Hydrogeologic Framework for the Madison and Minnelusa Aquifers in the Black Hills Area

by

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Abstract

More than 50 percent of the public drinking water systems and more than 90 percent of the population in South Dakota rely solely on groundwater. This dependence on groundwater raises important questions regarding the Madison and Minnelusa aquifers in and near the Black Hills of South Dakota, including groundwater availability, the effects of water use or drought, mixing of regional flow and local recharge, and the effects of capture zones of springs and wells on the groundwater-flow system. These questions are best addressed with a three-dimensional numerical groundwater-flow model that includes the entire Black Hills area. In preparation for such a model, a three-dimensional hydrogeologic framework was constructed for the Black Hills and surrounding area. The study area includes approximately 60,000 square miles, extending approximately 150 miles from the center of the Black Hills in all directions. Structural-contour maps, potentiometric maps, and summaries of aquifer properties presented in this report will enhance groundwater modeling of the Madison and Minnelusa aquifers on a regional scale and allow for more realistic modeling of boundary conditions on a local, site-specific scale.

Structural-contour maps and well logs quantifying the top and bottom altitudes of the Madison and Minnelusa aquifers were aggregated from numerous previous investigations to construct continuous surfaces defining the hydrogeologic framework. The primary challenge in this aggregation was that structural-contour maps from different sources frequently were inconsistent for overlapping areas, usually as a result of varying resolution in spatial data. For these inconsistencies, a systematic workflow was developed to determine which source was most accurate or reliable and would be used in the final aggregation.

Potentiometric maps delineating the hydraulic head of the Madison and Minnelusa aquifers are a result of aggregating numerous previous investigations using a method similar to the construction of the structural-contour maps, with modifications based on additional groundwater-level measurements. The data were combined to construct continuous surfaces defining the regional potentiometric surface for the Madison and Minnelusa aquifers. The Minnelusa aquifer potentiometric map is largely similar to recent publications. The Madison aquifer potentiometric map enhances understanding of a trough, or valley-shaped feature, in the potentiometric surface extending from Rapid City through Philip and eastward. This trough was previously identified by Downey in U.S. Geological Survey Professional Paper 1402-E but not shown in many other recent publications.

Aquifer properties, including hydraulic conductivity, transmissivity, and storage coefficient, also were summarized from 40 wells for which estimates were available from various types of aquifer tests. Hydraulic ranged from 2×10^{-3} ft/day to 113.62 ft/day for the Madison aquifer and from 0.36 ft/day to 24.43 ft/day for the Minnelusa aquifer. Storage coefficient values derived from pumping tests ranged from 1×10^{-7} to 2×10^{-3} for the Madison aquifer and from 7×10^{-5} to 2×10^{-3} for the Minnelusa aquifer.

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Introduction

Purpose and Scope

The purpose of this study is to create a hydrogeologic framework for future use in a regional groundwater model of the Madison and Minnelusa aquifers in the Black Hills area. Developing a regional groundwater flow model that includes the areas of numerous previous studies will have multiple benefits over a continuation of many site-specific modeling efforts. First, developing a single regional groundwater-flow model is more cost effective than developing several smaller models. Second, a regional groundwater model will provide better simulation of boundary conditions for site-specific models. Third, artesian springs, critical water sources common in the Black Hills, which capture groundwater from regional areas, will be better represented with a regional groundwater model. A regional groundwater model will provide a regional perspective on the following questions: (1) What is the influence of the regional aquifers on local groundwater flow? (2) What is the aquifer sensitivity in different areas to pumping and drought? (3) How might future data collection efforts be planned most effectively?

During this work, a hydrogeologic framework was constructed by aggregating data from previous studies of the Madison and Minnelusa aquifers. The scope of this work was on a regional scale including and surrounding the Black Hills of South Dakota and Wyoming. Focus was placed on previous studies in the immediate Black Hills area, but publications regarding the surrounding region were included. The hydrogeologic framework included delineation of elevations of aquifer tops and bottoms, creation of potentiometric surfaces, and summaries of available estimates for aquifer properties. It was outside the scope of the study to perform a detailed review of previous publications and their source data (e.g., evaluating specific well logs used in a previous publication to delineate the top of an aquifer). However, previous publications were evaluated relative to the apparent abundance and quality of source data (e.g., resolution of control points) in their respective study areas.

The products of this work are digital rasters defining aquifer tops, potentiometric surfaces, and a digital database summarizing existing estimates for aquifer properties. The results of this work should be considered preliminary and will be subject to U.S. Geological survey review before they are prospectively published in a Scientific Investigations Report.

Previous Investigations

Developing a numerical groundwater-flow model requires collecting and analyzing data, constructing surfaces for aquifer tops, bottoms, and potentiometric surfaces, and developing estimates for aquifer properties. As a result of various previous investigations in the Black Hills area, many of the basic data components necessary for developing a hydrogeologic framework for a numerical groundwater model already exist.

The Black Hills Hydrology Study, summarized by Carter and others (2002; 2003) and Driscoll and others (2002), included numerous investigations that described general hydrologic conditions in the Black Hills area. Other previous investigations with detailed information for focused areas of study in the northern, southern, and eastern Black Hills include Greene and others (1998), a groundwater flow model for Madison and Minnelusa aquifers in the Spearfish, South Dakota area, Long and Putnam (2002), a conceptual model for the Madison and Minnelusa aquifers in the Rapid City, South Dakota area, Putnam and Long (2007a; 2007b; 2009), dye test results for the Rapid City and Spearfish, South Dakota areas and a numerical groundwater model for the Rapid City, South Dakota area, and Long and others (2008; 2012), conceptual models using environmental tracers and mixing to describe hydrogeologic processes in the eastern and southern Black Hills. Regional data beyond the Black Hills are also available from Konikow (1976), a regional groundwater model of the Madison aquifer, and Downey (1986), part of a Regional Aquifer-System Analysis by the U.S. Geological survey.

The Regional Aquifer-System Analysis, initiated in 1978 and completed in 1995, defined regional hydrogeology and established a regional framework of background information for many of the principal aquifers of the United States. However, this regional information is of very coarse resolution and there have been many recent localized studies contributing more detailed information on the hydrogeology specific to the Madison and Minnelusa aquifers in and around the Black Hills area.

Geologic maps and cross sections for the Black Hills area are available from Strobel and others (1999), Redden and DeWitt (2008), and Love and Christiansen (1985). Many previous studies were used in delineating the structure tops of the Madison and Minnelusa aquifers in various areas in and around the Black Hills area, creating potentiometric surfaces for the Madison and Minnelusa aquifer, and in summarizing existing estimates for aquifer properties. These sources are summarized in sections of this report dedicated to the individual components of the hydrogeological framework.

Several groundwater-flow models exist for the Madison and/or Minnelusa aquifers that include the study area for this report (Figure 1). Regional models include Downey (1986) and Konikow (1976). These regional models were of coarse resolution, with Downey (1986) representing the entire Black Hills region in just a few grid cells.

Konikow (1976) improved on Downey's (1986) regional model but still represented the outcrop of the Madison aquifer in the Black Hills area with only 23 cells. As hydrologic information has become more readily accessible and computing power allowed for finer-gridded models, groundwater-flow models have been able to represent the Madison and Minnelusa aquifers at a finer resolution. The Madison and Minnelusa aquifers have been modeled by Greene and others (1998) in the northern Black Hills in the vicinity of Spearfish, South Dakota, and by Putnam and Long (2009) in the Rapid City, South Dakota, area.

Description of Study Area

Study Area

The study area is centered around the Black Hills of western South Dakota and eastern Wyoming, and extends west-east from approximately 50 miles west of Gillette, Wyoming, to 20 miles east of Philip, South Dakota. The study area extends north-south from the North Dakota border to about 10 miles south of Lusk, Wyoming. The Hartville and Laramie uplifts and a series of steep faults (Love and Christiansen, 1985) form an irregular boundary in the southeastern part of the study area. In parts of this irregular boundary, the Paleozoic rocks dip as steeply as 10,000 feet vertically over just a few miles in distance. In all, the study area includes approximately 60,000 square miles.

Regional Geology

The Black Hills uplift (Figure 2) is a domal structure situated east of the Powder River Basin and south southwest of the Williston Basin, originating approximately 60 to 65 million years ago during the Laramide orogeny (Darton and Paige, 1925). At the center of the Black Hills, Precambrian rocks of varying metamorphic and igneous origin

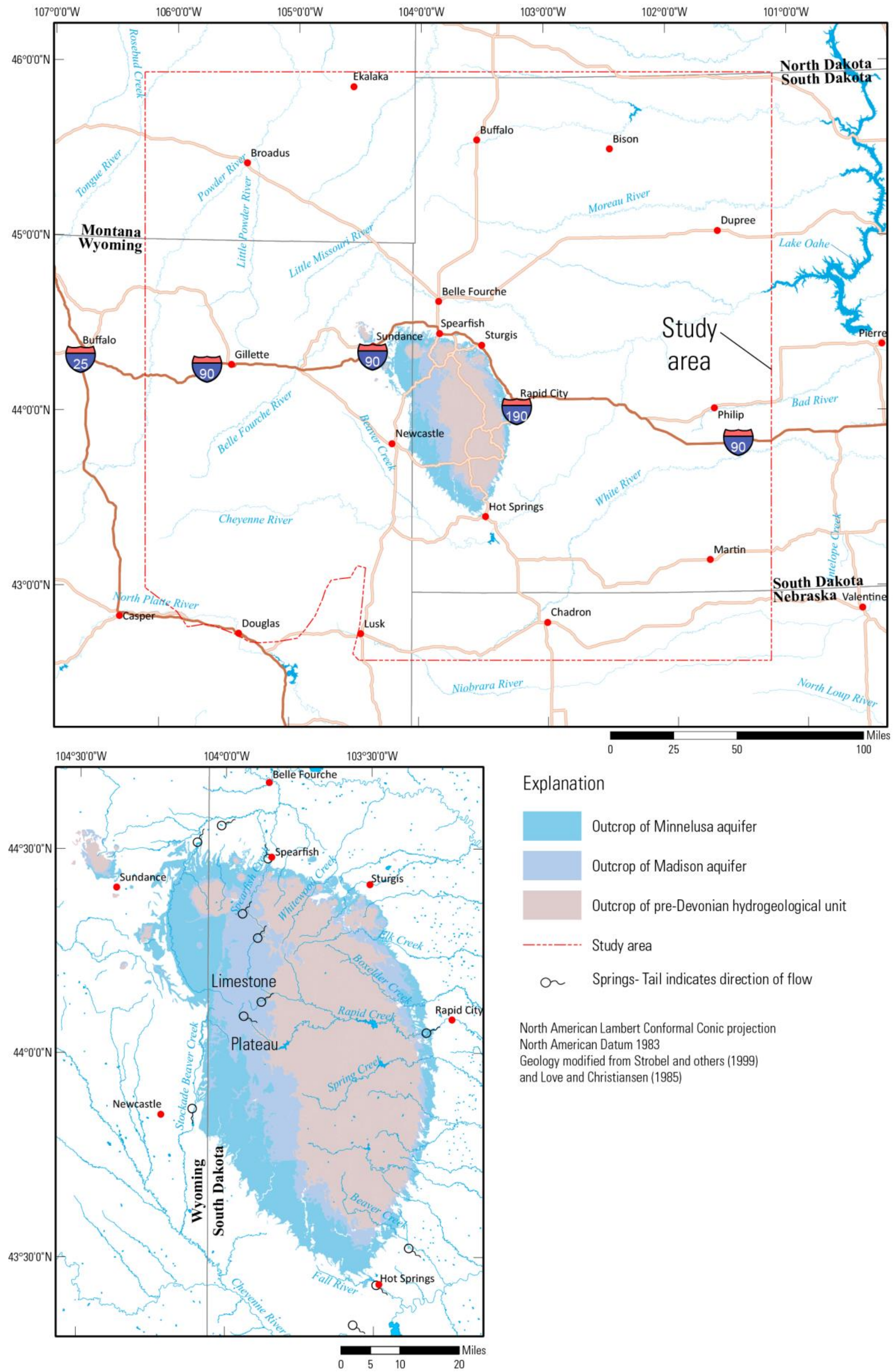

Figure 1. Delineation of study area and generalized geology.

are exposed. Geologic units overlying Precambrian rocks are exposed in a radial fashion around the Black Hills uplift and dip outward from the Precambrian core of the Black Hills. The western flank of the Black Hills dips steeply into the Powder River Basin just west of the lower Cretaceous principal aquifer (Figure 2). The Powder River Basin has a Precambrian basement elevation of approximately 11,000 feet below sea level. At Harney Peak, the highest point in the Black Hills, the Precambrian rocks reach 7,242 feet above sea level.

Several North American principal aquifers, as delineated by Miller (2000), are exposed in the study area (Figure 2). The Black Hills regional groundwater-flow model will simulate flow in the Madison and Minnelusa aquifers of Paleozoic age (Figure 2; Figure 3). These aquifers are of primary importance in the immediate vicinity of the Black Hills, where drilling depth and water quality are not limiting factors when considering a new well. Farther from the Black Hills, other primary aquifers (Figure 2) are shallower and more readily targeted for water wells. The Madison aquifer has been considered for large groundwater withdrawals in areas near the Black Hills for various industrial uses such as the ETSI coal slurry pipeline just north of Lusk, Wyoming, near where the Wyoming, Nebraska, and south Dakota state boundaries meet (Rahn, 1979).

Hydrogeology

The hydrogeologic units studied in this report are Precambrian through Paleozoic in age. The aquifers of focus are Paleozoic sedimentary rocks and are composed of mostly shallow-water marine carbonate, clastic, and evaporite deposits of Upper Devonion through early Permian age (Peterson, 1984). The three hydrogeologic units that will compose this study are the Minnelusa, the Madison, and the pre-Devonian hydrogeologic units, following the example of Putnam and Long (2009) and Long and Putnam (2002) (Figure 3).

