.P., 1983, Geologic and topographic bedrock map of North Dakota: North Dakota Geological Survey, Miscellaneous Map 25, scale 1:670,000. [Also available at *https://www.dmr.nd.gov/ndgs/Publication_List/miscellm.asp*.]

Bluemle, J.P., 1984, Geology of Emmons County, North Dakota: North Dakota Geological Survey Bulletin 66, part 1, and North Dakota State Water Commission County Groundwater Studies 23, part 1, 69 p. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubContentPDF/PB-233/Emmons_Part_1.pdf*.]

Bluemle, J.P., 1988, Generalized bedrock geologic map of North Dakota: North Dakota Geological Survey, Miscellaneous Map 28. [Also available at *https://www.dmr.nd.gov/ndgs/Publication_List/miscellm.asp*.]

Bluemle, J.P., 1998, The coalbed methane potential of North Dakota lignites: North Dakota Geological Survey Open-File Report 98–1, 38 p.

Carlson, C.G., 1979, Geology of Adams and Bowman Counties, North Dakota: North Dakota Geological Survey Bulletin 65, part I, and North Dakota State Water Commission County Groundwater Studies 22, part I, 29 p. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubContentPDF/PB-153/AdamsBowmanPart1.pdf*.]

Carlson, C.G., 1982, Structure map on top of the Cretaceous Pierre Formation in North Dakota: North Dakota Geological Survey Miscellaneous Map 23. [Also available at *https://www.dmr.nd.gov/ndgs/Publication_List/miscellm.asp*.]

Carlson, C.G., 1983, Geology of Billings, Golden Valley, and Slope Counties, North Dakota: North Dakota Geological Survey Bulletin 76, part I, and North Dakota State Water Commission County Groundwater Studies 29, part I, 40 p. [Also available at *http://www.swc.nd.gov/4dlink9/4dcgi/GetContentRecord/PB-250/BillingsGoldenValleySlope_Part_1.pdf*.]

Clayton, Lee, Carlson, C.G., Moore, G.G., Groenewold, Gerald., Holland, F.D., and Moran, S.R., 1977, The Slope (Paleocene) and Bullion Creek (Paleocene) Formations of North Dakota: North Dakota Geological Survey Report of Investigation 59, 14 p. [Also available at *https://www.dmr.nd.gov/ndgs/Publication_List/reportsnew.asp*.]

Croft, M.G., 1974, Ground-water basic data for Adams and Bowman Counties, North Dakota: U.S. Geological Survey for North Dakota State Water Commission County Ground-Water Studies 22, part II and North Dakota Geological Survey Bulletin 65, part II, 294 p. [Also available at *http://www.swc.nd.gov/4dlink9/4dcgi/GetContentRecord/PB-247*.]

Croft, M.G., 1985, Ground-water basic data for McKenzie County, North Dakota: U.S. Geological Survey for the North Dakota State Water Commission County Ground-Water Studies 37, part II and North Dakota Geological Survey Bulletin 80, part II, 455 p. [Also available at *http://www.swc.nd.gov/4dlink9/4dcgi/GetContentRecord/PB-269*.]

Cvancara, A.M., 1976a, Geology of the Cannonball Formation (Paleocene) in the Williston Basin, with reference to uranium potential: North Dakota Geological Survey, Report of Investigation 57, 22 p. [Also available at *https://www.dmr.nd.gov/ndgs/Publication_List/reportsnew.asp*.]

Cvancara, A.M., 1976b, Geology of the Fox Hills Formation (Late Cretaceous) in the Williston Basin of North Dakota, with reference to uranium potential: North Dakota Geological Survey Report of Investigation 55, 16 p. [Also available at *https://www.dmr.nd.gov/ndgs/Publication_List/pdf/RI%20SERIES/RI-55.pdf*.]

Diemer, J.A., Belt, E.S., and Metcalf, Lynn, 1992, Sedimentology and paleohydraulics for the Lebo, Fort Union Formation, southeastern Montana, *in* Sholes, M.A., ed., Coal geology of Montana: Montana Bureau of Mines and Geology Special Publication 102, p. 61–83.