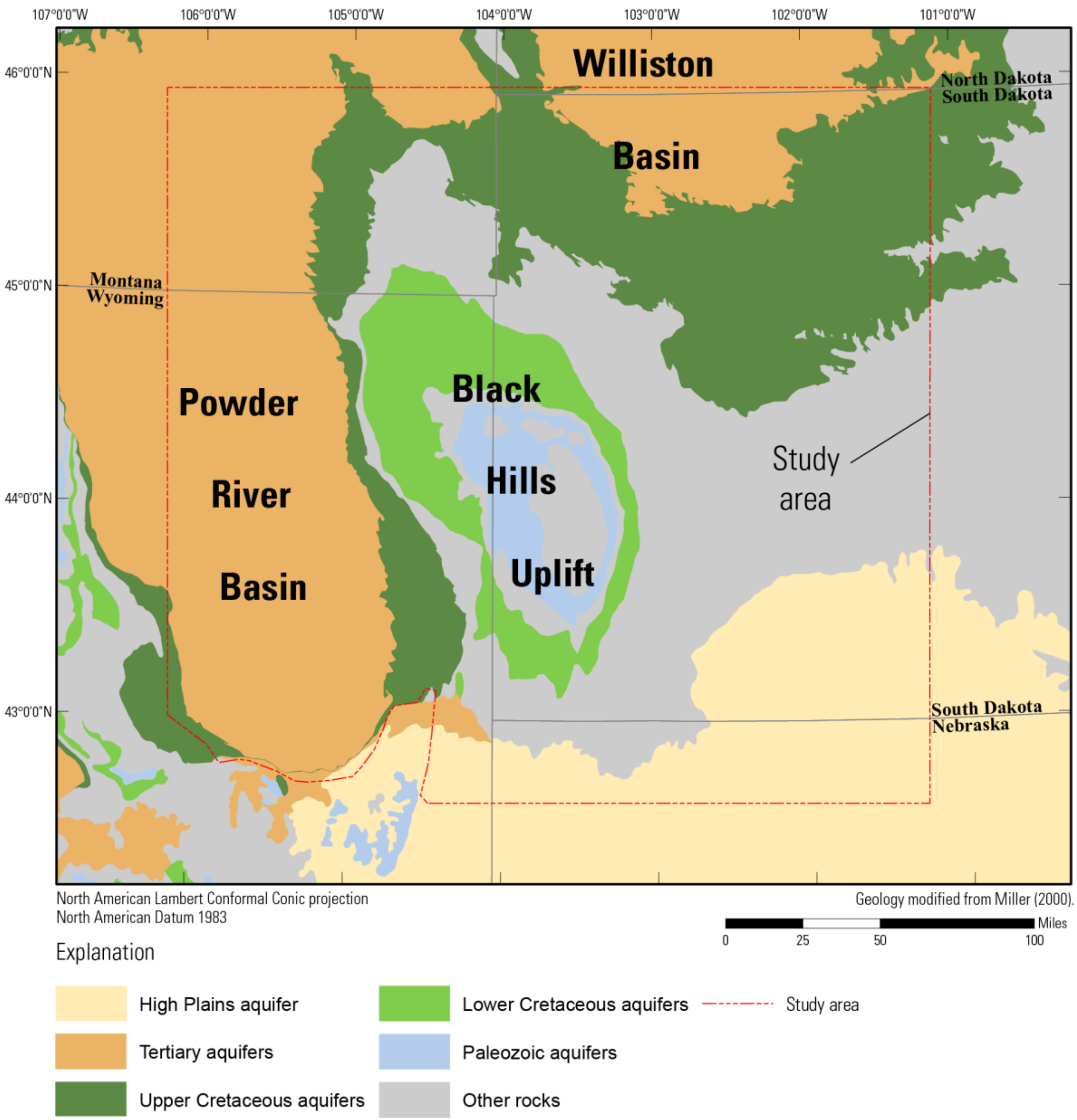

Figure 2. Distribution of North American principal aquifers in relation to the study area.

Erathem	System	Symbol	Stratigraphic unit	Description	Hydrogeologic Unit
Paleozoic	Permian	PIPm	Minnelusa Formation	Yellow to red cross-bedded sandstone, limestone, and anhydrite locally at top. Interbedded sandstone, limetone, dolomite, shale, and anhydrite in middle sections. Red shale with interbedded limestone and standstone at base.	Minnelusa
	Pennsylvanian				
	Mississippian	MDme	Madison (Pahasapa) Limestone	Massive light-colored limestone. Dolomite in part. Cavernous in upper part.	Madison
	Devonian		Englewood Formation	Pink to tan limestone. Shale locally at base.	
	Ordivician	Ou	Whitewood (Red River) Formation	Tan dolomite and limestone	pre-Devonian
			Winnepeg Formation	Green shale with siltstone	
	Cambrian	O€d	Deadwood formation	Massive to thin-bedded sandstone, glauconitic shale, dolomite, and limesone conglomerate.	
Precambrian		p€u	Undifferentiated metamorphic and igneous rocks	Schist, slate, quartzite, and arkosic grit. Intruded by diorite, metamorphosed to amphibolite, and by granite and pegmatite.	

Modified from Driscoll and others, 2002

Figure 3. Generalized hydrostratigraphic correlation chart of study area.

Minnelusa Aquifer

In the study area, the Pennsylvanian and Permian Minnelusa aquifer consists of sandstone, shale, carbonate, and some interbedded anhydrite (Downey, 1984). Putnam and Long (2009) considered the Minnelusa as two parts for modeling purposes. The upper 200 to 300 feet of the Minnelusa aquifer, composed of thick sandstone and thin limestone, dolomite, and mudstone, is more permeable because of the coarse sands, solution openings, and breccia pipes. This upper section has been assigned an age of lower Permian, based on correlations with the Hartville Formation south and west of the Black Hills (Robinson and others, 1964). The lower section of the Minnelusa aquifer, as designated by Long and Putnam (2002), is composed of shale, limestone, and dolomite, is less permeable and, on a regional scale, restricts flow between the Minnelusa aquifer and the underlying Madison aquifer (Kyllonen and Peter, 1987; Greene, 1993). Where the

Minnelusa aquifer is exposed at the surface, the formation tends to locally have greater permeability because of weathering (Long and Putnam, 2002). At the base of the Minnelusa is a discontinuous layer of red clay varying from 0 to 50 feet in thickness (Long and Putnam, 2002). This red clay layer is a paleosol that developed on the surface of the ancient karst topography of the Madison Limestone (Gries, 1996).

It is not certain whether the “upper and lower” division made in the Black Hills area by Long and Putnam (2002) can be extrapolated to other parts of the study area (e.g., the Wyoming area in the Powder River Basin), but similarities in change in hydraulic head over time indicate that it could be an appropriate assumption (Bartos and others, 2002).

The Minnelusa Formation is composed mostly of sandstone facies immediately surrounding most of the Black Hills, but in the southeastern Black Hills area it was described by Downey (1984) as primarily red shale with silt, some carbonate rock, gray shale, and evaporite (Downey, 1984). The source of the larger sandstone units in the Minnelusa aquifer was interpreted by Downey (1984) to be reworked sands deposited earlier and derived from paleostructures to the west.

The Minnelusa aquifer generally decreases in thickness to the north (Downey, 1984). In the Black Hills area, the Minnelusa decreases in thickness by 400 feet from the southern to northern Black Hills. The difference in thickness between these two areas is likely to be caused by the dissolution of as much as 80 percent gypsum and anhydrite from Minnelusa surface exposures (Redden and DeWitt, 2008). Dissolution is shown by pockets of breccias on the surface exposures of the Minnelusa aquifer. The dissolution of gypsum in the aquifer is also apparent on a more regional scale, causing the Minnelusa to be thinner nearer to surface outcrops than in areas of the deeper subsurface (Redden and DeWitt, 2008). This pattern of changes in thickness extends around the Black Hills and is referred to as a “dissolution front” (Bowles and Braddock, 1963). The dissolution of this gypsum started in the Tertiary period and is still continuing today, as demonstrated by periodic discharges of water mixed with gypsum and other constituents of the Minnelusa aquifer at springs such as Cascade Springs near Hot Springs, South Dakota (Hayes, 1999). The dissolution of gypsum is also shown by numerous sinkholes in units directly overlying the Minnelusa Formation. In the northeastern Black Hills, these gypsum beds are almost absent (Redden and DeWitt, 2008). The absence of gypsum beds in the northern Black Hills and the evidence of active dissolution of gypsum in the southern Black Hills likely indicates that the “dissolution front” is closer to surface exposures of the Minnelusa in the southern Black Hills than in the northern Black Hills.

In areas surrounding the Black Hills, the Minnelusa aquifer is defined as units equivalent to the Minnelusa Formation, including the Hartville Group, the Amsden Formation, and the Tensleep Sandstone where present in the study area (Schoon, 1979; Downey, 1984).

The Minnelusa aquifer is overlain by the Opeche Shale (Long and Putnam, 2002) in the vicinity of the Black Hills and by other Permian age shales in the rest of the study area of sufficient thickness to act as a confining bed (Long and Putnam, 2002).

The Minnelusa Formation is used as an aquifer by many residents in the Black Hills area. In terms of how productive the Minnelusa Formation is as an aquifer, in the Rapid City area of the eastern Black Hills, Long and Putnam (2002) determined that wells completed in the Minnelusa aquifer in their study area are typically able to produce

5 to 700 gallons per minute (gal/min). Of these, 66 percent produce 5 to 50 gal/min, 28 percent produce 50 to 200 gal/min, and only 6 percent produce 200 to 700 gal/min (Long and Putnam, 2002). The depths of wells range from 80 to 3000 feet in depth; 90 percent of those wells are shallower than 1000 feet depth, and 60 percent are less than 500 feet in depth (Long and Putnam, 2002). These percentages were determined from the model area of Putnam and Long (2009) in the Rapid City area.

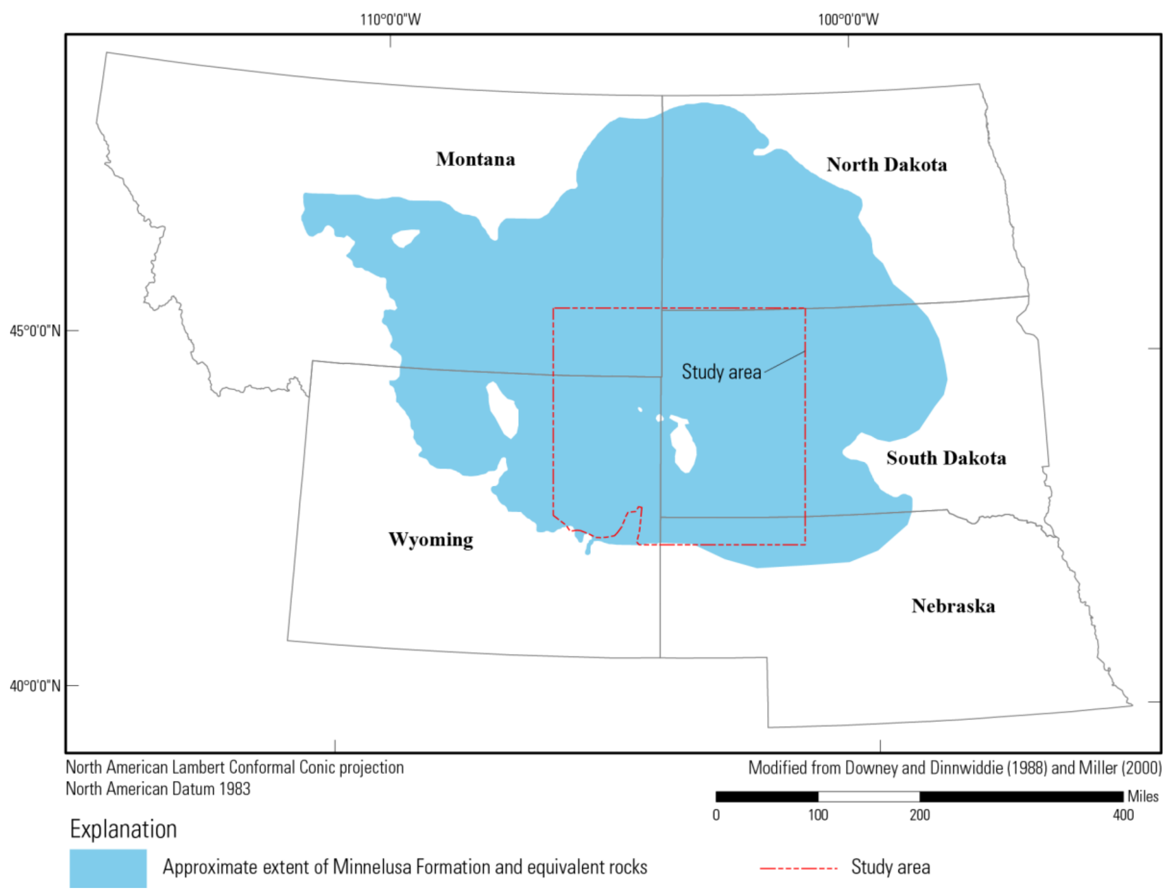

Figure 4. Approximate areal extent of Minnelusa formation and equivalent rocks.

Madison Aquifer

In the study area, the Madison aquifer consists of the Mississippian Madison Limestone and the Lower Mississippian-Devonian Englewood Formation. Although formal geologic nomenclature for the Madison Limestone in the immediate Black Hills area is the “Pahasapa Limestone” (Redden and DeWitt, 2008), the formation is equivalent to the regional Madison Limestone. The Madison Limestone is a massive grey limestone, generally dolomitic, ranging in thickness from about 250 feet to more than 1200 feet in thickness (Peale and Merrill, 1893; Darton, 1901). The outcrop of the Madison Limestone on the western flank of the Black Hills is one of the highest erosional features in the Black Hills. Although the Precambrian rocks at Harney Peak show the officially highest elevation in the Black Hills, the Limestone Plateau of the western flank of the Black Hills (Figure 1) composes most of the high-elevation land of continuous area in the Black Hills. Although the Madison Limestone composing the Limestone Plateau as a geologic formation is flat-lying or dips slightly westward, the potentiometric surface generally locally slopes eastward, allowing for emergent springs that are the headwaters for Rapid Creek, which flow easterly across the Black Hills (Figure 1). Spearfish Creek has the largest watershed within the Limestone Plateau (Figure 1) and is mostly fed by groundwater (Driscoll and Carter, 2001), which likely emerges as springflow from the base of the Madison aquifer at either side of the stream.

The Englewood Formation, included in the Madison hydrogeologic unit, underlies the Madison Limestone and is of lower Mississippian and upper Devonian age (Downey, 1984). The Englewood Formation is composed of argillaceous, dolomitic limestone. It was considered by Strobel and others (1999) as a single hydrogeologic unit with the Madison Limestone and could even be considered a “member” of the Madison Limestone because of its lithology (Long and Putnam, 2002), but not because of its hydrogeologic characteristics. The Englewood Formation acts as a confining layer for the Madison aquifer; several springs in the Black Hills emerge at the contact between the Madison aquifer and the underlying Englewood Formation.

The Madison Limestone is a sequence of carbonates and evaporates deposited in environments ranging from warm, shallow-water to deep-water facies (Downey, 1984). These facies vary both laterally and vertically (Downey, 1984). Coinciding with important paleostructure trends, the Madison Limestone is thickest in the central part of the Williston Basin and the deepest parts of the Powder River Basin (Peterson, 1984).

Sando and Dutro (1974) described ancient features in the Madison Limestone (e.g., enlarged joints, sinkholes, caves, and solution breccias) in north-central Wyoming and noted that many of these open surfaces are filled by sand and residual products of a transgressive sea of late Mississippian age (Downey, 1984). The carbonate rocks in the Madison Limestone are soluble in water, so dissolution of these rocks is common (Downey, 1984). Numerous, extensive cave networks in and near outcrop areas of the Madison Limestone near the Black Hills (e.g., Wind Cave and Jewel Cave) are evidence of this dissolution process leading to the development of secondary porosity zones in the Madison Limestone (Downey, 1984). The solution cavities at the surface also could exist elsewhere in the subsurface, explaining many anecdotal accounts of encountering zones of lost circulation while drilling for oil in deeper parts of the Williston Basin (Schoon, 1979). In April, 2013, a company attempting to drill to Precambrian rocks in Wasta, South Dakota asked to temporarily abandon a well due to an extended period of lost circulation in the Madison Limestone (Derric Iles, personal communication, 2013). Because of these extensive solution enlargements, resulting in primary flow resembling conduit flow, the Madison Limestone can be considered karstic (Long and Putnam, 2002).

The Madison Limestone has been subdivided into four geomorphic sub-units, based on cliff-forming characteristics (Miller, 2005). In the Black Hills area, these geomorphic sub-units described by Miller (2005) were designated as 1, 2, 3, and 4 (from lowest to highest) and range in thickness from 130 to 165 feet, 81 to 120 feet, 140 to 150 feet, and 0 to 85 feet respectively. The upper units, 3 and 4, are the most permeable because of the numerous breccias, caverns, and other karst features (Putnam and Long, 2009). Although the upper units have many solution openings, these features are less common in the contact zones between the geomorphic units (Miller, 2005) and generally decrease in frequency of occurrence in the stratigraphically lower parts of the formation (Greene, 1993). However, the lower parts of the Madison Limestone, geomorphic zub-units 1 and 2, are known to have zones of high secondary porosity in and near outcrop areas. Generally, the zone of relatively greater secondary permeability in the upper Madison Limestone ranges in thickness from 100 to 200 feet in the Black Hills area (Long and Putnam, 2002).

Surface exposures of the Madison aquifer have many depressions filled with reddish-brown sandstone and silt, marking the karst topography between the Madison Limestone and the Minnelusa Formation (Redden and DeWitt, 2008). This contact is considered to be an unconformity and can form as much as 180 feet of topography between the two units, as seen in Pringle, South Dakota (Redden and DeWitt, 2008).

The Madison Limestone is a source of petroleum in the northern Great Plains (Downey, 1984). During the 1960s, it was estimated that more than 90 percent of petroleum production in North Dakota was from the Madison Limestone (Downey, 1984).

In the Black Hills area, the Madison Limestone is considered as one geologic unit, but in Wyoming, Montana, and North Dakota, it is considered as the Madison Group (Schoon, 1979). The Madison Group consists of the Lodgepole Limestone, Mission Canyon Limestone, and Charles Formation (Downey, 1984). Rocks Miller's (2005) geomorphic sub-units of the Madison Limestone may be loosely correlated with the units of the Madison Group.

The Madison Limestone is overlain directly by the Big Snowy Group in far northwestern South Dakota, ranging in thickness from 0 to 50 feet. Elsewhere in the study area, the Madison Limestone is overlain directly by the Minnelusa formation.

The Madison Limestone is confined from below by the Englewood Limestone, Whitewood Formation, Deadwood Formation, and Precambrian rocks. Fracture interconnection between zones of greater permeability appears to be the major route of water flow in the Cambrian-Ordovician and Madison aquifers (from Downey, 1984).

In the Black Hills area, the Madison Limestone is used as an aquifer by many residents. Wells completed in the Madison Limestone typically have higher yields than other aquifers in the area and the potentiometric head is typically artesian or flowing-artesian in many areas, making the Madison Limestone a desirable target for water wells. In terms of the productivity of the Madison Limestone as an aquifer, in the Black Hills area, Long and Putnam (2002) determined that wells completed in the Madison aquifer in their study area are typically able to produce 5 to 2,500 gal/min. Of these, 64 percent produce 5 to 50 gal/min, 11 percent produce 50 to 200 gal/min, and 25 percent produce

200 to 500 gal/min (Long and Putnam, 2002). The wells range from 20 to 4,600 feet in depth; 78 percent of these are shallower than 1,000 feet in depth, and 41 percent are less than 50 feet in depth (Long and Putnam, 2002).

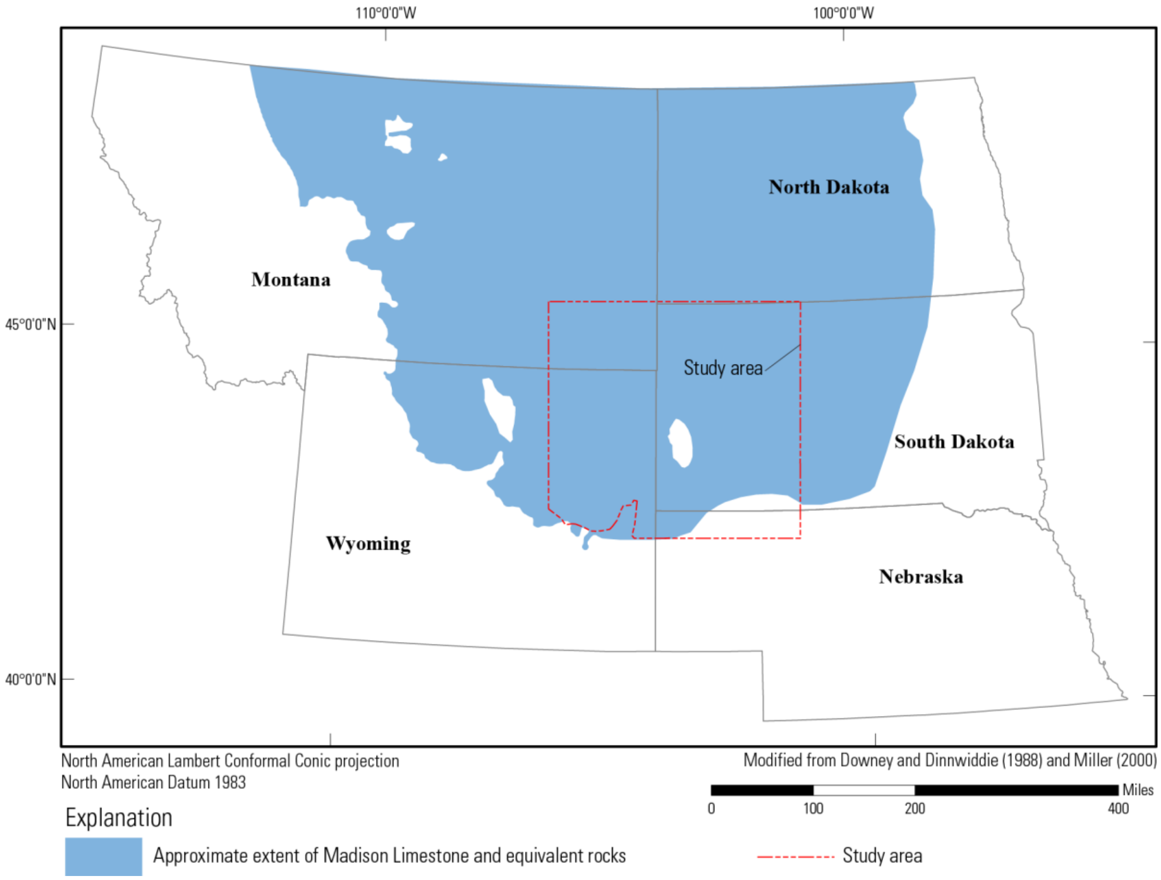

Figure 5. Approximate areal extent of Madison Limestone and equivalent rocks

Pre-Devonian Hydrogeologic Unit

The pre-Devonian hydrogeologic unit consists of various formations but mainly includes shaly carbonates, shale, and evaporates of Ordovician and Cambrian age representing shoreward facies of a transgressive sea. Precambrian rocks and Tertiary intrusions also are included in the pre-Devonian hydrogeologic unit. Geologic formations in the Black Hills area included in the pre-Devonian hydrogeologic unit from youngest to oldest are the Whitewood (Red River) Formation, the Winnipeg Formation, and the

Deadwood Formation. Hydrogeologically equivalent geologic formations in other parts of the study area include the Stony Mountain Formation, Bighorn Dolomite, Flathead Sandstone, and Emerson Formation. These formations are considered aquifers locally, where drilling depth or water quality does not prevent their use (Downey, 1984; Driscoll and others, 2002).

The Winnipeg Formation, stratigraphically equivalent to the Saint Peter Sandstone in the midwestern United States (Downey, 1984), is composed mostly of green shale and siltstone and ranges from 0 to 60 feet thick in the Black Hills area. The Whitewood Formation, often referred to as the Whitewood Dolomite or the Red River Formation, is a carbonate sequence composed of a pink to tan limestone and ranges from 0 to 60 feet in thickness in the Black Hills area (Downey, 1984). Both the Winnipeg and the Whitewood formations increase in thickness to the north. These formations have been eroded to a "feather edge" in the central Black Hills area trending east-northeast through Pactola Reservoir (Redden and DeWitt, 2008). Several meters of thickness of the Winnipeg Formation probably exist farther south but are largely concealed (Redden and DeWitt, 2008). The Whitewood Formation continues south of the line trending through Pactola Reservoir to just south of Little Elk Creek, but only discontinuously (Redden and DeWitt, 2008). In some areas of discontinuity, in place of the Whitewood Formation there exists a few meters of "very well rounded unfossiliferous sandstone" usually included in the Deadwood Formation. This sandstone indicates a possible break in erosion during the Silurian time period (Redden and DeWitt, 2008).

The Ordovician-age Winnipeg and Whitewood formations are major petroleum reservoirs in the Williston Basin, where they increase to a maximum thickness of approximately 1400 feet in the deepest parts of the basin (Redden and DeWitt, 2008).

In most of South Dakota, North Dakota, and eastern Wyoming, the Deadwood Formation is predominantly sandstone (Peterson, 1984). In the Black Hills, the Deadwood formation is primarily sandstone with layers of glauconitic shale, dolomite, with a sandstone conglomerate locally at the base (Driscoll and others, 2002). The Deadwood Formation ranges in thickness from 0 to 500 feet (Carter and others, 2002) and thins southward in the Black Hills area.

Precambrian rocks form the basement of the northern Great Plains and are included in the pre-Devonian hydrogeologic unit. The ages of Precambrian rocks in northwestern Wyoming and western South Dakota range from approximately 1,750 million years (m.y.) old to about 2,700 m.y. old. In most of the study area the Precambrian rocks are directly overlain by upper Cambrian rocks, except in the central Black Hills, where the Precambrian rocks form an "erosional high". In some areas, it is not certain whether the thinner areas of the upper Cambrian (e.g., Deadwood formation) are due to "depositional draping" over Cambrian structural highs or are buried hills on the Precambrian surface (Peterson, 1984; Redden and DeWitt, 2008). Intrusive bodies (e.g., Tertiary intrusions) are also included in the pre-Devonian hydrogeologic unit because of their low permeability.

Hydrogeologic Framework

Three hydrogeologic units were established to simplify the groundwater-flow model (Figure 3): the Minnelusa aquifer, the Madison aquifer, and the pre-Devonian hydrogeologic unit. After these hydrogeologic units were established, data pertaining to structural contours, potentiometric surfaces, and aquifer properties were assimilated from various sources, including existing structural contour maps, potentiometric maps, existing borehole logs, digital elevation data, and existing aquifer-test data. For assimilation of data, an iterative workflow (Figure 6) was established with these main steps: (1) gather and use the most reliable and consistent data, using ArcMap's "Topo to Raster" tool to aggregate and interpolate data, (2) check surfaces for consistency, re-evaluate the input data used, and correct the surface to match surface elevations at geologic contacts, and (3) prepare the data in a format convenient for data input for MODFLOW (Harbaugh, 2005).

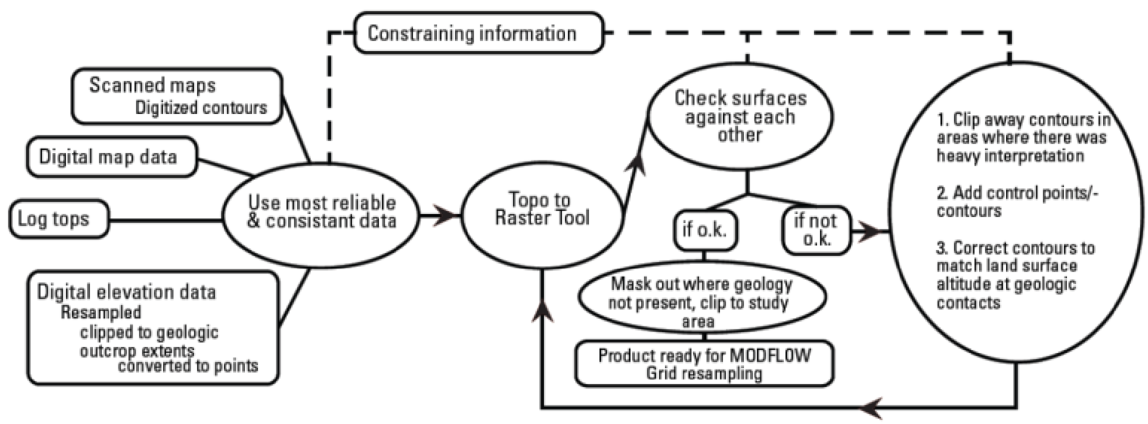

Figure 6. Iterative workflow for collection, interpretation, and interpolation of data for the creation of structural contour maps.

Altitudes of the Tops and Bottoms of Hydrogeologic Units

Structural-contour maps and well logs quantifying the top and bottom altitudes of the Madison and Minnelusa aquifers were aggregated from numerous previous investigations to construct continuous surfaces defining the hydrogeologic framework. The primary challenge in this aggregation was that structural-contour maps from different sources frequently were inconsistent for overlapping areas, usually because of varying resolution in spatial data. To determine which maps (or parts of maps) to use, several factors were considered. Generally, the most recent contour maps were considered first. If the most recent source map had good control, meaning that there were many data points to define a surface, then that map was used. If an older map had much better control for certain areas, data from those areas with better control were used instead. Contour data from different sources were edge matched by using the “Topo to Raster” tool in ArcGIS (ESRI, 2013). Occasionally, problems arose where contours from different sources did not edge-match perfectly. In these situations, the contour data were clipped back to leave a gap between contours from different sources, and the contour data with better control were given preference. The “Topo to Raster” tool was better able to interpolate between contour data after this process.

Resulting contours for the tops of the aquifers are shown with 500 ft contour intervals. Because some authors of the source data did not dash contours where approximated, and the source data were all completed at different resolutions, the resulting contours shown in this report are not dashed. The publication of the source data should be referenced if there is question about accuracy in a certain area.