Domenico, P.A., and Schwartz, F.W., 1990, Physical and chemical hydrogeology: New York, John Wiley and Sons, 824 p.

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, 87 p. [Also available at *http://pubs.er.usgs.gov/publication/pp1402E*.]

Downey, J.S., and Dinwiddie, G.A., 1988, The regional aquifer system underlying the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming—Summary: U.S. Geological Survey Professional Paper 1402–A, 64 p., 3 pls. [Also available at *http://pubs.er.usgs.gov/publication/pp1402A*.]

Eaton, T.E., Hart, D.J., Bradbury, K.R., and Wang, H.F., 2000, Appendix B—Hydraulic conductivity and specific storage of the Maquoketa shale: Wisconsin Geological and Natural History Survey Open-File Report, 30 p.

Ellis, M.S., and Colton, R.B., 1994, Geologic map of the Powder River Basin and surrounding area, Wyoming, Montana, South Dakota, North Dakota, and Nebraska: U.S. Geological Survey, Miscellaneous Investigation Series, Map I–2298. [Also available at *http://pubs.er.usgs.gov/publication/i2298*.]

Fan, Jianging, and Gijbels, Irene, 1996, Local polynomial modeling and its applications: London, Chapman and Hall, 341 p.

Feltis, R.D., Lewis, B.D., Frasure, R.L., Rious, R.P., Jauhola, C.A., and Hotchkiss, W.R., 1981, Selected geologic data from the Northern Great Plains area of Montana: U.S. Geological Survey Open-File Report 81–415, 63 p. [Also available at*http://pubs.er.usgs.gov/publication/ofr81415*.]

Fischer, Kimberly, 2013, Groundwater flow model inversion to assess water availability in the Fox Hills-Hell Creek aquifer: North Dakota State Water Commission, North Dakota Water Resource Investigation 54, 325 p. [Also available at *http://www.swc.nd.gov/4dlink9/4dcgi/GetContentPDF/PB-2246/WRI%2054.pdf*.]

Flores, R.M., 1992, Sedimentology of the Upper Cretaceous and Paleocene coal-bearing regressive sequences, Williston basin, Montana, *in* Sholes, M.A., ed., Coal geology of Montana: Montana Bureau of Mines and Geology Special Publication 102, p. 1–21.

Flores, R.M., and Bader, L.R., 1999, Fort Union coal in the Powder River Basin, Wyoming and Montana—A synthesis, chapter PS *of* Fort Union Coal Assessment Team, 1999 Resource assessment of selected Tertiary coal beds and zones in the Northern Rocky Mountains and Great Plains Region: U.S. Geological Professional Paper 1625–A, p. PS1–PS75. [Also available at *http://pubs.usgs.gov/pp/p1625a/*.]

Fullerton, D.S., Colton, R.B., Bush, C.A., and Straub, A.W., 2004, Map showing spatial and temporal relations of mountain and continental glaciations on the northern plains, primarily in northern Montana and northwestern North Dakota: U.S. Geological Survey Scientific Investigations Map 2843. [Also available at *http://pubs.usgs.gov/sim/2004/2843/*.]

Gaswirth, S.B., Marra, K.R., Cook, T.A., Charpentier, R.R., Gautier, D.L., Higley, D.K., Klett, T.R., Lewan, M.D., Lillis, P.G., Schenk, C.J., Tennyson, M.E., and Whidden, K.J., 2013, Assessment of undiscovered oil resources in the Bakken and Three Forks Formations, Williston Basin Province, Montana, North Dakota, and South Dakota, 2013: U.S. Geological Survey Fact Sheet 2013–3013, 4 p. [Also available at *http://pubs.usgs.gov/fs/2013/3013/*.]

Gesch, D.B., 2007, The National Elevation Dataset, *in* Maune, D.F., ed., Digital elevation model technologies and applications—The DEM users manual (2d ed.): Bethesda, Maryland, American Society for Photogrammetry and Remote Sensing, p. 99–118.