Minnelusa Aquifer

The altitude of the Minnelusa aquifer was interpreted by using five steps to combine source data (Figure 7) in order to develop a continuous structural surface (Figure 8). First, existing maps (Gries, 1981b; Peter and others, 1987; Peter and others, 1988; Crysdale, 1990; Carter and Redden, 2000b; and Bartos and others, 2002) in areas “b, c, d, e, f, and g” of Figure 7 were trimmed to edge match where they had good control for the top of the Minnelusa aquifer. Second, borehole data in area “h” of Figure 7 for the top of Minnelusa aquifer or Big Snowy unit (North Dakota Oil and Gas Division, 2011) were analyzed with geostatistics in ArcGIS (ESRI, 2013) to remove potentially spurious data points and then included as data. Third, missing data were filled. Areas labeled “a” in Figure 7 were filled by taking an existing map for the top of the Madison aquifer (Swenson, 1976) and adding the thickness of the Minnelusa aquifer (Downey, 1984). In some areas where the surface appeared to be relatively smooth, blank areas were left open for interpolation between contours. In some areas hand control points had to be added to assist in interpolation. Fourth, a 30-meter resolution digital elevation model (DEM) from the National Elevation Dataset (Gesch and others, 2002) was resampled to

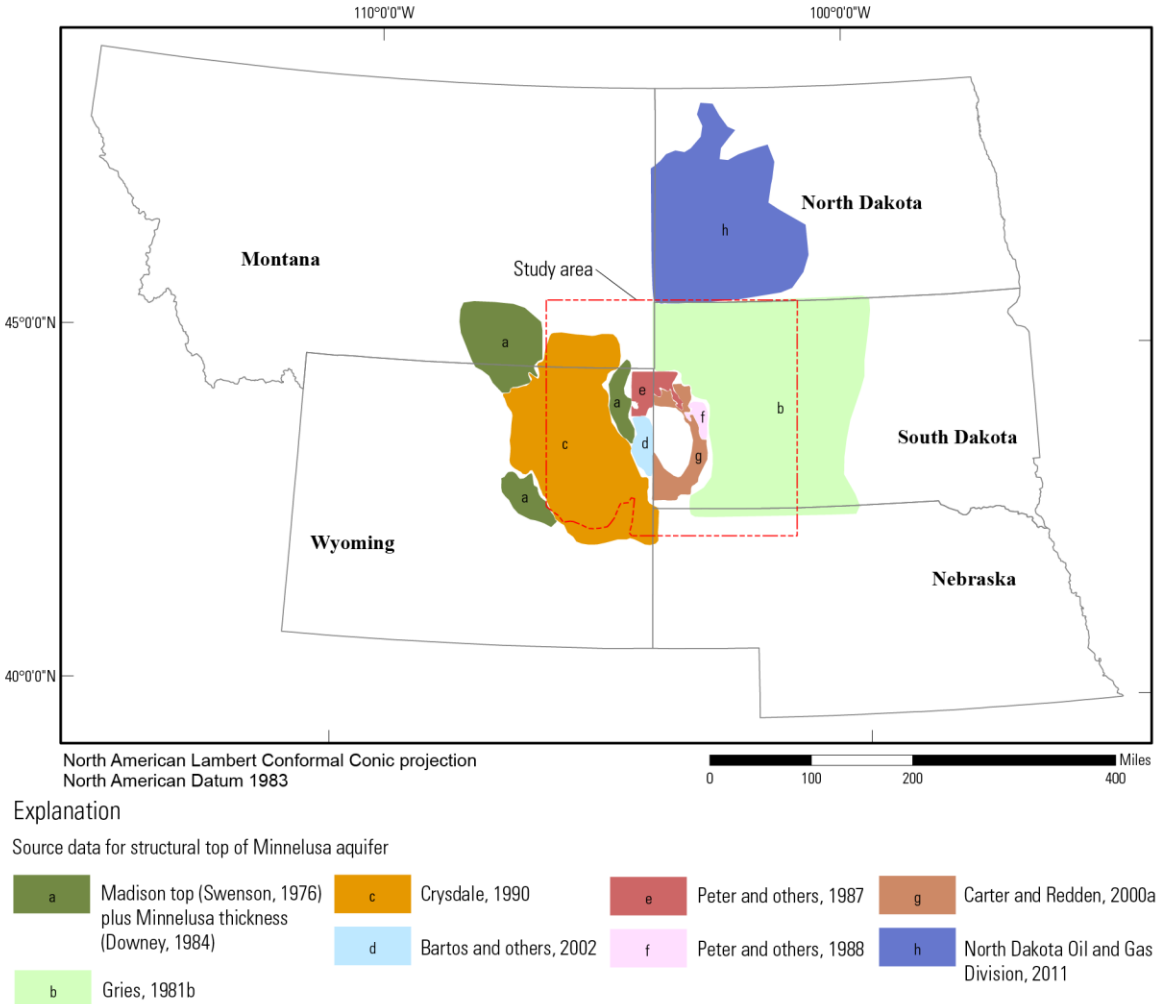

Figure 7. Source data for delineation of the altitude of the top of the Minnelusa aquifer.

100-meter resolution, clipped to outcrop areas of the Minnelusa aquifer, and converted to points for use in aquifer top delineation (not shown in Figure 7). Fifth, the resulting raster for the Minnelusa aquifer was evaluated and corrected at geologic contacts on the down-dip side of Minnelusa outcrops to ensure that the Minnelusa was not erroneously modeled as above the actual land surface in these areas.

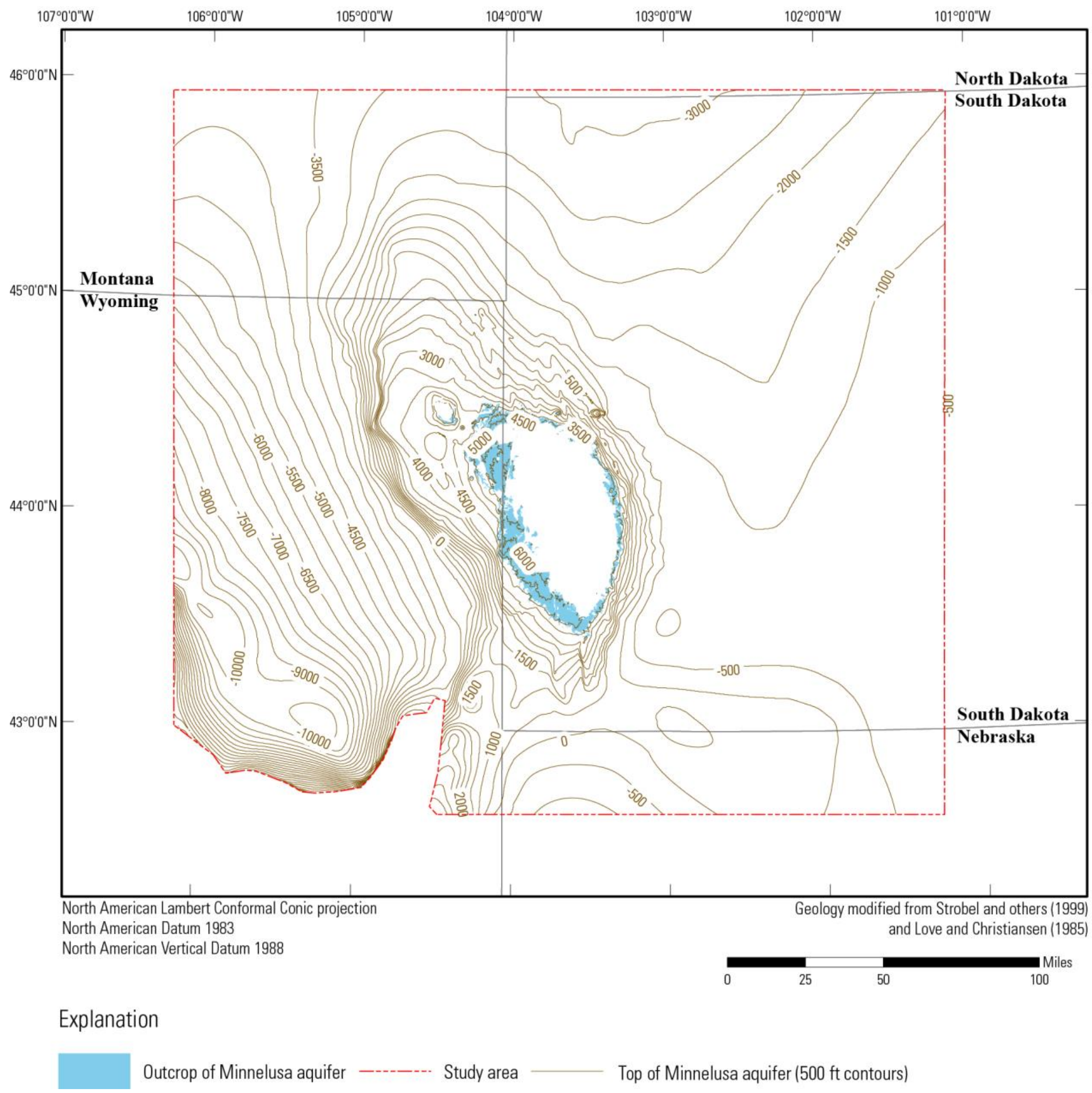

Figure 8. Altitude of the top of the Minnelusa aquifer.

Altitudes of the top of the Minnelusa aquifer range from 10,000 feet below sea level in the southern Powder River Basin to approximately 6,000 feet above sea level in the western Black Hills. The altitude of the top of the Minnelusa aquifer drops to approximately 3,000 feet below sea levelat the North Dakota-South Dakota border, dipping farther northward into the Williston Basin. In the focus area of the study, the dip of the Minnelusa aquifer is steepest in the eastern Black Hills dropping approximately

4,000 feet in altitude in less than 20 miles before it levels off just east of Rapid City, South Dakota.

Madison Aquifer

The altitude of the Madison aquifer was interpreted by using six steps to combine source data in various areas (Figure 9), in order to develop a continuous structural surface (Figure 10). First, existing maps (Swenson, 1976; Gries, 1981a; Bergantino and Feltis, 1985; Carter and Redden, 1999b; Bartos and others, 2002) in areas “a, c, e, f, and g” in Figure 9 were trimmed to edge match where there was good control for the Madison

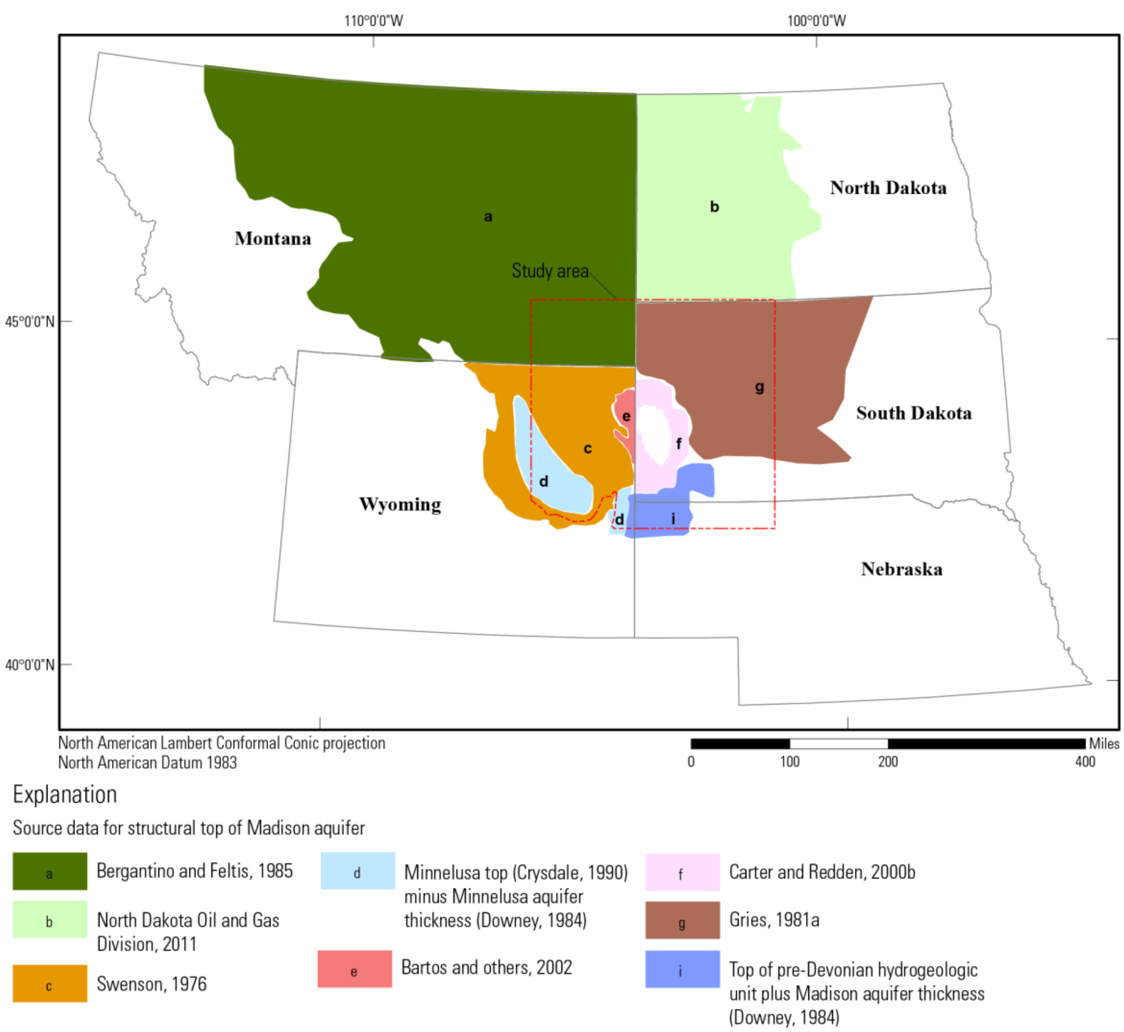

Figure 9. Source data for delineation of the altitude of the top of the Madison aquifer.

aquifer surface. Second, borehole data in area “b” of Figure 9 for the top of the Madison aquifer (North Dakota Oil and Gas Division, 2011) were analyzed with geostatistics in ArcGIS (ESRI, 2013) to remove potentially spurious data points and then included as data. Third, missing data in areas labeled “d” in Figure 9 were filled by taking an existing map for the top of the Minnelusa aquifer (Crysdale, 1990) and subtracting the thickness of the Minnelusa aquifer (Downey, 1984). Fourth, in area “i” of Figure 9 the thickness of the Madison aquifer (Downey, 1984) was added to the pre-Devonian hydrogeologic structure top surface developed in this report. Fifth, a 30-meter resolution DEM from the National Elevation Dataset (Gesch and others, 2002) was resampled to 100-meter resolution, clipped to outcrop areas of the Madison aquifer, and converted to points for use in aquifer top delineation (not shown in Figure 9). Using any finer than 100-meter resolution was too memory-intensive for the interpolation program, but 100-meter resolution will be sufficient for the 250-meter grid cell size in the focus area of the model. Sixth, the resulting raster for the Madison aquifer was evaluated and corrected at geologic contacts on the down-dip side of Madison outcrops to ensure that the Madison was not erroneously modeled as above the actual land surface.

Altitudes of the top of the Madison aquifer range from -11,000 feet in the southern Powder River Basin to approximately 7,000 feet in the western Black Hills along the Limestone Plateau (Figure 1). The altitude of the top of the Madison aquifer drops to approximately -4,000 feet at the North Dakota-South Dakota border, dipping farther northward into the Williston Basin. In the focus area of the study, the dip of the Madison aquifer is steepest in the eastern Black Hills dropping approximately 5,000 feet in altitude in less than 20 miles before it levels off to the east toward Philip, South Dakota.