Gesch, Dean, Oimoen, Michael, Greenlee, Susan, Nelson, Charles, Steuck, Michael, and Tyler, Dean, 2002, The National Elevation Dataset: Photogrammetric engineering and remote sensing, v. 68, no. 1, p. 5–11.

Groundwater Information Network, 2011, Water wells database: Manitoba Water Stewardship Division. [Also available at *http://ngwd-bdnes.cits.nrcan.gc.ca/service/api_ngwds:gin/en/wmc/aquifermap.html*.]

Hart, D.J., Bradbury, K.R., and Feinstein, D.T., 2006, The vertical hydraulic conductivity of an aquitard at two spatial scales: Ground Water, v. 44, no. 2, p. 201–211.

Hotchkiss, W.R., and Levings, J.F., 1986, Hydrogeology and simulation of water flow in strata above the Bearpaw Shale and equivalents of eastern Montana and northeastern Wyoming: U.S. Geological Survey Water-Resources Investigations Report 85–4281, 72 p. [Also available at *http://pubs.er.usgs.gov/publication/wri854281*.]

Jorgensen, D.G., 1989, Using geophysical logs to estimate porosity, water resistivity, and intrinsic permeability: U.S. Geological Survey Water-Supply Paper 2321, 24 p. [Also available at *http://pubs.er.usgs.gov/publication/wsp2321*.]

Klassen, R.W., Wyder, J.E., and Bannatyne, B.B., 1970, Bedrock topography and geology of southern Manitoba: Geological Survey of Canada and Manitoba Deparment of Mines and Natural Resources, Map 25–1970, Paper 70–51, scale 1:500,000,. [Also available at *http://pubs.er.usgs.gov/publication/wsp2321*.]

Klausing, R.L., 1976, Ground-water basic data for Dunn County, North Dakota: U.S. Geological Survey for North Dakota State Water Commission County Ground-Water Studies 25, part II, and North Dakota Geological Survey Bulletin 68, part II, 501 p. [Also available at *http://www.swc.nd.gov/4dlink9/4dcgi/GetContentRecord/PB-258*.]

Kume, Jack, and Hansen, D.E., 1965, Geology and ground water resources of Burleigh County, North Dakota: North Dakota Geological Survey Bulletin 42, and North Dakota State Water Conservation Commission County Ground Water Studies 3, part I, Geology, 111 p. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubContentPDF/PB-195/Burleigh_Part_1.pdf*.]

Levings, J.F., Levings, G.W., Feltis, R.D., Hotchkiss, W.R., and Lee, R.W., 1981, Selective annotated bibliography of geology and ground-water resources for the Montana part of the Northern Great Plains Regional Aquifer-System Analysis: U.S. Geological Survey Water-Resources Investigations Open-File Report 81–401, 91 p. [Also available at *http://pubs.er.usgs.gov/publication/ofr81401*.]

Lewis, B.D., and Hotchkiss, W.R., 1981, Thickness, percent sand, and configuration of shallow hydrogeologic units in the Powder River Basin, Montana and Wyoming: U.S. Geological Survey Miscellaneous Investigations Map 1–1317, 16 maps, 6 sheets. [Also available at *http://pubs.er.usgs.gov/publication/i1317*.]

Long, A.J., Aurand, K.R., Bednar, J.M., Davis, K.W., Mckaskey, J.D.R.G., and Thamke, J.N., 2014, Conceptual model of the uppermost principal aquifer systems in the Williston and Powder River structural basins, United States and Canada: U.S. Geological Survey Scientific Investigations Report 2014–5055, 41 p. [Also available at *http://pubs.usgs.gov/sir/2014/5055/*.]

Love, J.D., and Christiansen, A.C., 1985, Geologic map of Wyoming: U.S. Geological Survey, other Government Series, 50–IT, scale 1:500,000, 3 sheets, *digitially mapped by* Green, G.N., and Drouillard, P.H., 1994, The digital geologic map of Wyoming in ARC/INFO format: U.S. Geological Survey Open-File Report 94–425. [Also available at *http://pubs.er.usgs.gov/publication/ofr94425*.]

Maathuis, Harm, and Simpson, Mark, 2007a, Groundwater resources of the Cypress Lake (72F) area, Saskatchewan: Saskatchewan Research Council Environment and Forestry SRC Publication 11974-1E07, prepared for Saskatchewan Watershed Authority, 38 p., 51 figs., 1 app.

Maathuis, Harm, and Simpson, Mark, 2007b, Groundwater resources of the Wood Mountain (72G) area, Saskatchewan: Saskatchewan Research Council Environment and Forestry SRC Publication 12177-1E07, prepared for Saskatchewan Watershed Authority, 32 p., 42 figs., 1 app.

Macdonald, R., and Slimmon, W.L., comps., 1999, Geological map of Saskatchewan: Saskatchewan Industry and Resources, Saskatchewan Geological Survey, 1 sheet, 1:1,000,000 scale. [Also available at *http://economy.imaginesask.ca/geology_map*.]

Martin, J.E., Sawyer, J.F., Fahrenbach, M.D., Tomhave, D.W., and Schulz, L.D., 2004, Geologic map of South Dakota: South Dakota Geological Survey, Map 10, scale 1:500,000.

McLellan, Marguerite, 1992, Interpretation of Paleocene coal and clastic deposition, and evolution of the northern and central Powder River Basin, Montana and Wyoming, *in* Sholes, M.A., ed., Coal geology of Montana: Montana Bureau of Mines and Geology Special Publication 102, p. 83–105.

Millard, M.J., 1993, Geology and groundwater resources of the Willow Bunch Lake area (72H), Saskatchewan: Saskatchewan Research Council Environment and Forestry SRC Publication No. R–1210–1–E–93, prepared for Saskatchewan Watershed Authority, 15 p., 3 apps.

Montana Bureau of Mines and Geology, 2011, Water well database: Montana Groundwater Information Center. [Also available at *http://mbmggwic.mtech.edu/*.]

Multi-Resolution Land Characteristics Consortium, 2011, National land cover database—Conterminous United States NLCD 2006 land cover: Multi-Resolution Land Characteristics Consortium, 30-m data. [Also available at *http://www.mrlc.gov/nlcd06_data.php*.]

Murphy, E.C., 2001, Geology of Dunn County: North Dakota Geological Survey Bulletin 68, part I, and North Dakota State Water Commission County Groundwater Studies 25, part I, 36 p. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubContentPDF/PB-221/Dunn_Part_1.pdf*.]

Murphy, E.C., Nordeng, S.H., Juenker, B.J., and Hoganson, J.W., 2009, North Dakota stratigraphic column: North Dakota Geological Survey Miscellaneous Series 91, 1 p. [Also available at *https://www.dmr.nd.gov/ndgs/Publication_List/pdf/Strat-column-NDGS-(2009).pdf*.]

Musin, O.R., 1997, Properties of the Delauney triangulation, *in* Proceedings of the 13th Annual Symposium on Computational Geometry: New York, Association for Computing Machinery, p. 424–426. [Also available at *http://dl.acm.org/citation.cfm?id=263061*.]

Nicolas, M.P.B., Matile, G.L.D., Keller, G.R., and Bamburak, J.D., 2010, Phanerozoic geology of southern Manitoba: Manitoba Innovation, Energy and Mines, Manitoba Geological Survey Stratigraphic Map SM2010–1, 2 sheets, scale 1:600,000.

Noble, R.A., Bergantino, R.N., Patton, R.W., Sholes, B.C., and Scofield, D.F., 1982, AT211.21E (10) Contours in feet on top of the Bearpaw Shale: Montana Bureau of Mines and Geology Open-File Report 99E–I, 1 sheet.