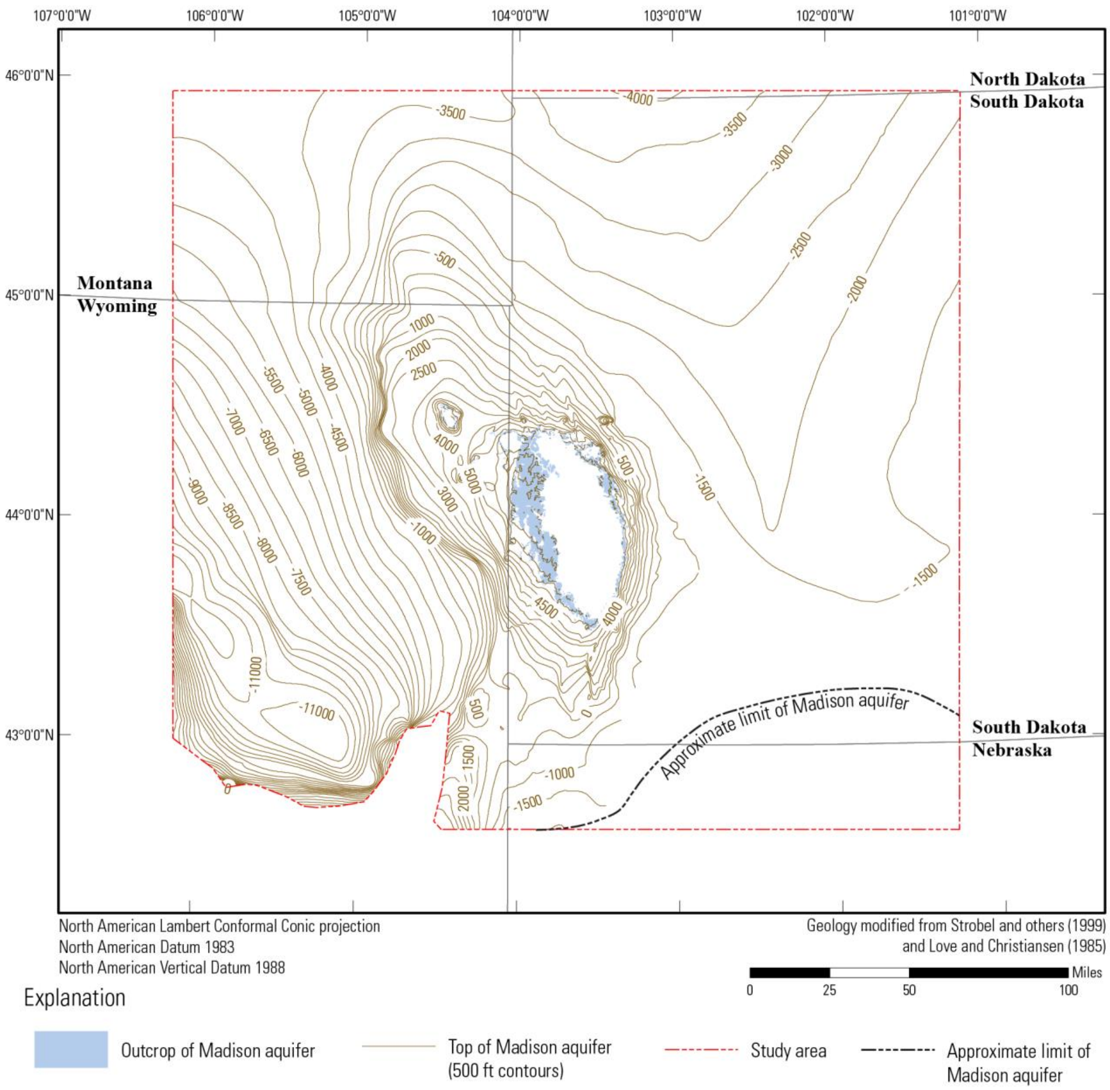

Figure 10. Altitude of the top of the Madison aquifer.

Pre-Devonian Hydrogeologic Unit

The altitude of the pre-Devonian hydrogeologic unit was interpreted by using six steps to combine source data (Figure 11), in order to develop a continuous structure surface (Figure 12). First, existing maps (Bergantino and Clark, 1985; Blackstone, 1993; McCormick, 2010; Nebraska Conservation and Survey Division, 2011) in areas “a, c, g, and h" in Figure 11 were trimmed to edge-match where there was good control for the pre-Devonian hydrogeologic unit surface. Second, borehole data in area "b" of Figure 11 for the top of the pre-Devonian hydrogeologic unit (North Dakota Oil and Gas Division, 2011) were analyzed with geostatistics in ArcGIS (ESRI, 2013) to remove potentially spurious data points and then included as data. Third, in area "e", an interpolated thickness of the Whitewood Formation and the Winnipeg Formation was added to existing map data for the top of the Deadwood Formation (Carter and Redden, 1999c).

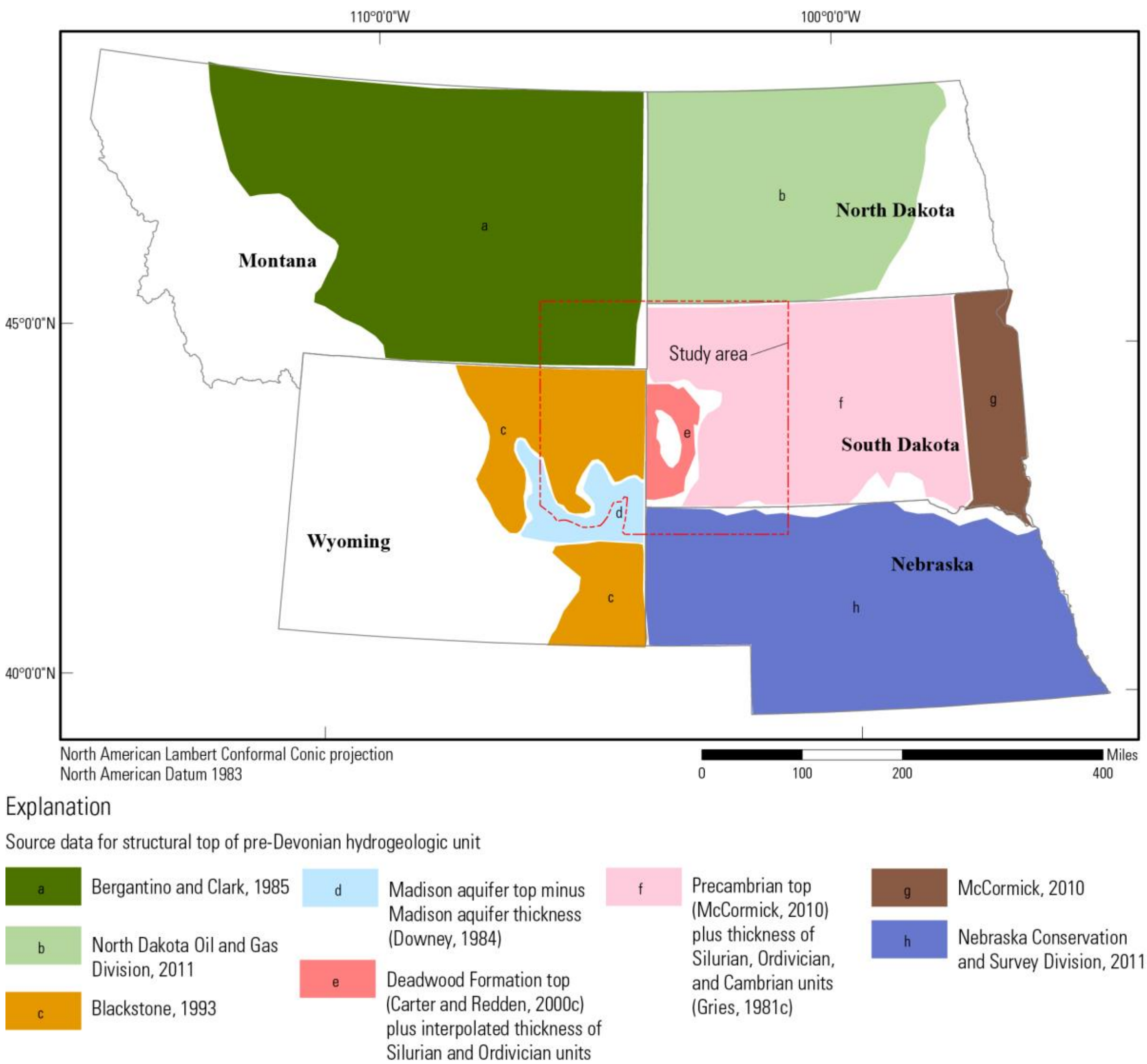

Figure 11. Source data for delineation of the altitude of the pre-Devonian hydrogeologic unit.

Fourth, in area “f” existing map data for the thickness of Silurian, Ordovician, and Cambrian formations (Gries, 1981c) were added to the top of the Precambrian surface (McCormick, 2010). Fifth, similar to the construction of a 30-meter resolution DEM from the National Elevation Dataset (Gesch and others, 2002) was resampled to 100-meter resolution, clipped to outcrop areas of the pre-Devonian hydrogeologic unit, and converted to points for use in aquifer top delineation (not shown in Figure 11).Sixth, missing data in area “d” were filled by subtracting the thickness of the Madison aquifer (Downey, 1984) from the Madison aquifer structure top surface developed in this report. Seventh, the resulting raster surface for the pre-Devonian hydrogeologic unit was evaluated and corrected at contacts on the down-dip side of outcrops to ensure that the surface was not erroneously modeled as above the land surface

Altitudes of the top of the pre-Devonian hydrogeologic unit range from -12,500 feet in the southern Powder River Basin to approximately 7,200 feet in the central core of the Black Hills at Harney Peak. The surface elevation at the point where Harney Peak would be located is not shown as 7,242 feet because of resampling the DEM from 30-meter to 100-meter resolution. The altitude of the top of pre-Devonian hydrogeologic unit drops to approximately -7,000 feet at the North Dakota-South Dakota border, dipping farther northward into the Williston Basin. In the focus area of the study, the dip of the pre-Devonian hydrogeologic unit is steepest in the eastern Black Hills dropping approximately 5,000 feet in altitude in less than 20 miles before it levels off to the east toward Philip, South Dakota.

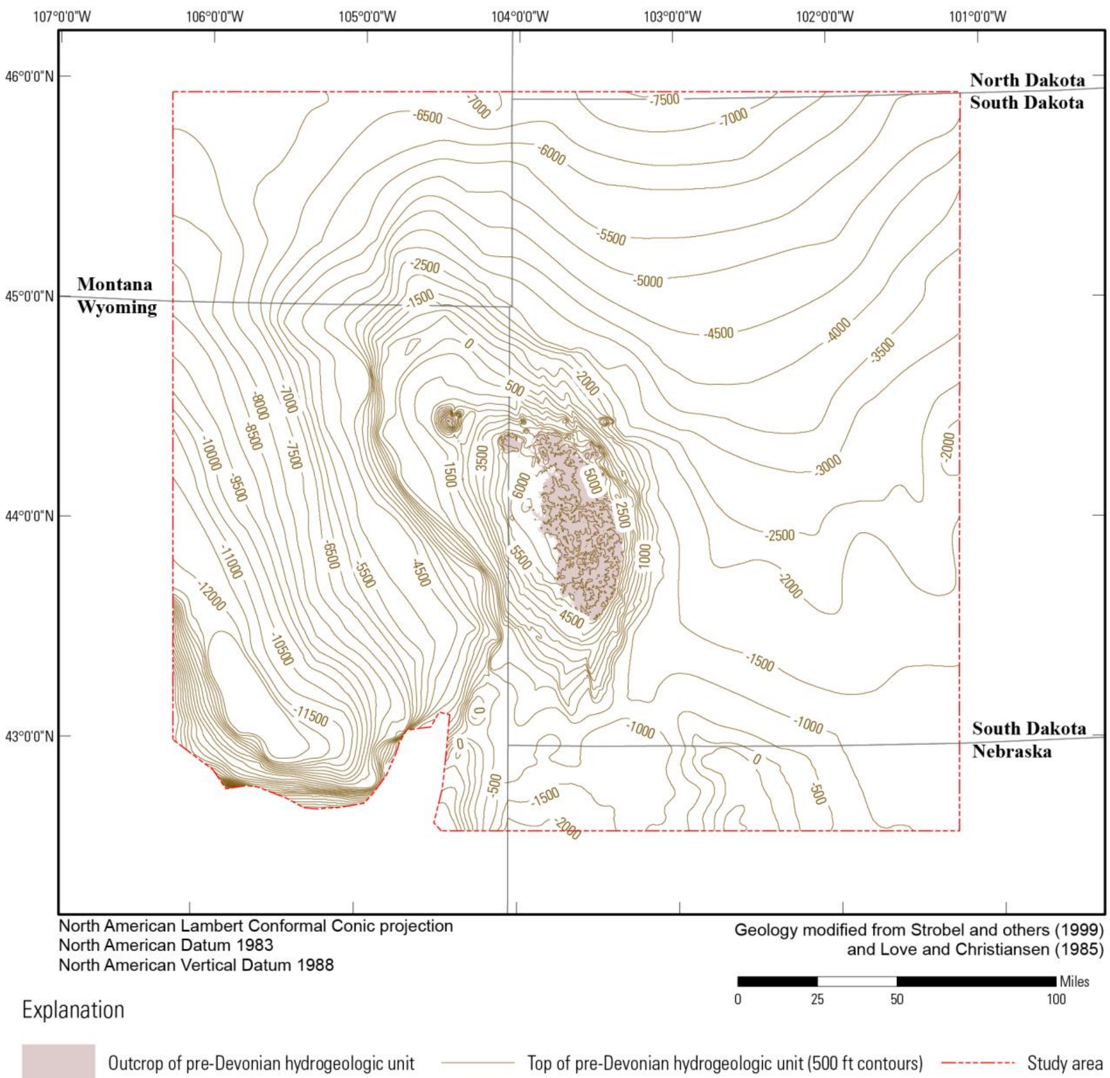

Figure 12. Altitude of the top of the pre-Devonian hydrogeologic unit.

Aquifer Properties

Aquifer properties summarized in this report include horizontal hydraulic conductivity, vertical hydraulic conductivity, transmissivity, and storage coefficient. The estimates are based on previous investigations, and the methods of estimation vary (Appendix A). Locations of estimates for hydraulic conductivity, transmissivity, and storage coefficient are shown on Figure 13 and are summarized in (Appendix A). The aquifer tests are composed of both single and multiple-well tests and also include a

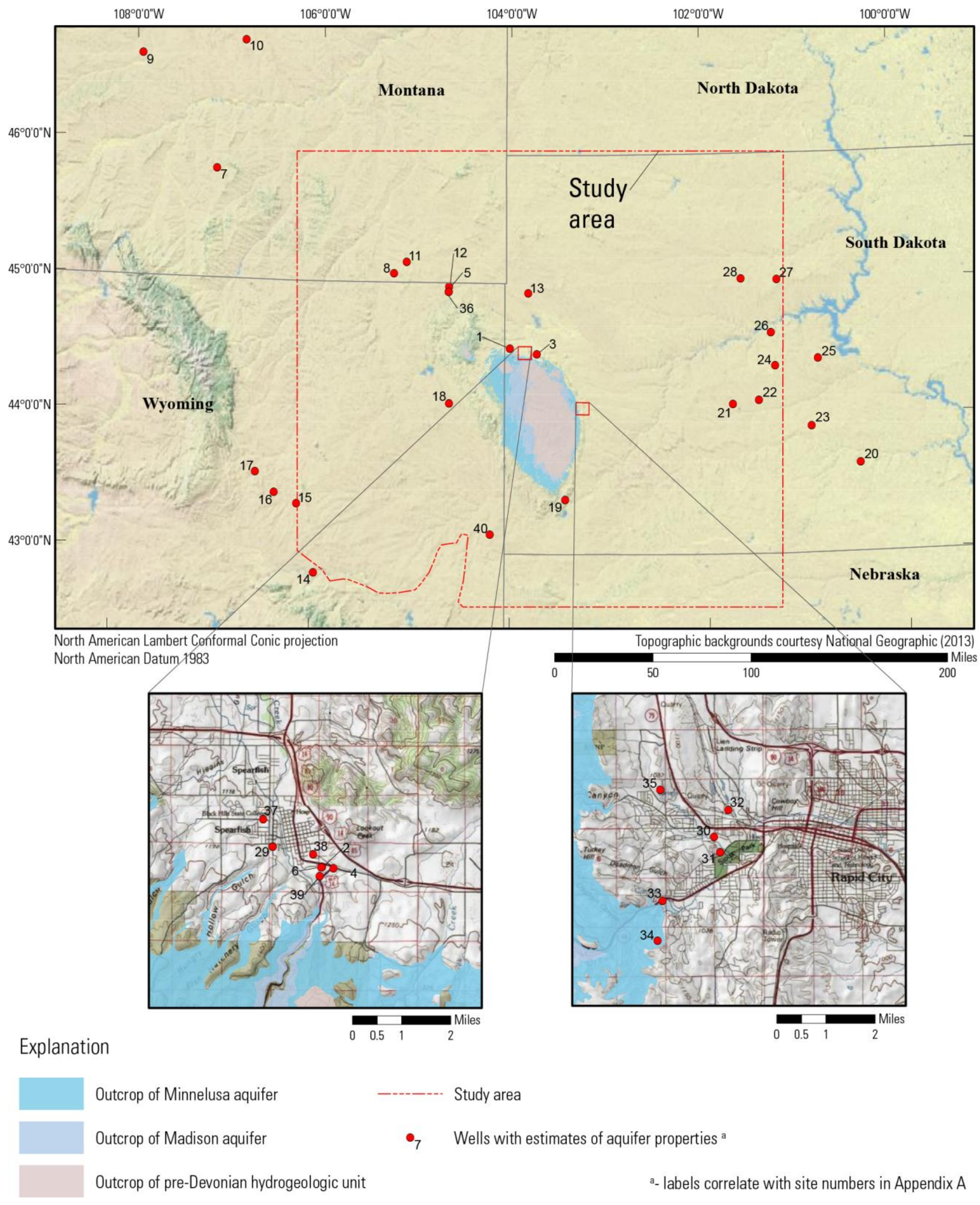

Figure 13. Locations of aquifer tests for hydraulic conductivity, transmissivity, and storativity for the Madison and Minnelusa aquifers.