North Dakota Information Technology Department, 2012, Water data sites database: North Dakota State Water Commission. [Also available at *http://www.nd.gov/gis/apps/DataDownload/?clipping=Full&coord=ND83-SF&format=SHAPE&layers=NDHUB.WATERDATASITES*.]

North Dakota State Water Commission, variously dated, County ground water studies. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubCategoryRecord/Reports%20and%20Publications/County%20Ground%20Water%20Studies*.]

Peterson, J.A., 1984, Stratigraphy and sedimentary facies of the Madison Limestone and associated rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–A, 34 p., 20 pls. [Also available at *http://pubs.er.usgs.gov/publication/pp1273A*.]

Piersol, R.J., Workman, L.E., and Watson, M.C., 1940, Porosity, total liquid saturation, and permeability of Illinois oil sands: Illinois Geological Survey Report Investigation 67, 72 p.

Pokar, Magdeline, West, L.J., and Odling, N.E., 2006, Petrophysical characterization of the Sherwood Sandstone from East Yorkshire, UK *in* Barker, R.D., and Tellam, J.H., eds., Fluid flow and solute movement in sandstones: The Onshore UK Permo-Triassic Red Bed Sequence, Geological Society, London, Special Publications 263, p. 103–118.

Powertech (USA) Inc., 2009, Dewey-Burdock project supplement to application for NRC uranium recovery license, variously paged.

Randich, P.G., 1975, Ground-water basic data for Grant and Sioux Counties, North Dakota: U.S. Geological Survey for North Dakota State Water Commission County Ground-Water Studies 24, part II, and North Dakota Geological Survey Bulletin 67, part II, 303 p. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubContentPDF/PB-247/GrandSouix_Part_2.pdf*.]

Randich, P.G., 1977, Ground-water resources of Benson and Pierce Counties, North Dakota: North Dakota State Water Commission County Ground-Water Studies 18, part III, and North Dakota Geological Survey Bulletin 59, part III, 76 p. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubContentPDF/PB-170/*.]

Randich, P.G., and Kuzniar, R.L., 1984, Ground-water resources of Bottineau and Rollette Counties, North Dakota: North Dakota State Water Commission County Ground-Water Studies 35, part III, and North Dakota Geological Survey Bulletin 78, part III, 41 p. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetSubContentPDF/PB-180/BottinearRolette_Part_3.pdf*.]

Reilly, T.E., Dennehy, K.F., Alley, W.M., and Cunningham, W.L., 2008, Ground-water availability in the United States: U.S. Geological Survey Circular 1323, 70 p. [Also available at *http://pubs.usgs.gov/circ/1323/*.]

Rigby, J.K., and Rigby, J.K., Jr., 1990, Geology of the Sand Arroyo and Bug Creek quadrangles, McCone County, Montana: Brigham Young University Geology Studies, v. 36, p. 69–134.

Schuh, W.M., 2010, Water appropriation requirements, current water use, and water availability for energy industries in North Dakota—A 2010 summary: North Dakota State Water Commission Water Resources Investigation 49, 415 p. [Also available at *http://www.swc.state.nd.us/4dlink9/4dcgi/GetContentPDF/PB-1800/W&E%20RPT%20FinalR.pdf*.]

Simpson, M.A., 1993, Geology and groundwater resources of the Weyburn/Virden area (62E/F), Saskatchewan: Saskatchewan Research Council Environment and Forestry SRC Publication R–1210–3–E–93, prepared for Saskatchewan Watershed Authority, 14 p., 3 app.

Smith, L.N., LaFave, J.I., Patton, T.W., Rose, J.C., and McKenna, D.P., 2000, Groundwater resources of the Lower Yellowstone River area—Dawson, Fallon, Prairie, Richland, and Wibaux Counties, Montana: Montana Bureau of Mines and Geology Groundwater Assessment Atlas 1, 43 p.

Soller, D.R., 1992, Text and references to accompany “Map showing the thickness and character of Quaternary sediments in the glaciated United States east of the Rocky Mountains”: U.S. Geological Survey Bulletin 1921, 54 p. [Also available at *http://pubs.usgs.gov/bul/1921/*.]

Soller, D.R., Packard, P.H., and Garrity, C.P., 2012, Database for USGS Map I–1970—Map showing the thickness and character of Quaternary sediments in the glaciated Unites States east of the Rocky Mountains: U.S. Geological Survey Data Series 656, scale 1:1,000,000. [Also available at *http://pubs.usgs.gov/ds/656*.]

South Dakota Department of Environment and Natural Resources, 2011, South Dakota water well completion reports: South Dakota Department of Environment and Natural Resources database. [Also available at *http://denr.sd.gov/des/wr/wr.aspx*.]

Statistics Canada, 2001, Population counts, land area and population density, for Canada, Provinces and Territories, 2001 census. [Also available at *http://www12.statcan.ca/english/census01/products/standard/popdwell/Table-PR.cfm?T=2&S=1&O=A*.]

Stoner, J.D., and Lewis, B.D., 1980, Hydrogeology of the Fort Union coal region, eastern Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I–1236, 2 sheets. [Also available at *http://pubs.er.usgs.gov/publication/i1236*.]

Theis, C.V., Brown, R.H., and Meyer, R.R., 1963, Estimating the transmissibility of aquifers from the specific capacity of wells, *in* Bentall, Ray, ed., Methods of determining transmissibility and drawdown: U.S.Geological Survey Water-Supply Paper 1536–I, p. 331–341. [Also available at *http://pubs.usgs.gov/wsp/1536i/report.pdf*.]

Tourtelot, H.A., 1962, Preliminary investigation of the geologic setting and chemical composition of the Pierre Shale Great Plains Region: U.S. Geological Survey Professional Paper 390, 75 p. [Also available at *http://pubs.er.usgs.gov/publication/pp390*.]

U.S. Census Bureau, 2001, Counties ranked by population size—July 1, 2001. [Also available at *http://www.census.gov/popest/data/counties/totals/2001/CO-EST2001-06.html*.]

U.S. Energy Information Administration, 2013, Annual energy outlook 2013 with projections to 2040: U.S. Department of Energy, DOE/EIA-0383(2013), 233 p. [Also available at *http://www.eia.gov/forecasts/aeo/pdf/0383(2013).pdf*.]

U.S. Environmental Protection Agency, 2011, Level III ecoregions of the conterminous United States: Corvallis, Oregon, U.S. EPA, National Health and Environmental Effects Research Laboratory, map scale 1:3,000,000.

U.S. Geological Survey, 2013, National Water Information System (NWIS): U.S. Geological Survey database. [Also available at *http://waterdata.usgs.gov/usa/nwis/nwis*.]

U.S. Geological Survey, 2014, Principal aquifers of the 48 conterminous United States, Hawaii, Puerto Rico, and the U.S. Virgin Islands. [Also available at *http://www.nationalatlas.gov/mld/aquifrp.html*.]

Vuke, S.M., Porter, K.W., Lonn, J.D., Lopez, D.A., 2007, Geologic map of Montana: Montana Bureau of Mines and Geology Geologic Map 62C, 73 p., 2 sheets, scale 1:500,000.

Wanek, Alan, 2009, Recommended decision for City of Alexander Water Permit Application No. 5990: Bismarck, North Dakota, Office of the State Engineer, North Dakota State Water Commission.

Whitehead, R.L., 1996, Ground water atlas of the United States—Segment 8, Montana, North Dakota, South Dakota, Wyoming: U.S. Geological Survey Hydrologic Atlas 730-I, 24 p. [Also available at *http://pubs.usgs.gov/ha/730i/report.pdf*.]