number of estimates based on carbon-14 (C-14) ages of groundwater. The area for which these estimates should be considered accurate varies with test method. Although an estimate based on an air-pressurized slug-test might be valid for only a few feet surrounding the borehole of a well, an estimate based on a multiple-well pumping test could be valid for distances of 2,000 feet or more from the observation well. For multiple-well pumping tests with many observation wells covering a large area, estimates of aquifer properties could represent values on a regional scale. Estimates of aquifer properties vary greatly due to anisotropy and secondary porosity. Other aquifer tests might be useful for general properties of the Madison and Minnelusa aquifers but are located along the edges of the Bighorn Mountains in steeply dipping, highly fractured rock (Cooley, 1986; Blankennagel and others, 1981).

Hydraulic Conductivity (K_h) Estimates

Hydraulic conductivity is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (Heath, 1983). Estimates for horizontal hydraulic conductivity in and near the study area were described in Appendix A. In and near the study area, horizontal hydraulic conductivity ranges from 0.002 to 113.64 feet per day, with an average of 11.4 feet per day (Appendix A). Zonal model-calibrated estimates of horizontal hydraulic conductivity for the Madison aquifer in the area of Rapid City, South Dakota range from 0.1 to 388.8 ft/day (Putnam and Long, 2009). Model calibrated estimates of horizontal hydraulic conductivity for the same area range from 1.0 to 5.2 ft/day.

Factors affecting hydraulic conductivity include effective porosity (including secondary porosity) and pore diameters (Freeze and Cherry, 1979). Hydraulic conductivity also varies with the temperature and density of groundwater (Freeze and

Cherry, 1979). In areas where there is a relatively high geothermal gradient, water density and viscosity at the hotter temperature will affect the fluid properties of the groundwater and thus the hydraulic conductivity.

Vertical hydraulic conductivity describes the ease of groundwater flow in the vertical direction from one aquifer to another. In and near the study area, estimates of vertical hydraulic conductivity range from approximately 0.1 to 0.5 times the horizontal hydraulic conductivity. Bulk estimates of vertical hydraulic conductivity vary, based on the aquifer material and other factors such as the presence of fracturing, faulting, or breccia pipes (Hayes, 1999). In the groundwater-flow model, individual breccia pipes or instances of faulting will not be modeled individually, so vertical hydraulic conductivity estimates should be adjusted in large grid cells where they are present. Also, model inputs for vertical hydraulic conductivity should be increased in areas where direct hydraulic connection between the Madison and Minnelusa aquifers is inferred based on field data or conceptual models.

Transmissivity (T) Estimates

Transmissivity is defined as the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Heath, 1983) and is equal to hydraulic conductivity multiplied by the saturated thickness (Freeze and Cherry, 1979). Estimates for transmissivity in and near the study area range from 0.9 to 41,700 ft^2/day, with an average of approximately 11,850 ft^2/day (Appendix A). For modeling purposes, estimates of transmissivity from previous reports have been converted to estimates of hydraulic conductivity based on the thickness of the aquifer (as derived from surfaces created as part of this project) where the well is located (Appendix A).

Storage Coefficient (S) Estimates

Storage coefficient is the volume of water released from an aquifer per unit decline in hydraulic head per unit area of the aquifer (Heath, 1983). The value of storage coefficient can vary from zero up to the effective porosity of the aquifer. In confined aquifers, storage coefficient is usually much less than 0.01, typically from 10^{-3} to 10^{-5} (Freeze and Cherry, 1979). Storage coefficient could vary greatly from unsaturated zones of an aquifer to saturated and confined areas. Storage coefficient values gathered from previous publications for the study area ranged from 6×10^{-9} to 2×10^{-3}, with an average of 2.9×10^{-4} (Appendix A). Putnam and Long (2009) zonal estimates storage coefficient of the Madison and Minnelusa aquifers to range from 0.03 to 0.09 where the aquifers are unconfined and approximately 0.0003 where the aquifers are confined.

Potentiometric Surfaces

Potentiometric surfaces were constructed in a method similar to the creation of structural tops, as described above. Potentiometric maps from previous investigations were aggregated into a single dataset, although the full extents of the individual data were not always used. The determination of what parts of each dataset to use in final aggregation was made with the following considerations: (1) the most recent potentiometric contour maps were given priority (if they had good control points), (2) if another map had better control in an area and the added control changed the interpretation of the surface, the map with better control in the area was used. These data were edge matched, with weight given to map sections with better control, using the “Topo to

Raster" tool in ArcGIS (ESRI, 2013). Given problems in interpolation, edge-matching then was adjusted using the same method of "clipping" as in the creation of structural top data. In some areas, hand contouring was needed to assist the computer interpolator in developing a realistic potentiometric surface. The resulting raster surfaces representing the potentiometric surfaces were contoured at an interval of 200 feet. Apparent groundwater-flow were based on the 200 feet potentiometric contours. The actual groundwater flow direction could differ from drawn flow directions because of anisotropy in the Madison and Minnelusa aquifers (Greene and Rahn, 1995).

Because the hydraulic heads in the various publications were measured at various times, and these different sources were combined into one map, potentiometric levels were not interpreted for a particular date. Therefore, the potentiometric maps represent an average potentiometric surface for the area. It was outside the scope of the study to perform a detailed analysis correcting individual water-level measurements based on an available long-term records showing fluctuation of potentiometric water levels in their respective aquifers. This would be a task spanning several years at great expense, with little benefit gained. For a groundwater-flow model at a regional scale, an average potentiometric surface should suffice, especially given a coarse-resolution model grid farther away from the focus area in the study in the immediate vicinity of the Black Hills.

Resulting contours for the potentiometric surface of the aquifers are shown with 200 ft contour intervals. Although structural contour maps in this report were not dashed where approximated, the potentiometric contours are dashed where approximated. The publications of the source data gave sufficient data for inference of where the potentiometric contours should be dashed in this report.

Madison Aquifer

The potentiometric surface for the Madison aquifer was constructed from seven existing datasets, as outlined in Figure 14. In some areas where existing data were not reliable or did not exist, contours were added by hand. One area where contours were added by hand is area “g”, east of the Black Hills. There are several U.S. Geological

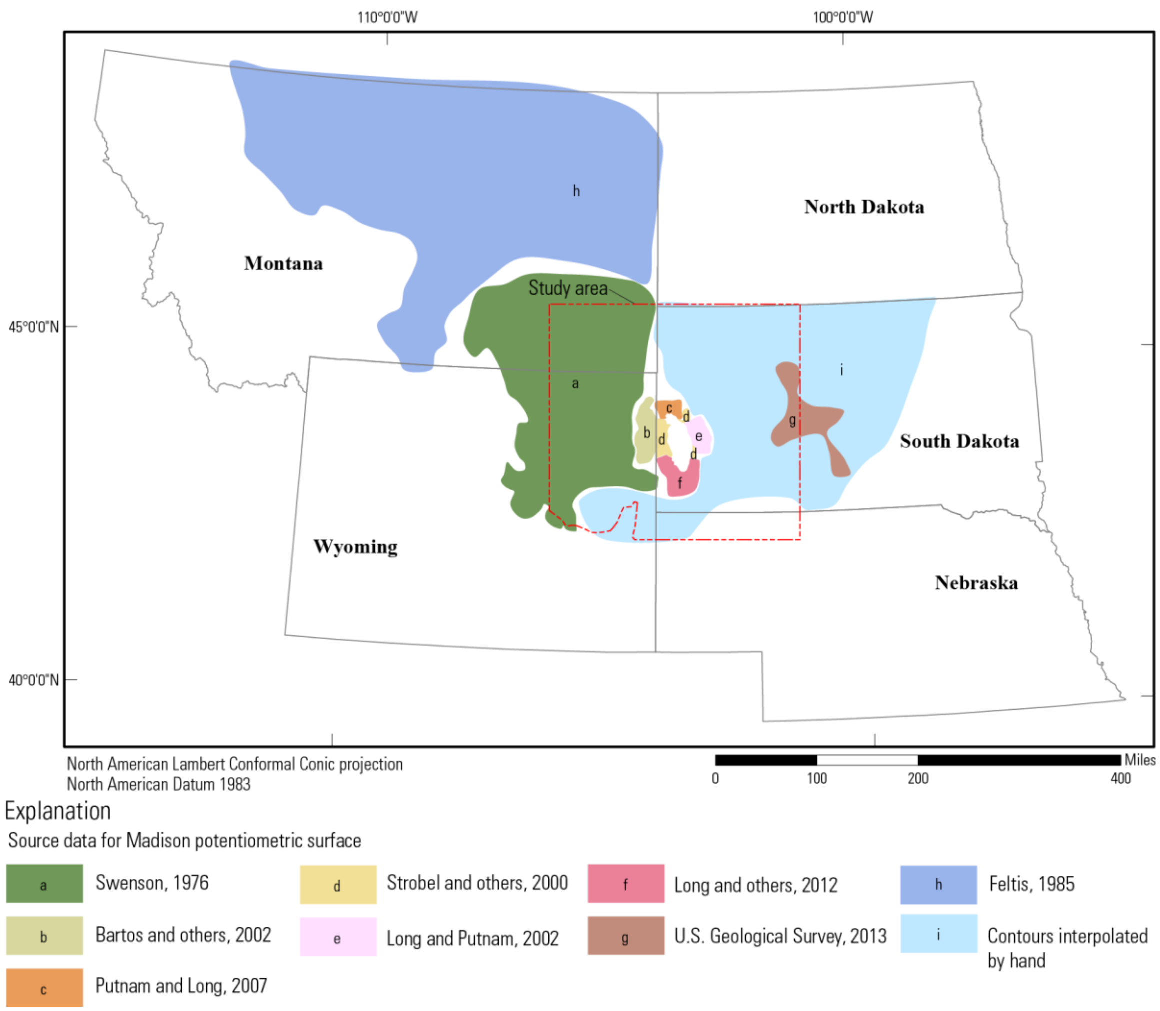

Figure 14. Data sources used in development of the Madison potentiometric surface.

Survey wells (area “h” in Figure 14; U.S. Geological Survey, 2013) that are not known to have been used in previous descriptions of the potentiometric surface of the Madison aquifer. These wells support Downey’s (1986) interpretation of a slight trough in the potentiometric surface of the Madison aquifer extending eastward from Rapid City. Hand-drawn contours were added to further reflect this interpretation; the resulting contours are shown in Figure 15. This interpretation shows a zone of greater transmissivity and a subsequent lowering of hydraulic heads of the Madison aquifer in the area. This zone of greater transmissivity could be caused by complicated faulting in the basement rock in the area (P.H. Rahn and K.A. McCormick, personal communication, 2012). In a pumping test of the Arikaree Formation near Pine Ridge, SD, Greene and others (1991) hypothesize that temperature departures from normal geothermal gradients seen during pumping was due to leakage from lower units- presumably the Madison aquifer. Lowering of the head in the Madison aquifer would likely also lower the head in the Minnelusa aquifer, especially if there is increased vertical hydraulic conductivity in the Minnelusa confining unit (Long and Putnam, 2002).

Generally, groundwater flows from the west to the east in the study area, around the Black Hills. Two main regional groundwater divides exist in the study area. The first extends westward from the northwestern corner of the Black Hills. North of this regional groundwater divide, water flows to the north and then continues into the Williston Basin, or flows east-southeasterly through South Dakota, although data in North Dakota and northern South Dakota area insufficient to say this definitively. South of this regional groundwater divide, water flows southeasterly through the Powder River Basin, eastward through an area south of the Black Hills, and continues eastward. The second regional groundwater divide of note extends eastward from the northeastern corner of the Black Hills. North of this regional groundwater divide water flows east and likely leaks into other hydrogeologic units, including the Dakota Sandstone, as shown by Stotler and

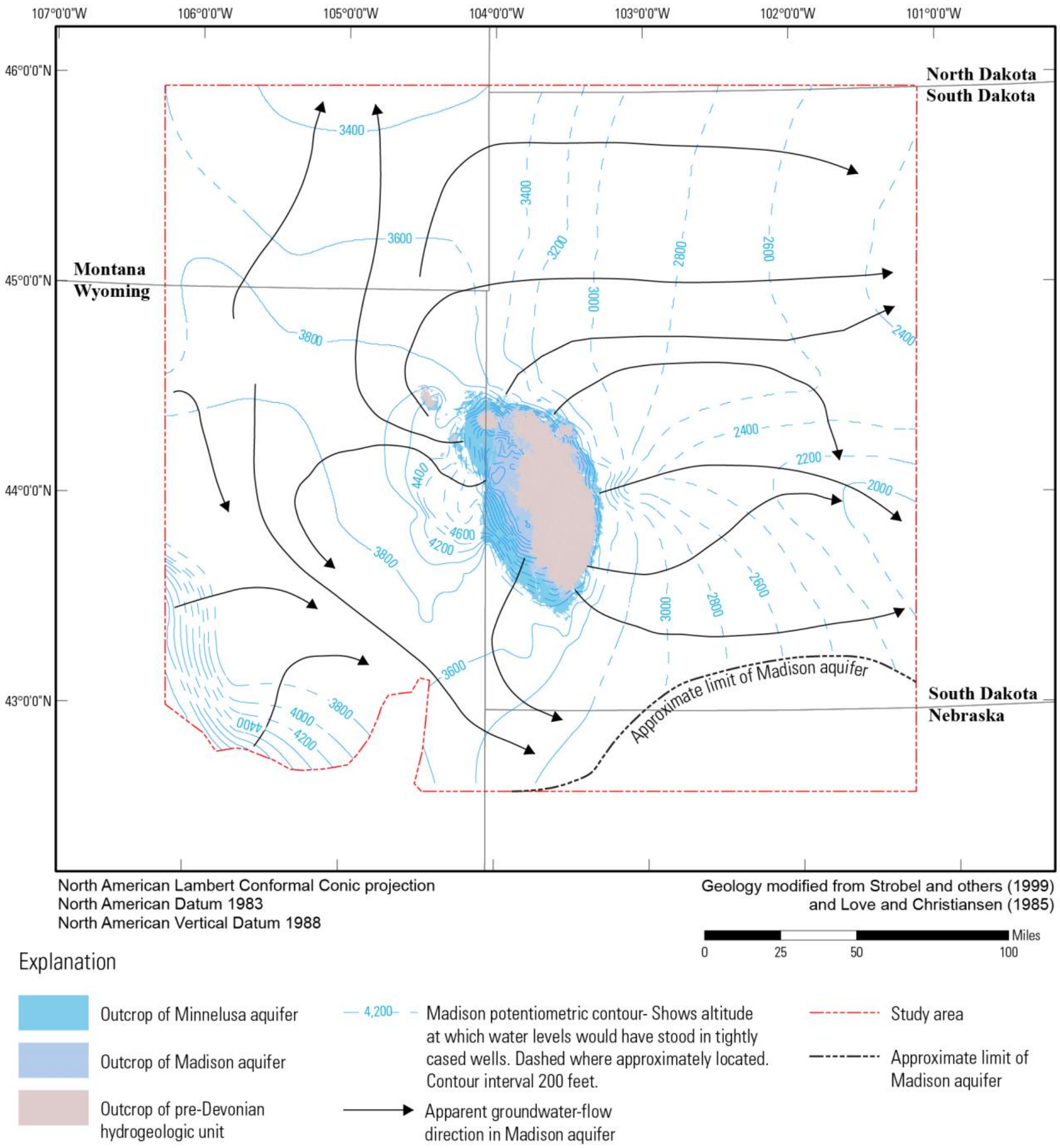

Figure 15. Potentiometric surface of the Madison aquifer.

others (2010). South of this regional groundwater divide, water flows into the trough in the potentiometric surface and continues to flow toward the southeast.