Appendixes

Appendix 1. Interactive Maps

The interpolated spatial distribution of horizontal hydraulic conductivity that was interpreted from resistivity logs for each of the hydrogeologic units is shown in figure 1–1, which is an interactive figure containing multiple layers that can be viewed in different combinations to aid interpretation. To turn layers on or off, select the layers icon on the left sidebar to open the Layers menu. To view one or more layers, click in the boxes next to each layer name in the menu. Some layers can be viewed simultaneously; for example, "Wells used in resistivity log analysis," "Wells used in specific capacity analysis", and "Glacial aquifer system (WB)." Opaque layers (for example "Glacial aquifer system (WB)" will cover any other activated layers that are listed below in the Layers menu. The figure explanation will show the corresponding information for any combination of visible layers. Estimated potentiometric surfaces for the upper Fort Union and lower Fort Union aquifers and the Upper Cretaceous aquifer system are shown in figure 1–2, which also has interactive layers. Although the three potentiometric surfaces can be viewed simultaneously, it may be confusing to do so.

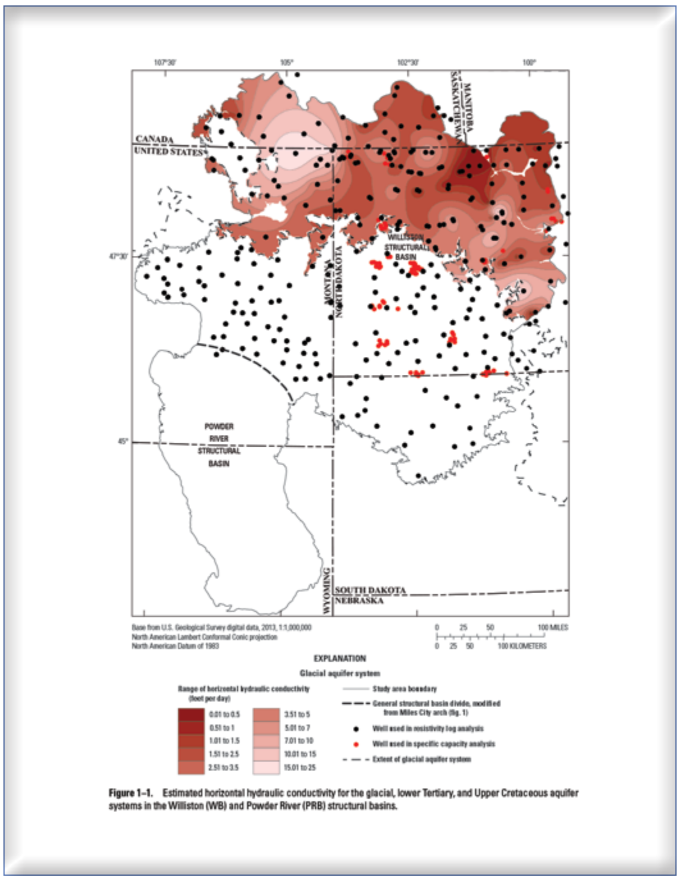


Figure 1–1. Interactive map showing estimated horizontal hydraulic conductivity for the glacial, lower Tertiary, and Upper Cretaceous aquifer systems in the Williston and Powder River structural basins. Click on the thumbnail image above to view the maps (*http://pubs.usgs.gov/sir/2014/5047/appendix/appendix_figures/figure1_1_sir2014-5047.pdf*).