Along the edge of the southwestern Black Hills, the potentiometric surface of the Madison aquifer follows the edge of the zone where the Powder River Basin meets the

Black Hills uplift (Figure 17; Figure 2). This could be a zone of structural weakness where greater fracturing of the Madison aquifer occurred.

Minnelusa Aquifer

The potentiometric map of the Minnelusa aquifer was constructed from seven existing datasets, as outlined on Figure 16. Areas in which existing data were not reliable or did not exist were contoured in a manner similar to the potentiometric map of the Madison aquifer. U.S. Geological Survey wells (U.S. Geological Survey, 2013; area "h" on figure Figure 16) were used to interpolate a hydraulic gradient between existing contours east of

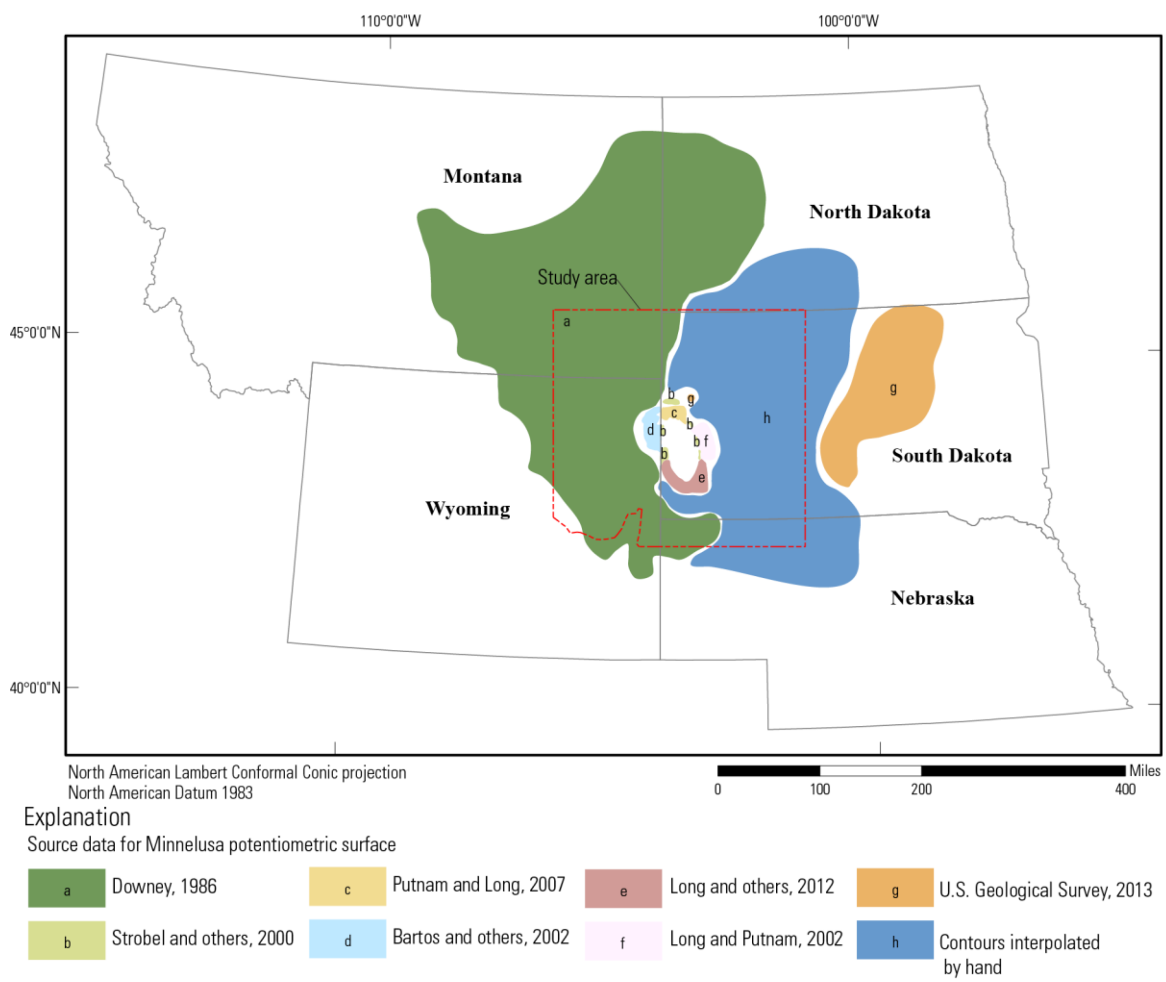

Figure 16. Data sources used in the development of the Minnelusa potentiometric surface.

Rapid City to the eastern boundary of the study area. In the construction of the potentiometric surface, care was taken to represent a slight lowering of head in the Minnelusa aquifer in the area of the trough in the potentiometric surface of the Madison aquifer extending east of Rapid City, because there is evidence to show these aquifers are in hydraulic connection (Long and Putnam, 2002).

Regional groundwater flow in the Minnelusa aquifer (Figure 17) mirrors that of the Madison aquifer, with the same general groundwater divide areas. There was not enough supporting evidence in the data for the Minnelusa aquifer to interpret a trough as pronounced as in the Madison aquifer trending eastward from the Black Hills, although a shallow trough was interpreted. Increased resolution of data could better align the placement of these troughs. Regional groundwater flow directions are similar in both the Madison and Minnelusa aquifers, but hydraulic gradients in the Minnelusa aquifer do not appear to be as steep as in the Madison aquifer. Along the edge of the southwestern Black Hills, similar to the Madison aquifer, the potentiometric surface of the Minnelusa Formation follows the edge of the zone where the Powder River Basin meets the Black Hills uplift (Figure 17; Figure 2). This may be a zone of structural weakness and an indication of greater fracturing in the Minnelusa aquifer.

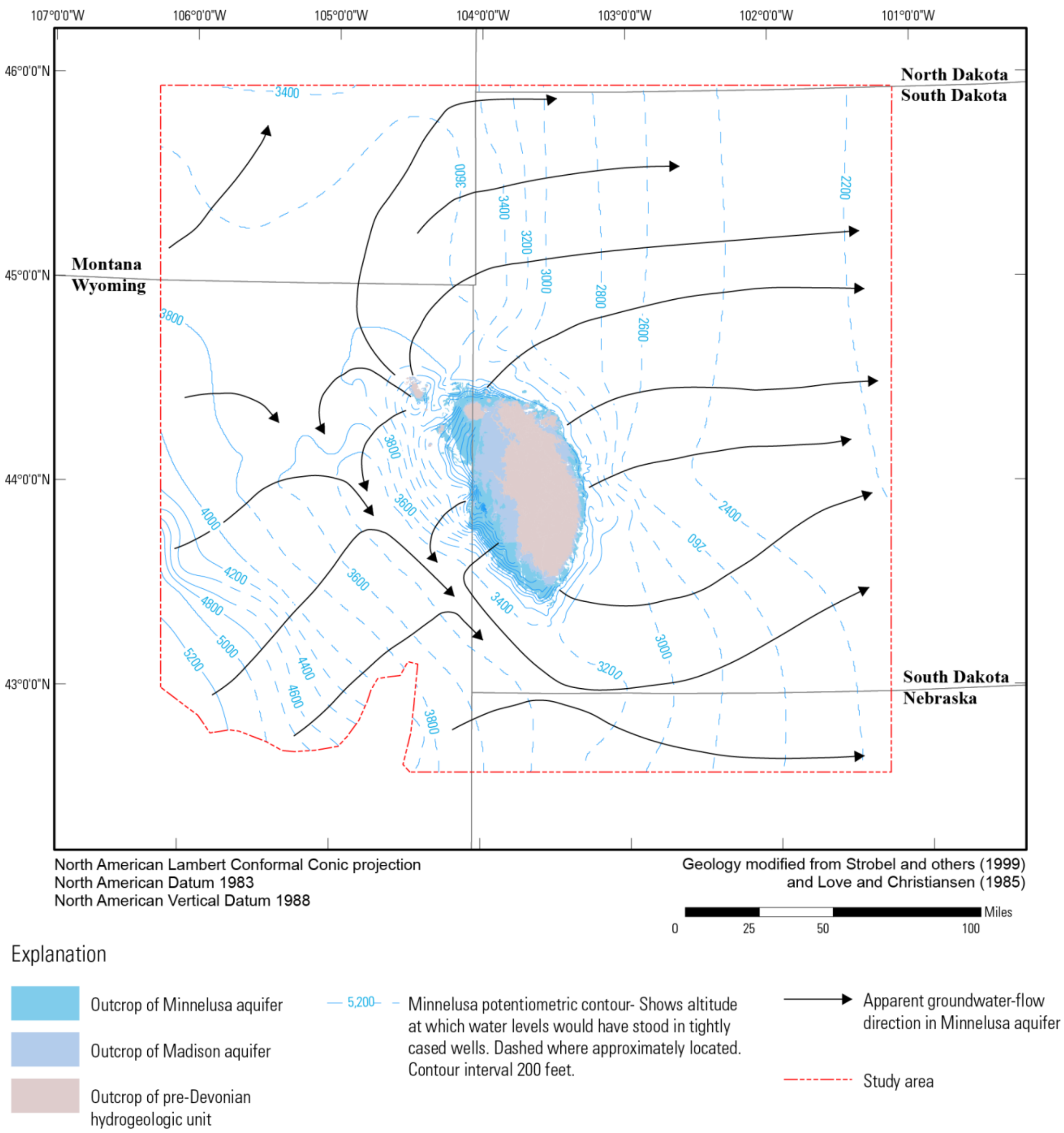

Figure 17. Potentiometric surface of the Minnelusa aquifer.

Discussion on Potentiometric Surfaces

North central south Dakota and all of North Dakota lack potentiometric data. These areas should be considered for placement of observation wells in the Madison and Minnelusa aquifers. Additional wells in this area would be beneficial in further delineation of potentiometric surfaces of the Madison and Minnelusa aquifers.

As part of the work with the potentiometric maps, unsaturated zones of the Madison and Minnelusa aquifer were determined. The term unsaturated will be used to mean the aquifer is unsaturated or partially saturated, but not confined. To determine the unsaturated zones in each aquifer, the altitudes of the structural tops were subtracted from the potentiometric surface maps. For example, to form one side of the boundary of the Madison aquifer's unsaturated zone, the altitude of the top of the pre-Devonian hydrogeological unit was subtracted from the altitude of the Madison potentiometric surface. The other side of the boundary was determined by subtracting the altitude of the structural top of the Madison aquifer from the altitude of the Madison potentiometric surface. The area between the zones where these two calculations yielded values of approximately zero were considered unsaturated (Figure 18). The Minnelusa unconfined zone (Figure 18) was constructed similarly.

The unsaturated zones of the Minnelusa and Madison aquifers are thinner along the eastern flank of the Black Hills. This is likely because of the influence sinking streams have on the recharge rate in the eastern Black Hills. Streams in the Black Hills are noted to have lost as much as 100 ft^3/second (Brown, 1944) across the Madison and Minnelusa outcrops, often leaving the stream dry across much of the outcrop. The stream losses have enough concern that citizens have attempted to plug these loss zones with rip-rap and concrete (Brown, 1944). After an attempt to plug loss zones on Spring Creek, the loss threshold across the outcrop of the Madison aquifer was reduced from >100 ft^3/second to approximately 6 ft^3/second (Brown, 1944). In the western Black Hills, the unsaturated zones are much wider, indicating that either groundwater flow is much faster in these areas or is rather emerging as spring flow at the headwaters of streams that flow east across the Black Hills (Figure 1).