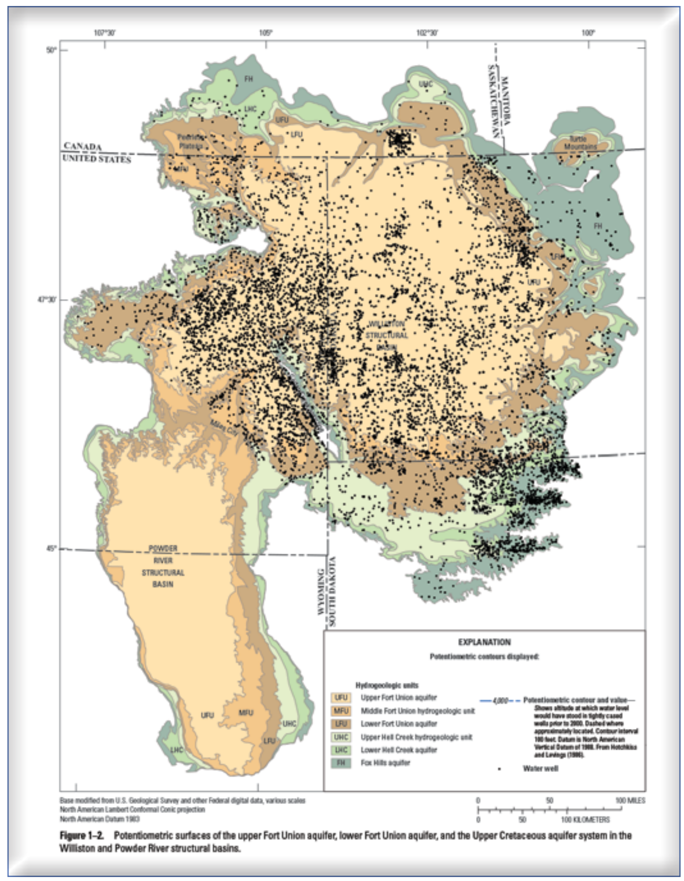


Figure 1–2. Interactive map showing potentiometric surfaces of the upper Fort Union aquifer, lower Fort Union aquifer, and the Upper Cretaceous aquifer system in the Williston and Powder River structural basins. Click on the thumbnail image above to view the maps (*http://pubs.usgs.gov/sir/2014/5047/appendix/appendix_figures/figure1_2_sir2014-5047.pdf*).

Appendix 2. Lithologic and Hydraulic Characteristics Determined from Well Logs at Selected Sites in the Williston Structural Basin

This appendix contains tables listing or summarizing lithologic and hydraulic characteristics determined from well logs at selected sites in the Williston structural basin. The tables are presented as a Microsoft Excel workbook (*http://pubs.usgs.gov/sir/2014/5047/appendix/appendix_tables/Appendix2_sir2014-5047.xlsx*), with individual worksheets for each table.

Table 2–1. Lithologic and hydraulic characteristics determined from well logs at selected sites, North Dakota.

Table 2–2. Lithologic and hydraulic characteristics determined from well logs at selected sites, Montana.

Table 2–3. Lithologic and hydraulic characteristics determined from well logs at selected sites, South Dakota.

Table 2–4. Lithologic and hydraulic characteristics determined from well logs at selected sites, Saskatchewan.

Table 2–5. Statistical summary of the interpreted horizontal hydraulic conductivity values for the hydrogeologic units of the Williston structural basin.

Table 2–6. Summary of the horizontal-to-vertical hydraulic conductivity ratings for the hydrogeologic units of the Williston structural basin.

Table 2–7. Statistical summary of the interpreted transmissivity values for the hydrogeologic units of the Williston structural basin.

Appendix 3. Hydraulic Head Data in Selected Wells for the lower Tertiary and Upper Cretaceous Aquifers in the Williston Structural Basin

This appendix contains selected data used for potentiometric surfaces for wells in the Williston structural basin. Table 3–1 is presented as a Microsoft Excel worksheet (*http://pubs.usgs.gov/sir/2014/5047/appendix/appendix_tables/Appendix3_sir2014-5047.xlsx*), and includes LSA and mean hydraulic head data for selected wells in the Williston structural basin.

Table 3–1. Hydraulic head data in selected wells for the lower Tertiary and Upper Cretaceous aquifers in the Williston structural basin.

Publishing support provided by:
Rolla Publishing Service Center

For more information concerning this publication, contact:
Director, Wyoming-Montana Water Science Center
U.S. Geological Survey
3162 Bozeman Ave
Helena, MT 59601
(406) 457-5900

Or visit the Wyoming-Montana Water Science Center Web site at:
http://wy-mt.water.usgs.gov/

USGS

Thamke and others—**Hydrogeologic Framework of the Uppermost Principal Aquifer Systems, Williston and Powder River Structural Basins**—SIR 2014–5047

ISSN 2328-0328 (online)

http://dx.doi.org/10.3133/sir20145047