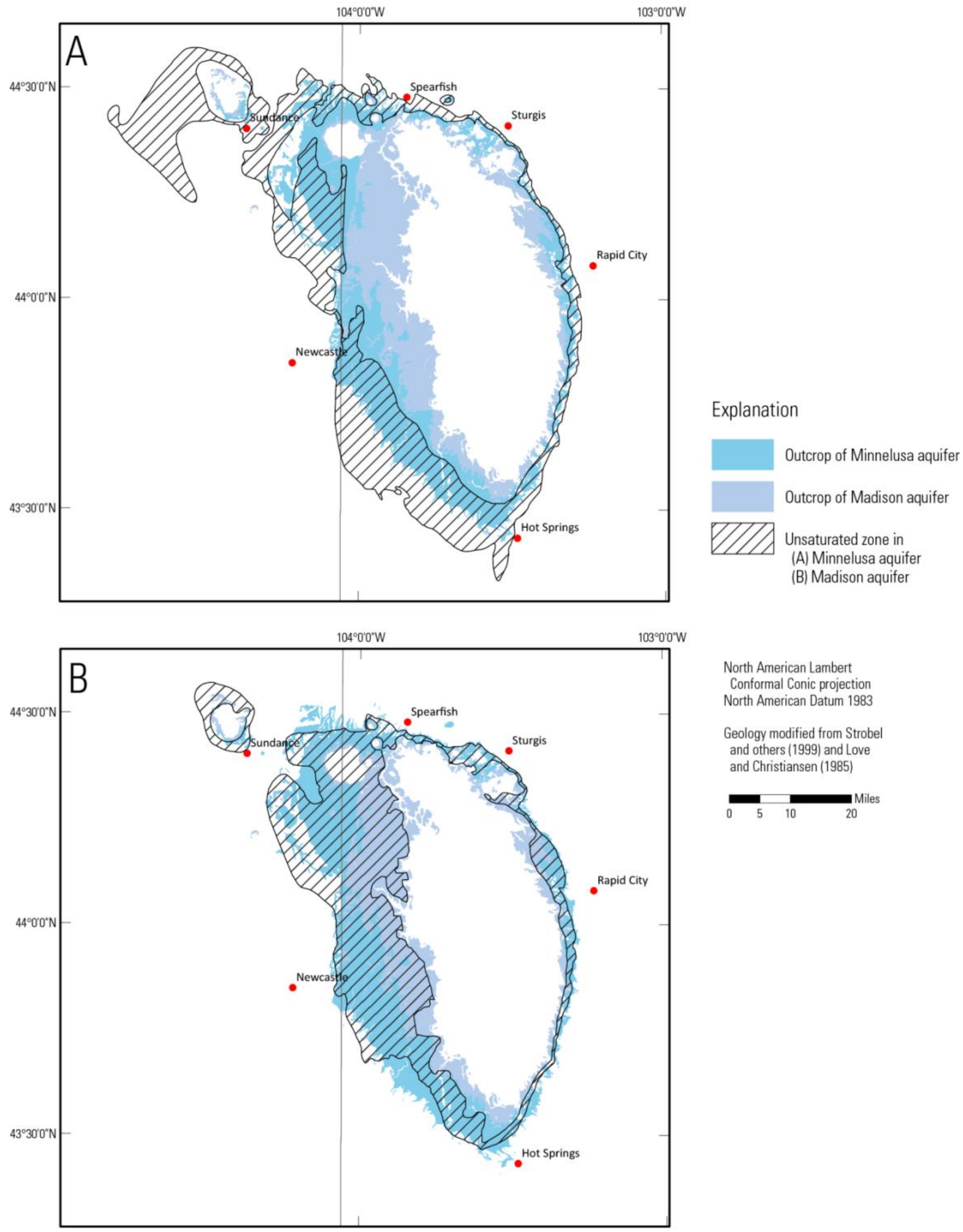

Figure 18. Unsaturated zones for (A) Minnelusa aquifer and (B) Madison aquifer

Conceptually, the Madison aquifer will have higher head closer to the outcrops of the two aquifers, allowing some vertical flow from the Madison aquifer, at a higher head, to the Minnelusa aquifer, at a lower head (Figure 19). Farther from the outcrops of the aquifers, the Minnelusa aquifer often has higher head, allowing for vertical flow from the Minnelusa aquifer, at a higher head, to the Madison aquifer, at a lower head (Figure 19). Analysis of the potentiometric surfaces of the Madison and Minnelusa aquifers, as produced for this report, supports this conceptual idea (Figure 19, Figure 20).

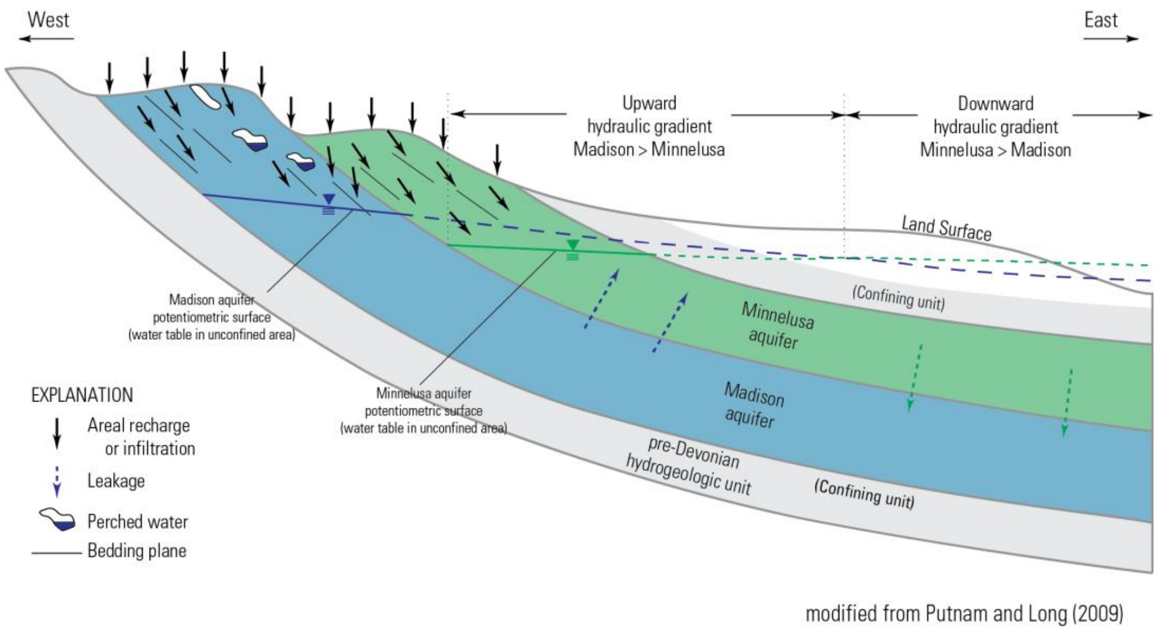

Figure 19. Conceptual model of vertical gradients in the Madison and Minnelusa aquifers.

The potentiometric surface of the Minnelusa aquifer was subtracted from that of the Madison aquifer to determine the magnitude and direction of vertical hydraulic gradient between the two aquifers (Figure 20). Areas A and B in Figure 20 could be a result of insufficient potentiometric data in one of the aquifers (e.g., in area A, where, given current data, troughs in the potentiometric surfaces do not line up exactly). Given more reliable information, shifting the potentiometric contours slightly could change the apparent vertical hydraulic gradient. Generally, the Minnelusa aquifer has a higher potentiometric surface than the Madison aquifer in and near outcrops of the Minnelusa

Formation. Farther away from outcrops, the Madison aquifer generally has a higher potentiometric surface. In much of the study area the elevation of the potentiometric surfaces of the Madison and Minnelusa aquifers are within +/- 250 feet of one another. Significant pumping (i.e., for coal slurry, hydraulic fracturing, or other heavy industrial use) in the areas where the difference between the respective potentiometric surfaces is relatively small could greatly influence the potentiometric surfaces in areas surrounding the wells.

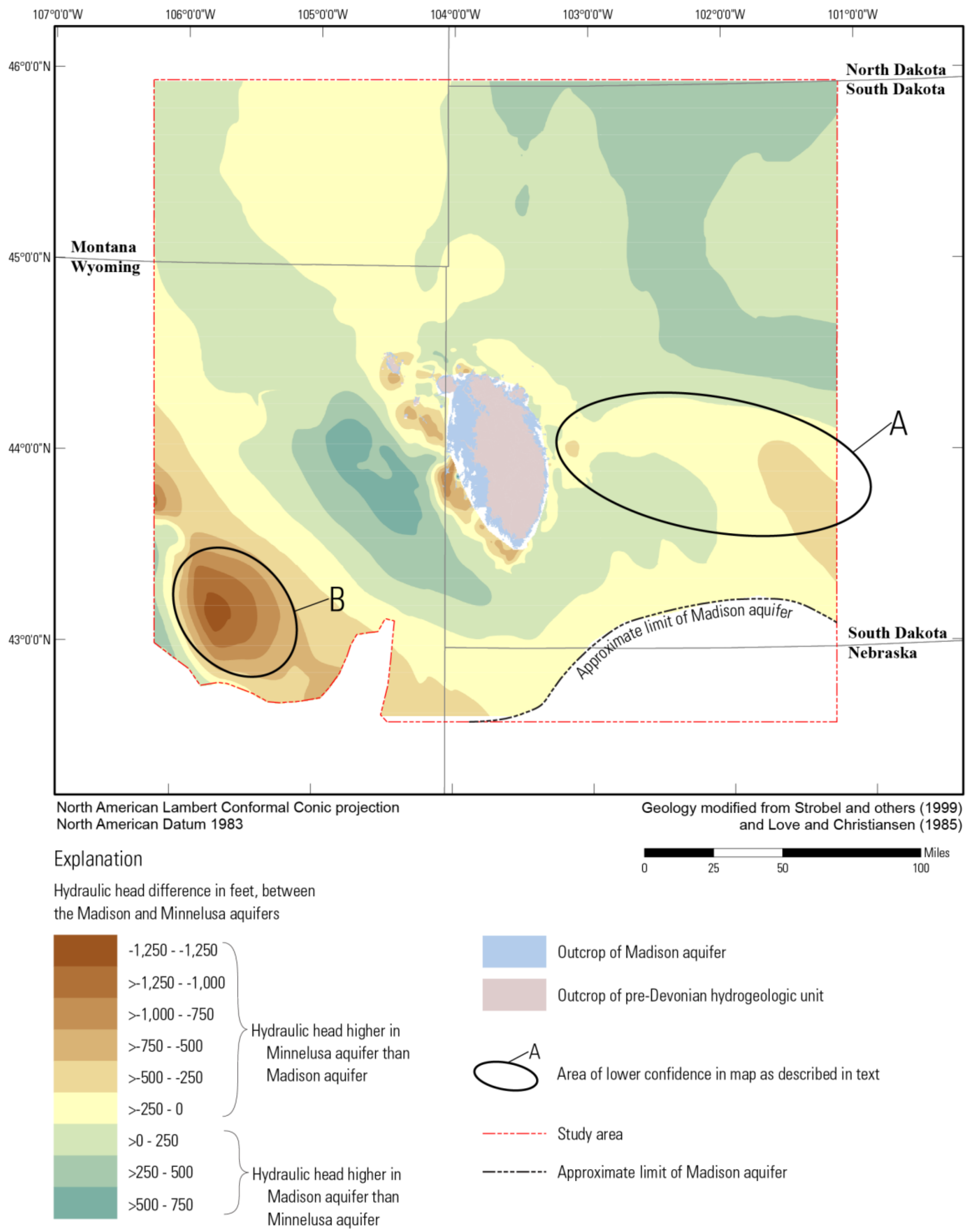

Figure 20. Difference in hydraulic head between the Madison and Minnelusa aquifers.

Summary and Conclusions

The dependence of residents in the Black Hills area on groundwater raises important questions regarding groundwater availability, effects of water use or drought, mixing of regional groundwater flow and local recharge, and the effects of capture zones of springs and wells on the groundwater-flow system. These questions are best addressed with a groundwater-flow model including the entire Black Hills and surrounding area.

The hydrogeologic framework created in this report for the Madison and Minnelusa aquifers, including data delineating aquifer tops and bottoms, potentiometric surfaces, and summaries of existing estimates of aquifer properties, will assist in creation of a regional groundwater flow model.

The structural contours shown in this report were aggregated from the most current available data and will aid in estimation of drilling depths. The potentiometric surface of the Madison aquifer presented in this report has supported previous interpretations of a trough extending east-southeastward from Rapid city. The vertical gradient between potentiometric surfaces of the Madison and Minnelusa aquifer will assist in determining likely flow direction of leakage between the two aquifers. In most of the study area the potentiometric surfaces of the Madison and Minnelusa aquifers are within +/- 250 feet of one another. Significant pumping of one of the aquifers could change the vertical gradient over a large area.

This hydrogeologic framework will be an integral part of a regional groundwater flow model as well as for water inventories and water-resources management in the future.

Future Work

Additional water-level measurements for the Madison and Minnelusa aquifers could be helpful for future interpretations of potentiometric surfaces. An effort should be made to establish additional paired observation wells for these two aquifers where potentiometric data for the Madison aquifer are scarce or do not exist. This effort could include drilling new wells or less-expensive options such as locating abandoned wells, drilling through the concrete plugs, and perforating the well through the aquifer of interest. This option would likely be a fraction of the cost of drilling a new well. Although locating wells could be difficult, the lithologies of many abandoned oil wells are well documented and geophysical logs are often available. The information gained through this process could be invaluable to the long-term water management goals of various government agencies, local municipalities, and private interests. The areas that could benefit the most from this are northern and central South Dakota and all of North Dakota where the aquifers are present. There are no known water levels for the Madison or Minnelusa aquifer in all of North Dakota, and in most of the northern and central areas of South Dakota (Figure 14; Figure 15). These areas will be important in water management of the Madison and Minnelusa aquifers because of the potential for increased use for hydraulic fracturing and other heavy industrial needs.

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Appendix A. Table Summarizing Aquifer Property Estimates

[ft, feet; K_h, horizontal hydraulic conductivity; K_v, vertical hydraulic conductivity; T, transmissivity S, storage coefficient; --, no data or not applicable; ^{14}C, Carbon-14]

		Approximate Location									
Site number	**Well name**	**Latitude**[a]	**Longitude**[a]	**Aquifer**	**K_h (ft/day)**	**K_v (ft/day)**	**T (ft^2/day)**	**S**	**Test Method**	**Distance from well estimate is accurate**[b]	**Source**
1	LA-87B	44.517889	-104.006958	Minnelusa	0.36[c]	--	125	--	Air-pressurized slug test	Few feet around borehole	Greene and others, 1998
2	LA-88B	44.481838	-103.848368	Minnelusa	0.48[c]	--	185	0.000000006	Air-pressurized slug test	Few feet around borehole	Greene and others, 1998
3	LA-88A	44.476373	-103.729515	Minnelusa	1.12[c]	--	396	0.000000004	Air-pressurized slug test	Few feet around borehole	Greene and others, 1998
4	Golf Course	44.481419	-103.843724	Minnelusa	24.43[c]	--	9,600	0.00007	Interference test	1000-2000 ft	Greene and others, 1998
5	Madison no. 1	44.933185	-104.643616	Minnelusa	1.40	--	--	--	Single well Test	--	Blankennagel and others, 1977
6	LA-88C	44.481796	-103.848725	Madison	0.002[c]	--	0.9	0.001	Air-pressurized slug test	Few feet around borehole	Greene and others, 1998
7[d]	Sarpy Mine	45.80358307	-107.0985389	Madison	1.78	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
8	Ranch Creek	45.06220363	-105.2139426	Madison	0.79	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
9[d]	Keg Coulee	46.63103248	-107.9374832	Madison	0.59	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
10[d]	Mysse flowing well	46.75858261	-106.8404374	Madison	0.28	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
11	Belle Creek	45.14664317	-105.0845517	Madison	0.80	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
12	Mysse flowing well	44.97209255	-104.6391994	Madison	0.34	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
13	Delzer No.2	44.92326845	-103.8188996	Madison	0.18	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
14[d]	Conoco No.175	42.84371127	-105.9708737	Madison	0.30	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
15[d]	MKM	43.35052334	-106.1606679	Madison	0.36	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
16[d]	Shidler	43.428019	-106.3912799	Madison	0.43	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
17[d]	Conoco No.44	43.5749758	-106.5879574	Madison	0.08	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
18	Upton	44.10970694	-104.6262154	Madison	0.13	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
19	Evans Plunge	43.40140258	-103.4416782	Madison	0.53	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
20[d]	Kosken	43.64019764	-100.4393345	Madison	2.23	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
21	Philip	44.09390844	-101.7223655	Madison	0.59	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
22	Midland	44.12009818	-101.4555674	Madison	0.80	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
23[d]	Murdo	43.92223086	-100.9256065	Madison	0.92	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
24	Hilltop Ranch	44.37016948	-101.2801487	Madison	0.89	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
25[d]	Prince	44.41702922	-100.8375167	Madison	1.53	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
26	Hamilton	44.61410872	-101.3137104	Madison	0.69	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
27	Eagle Butte	45.00590203	-101.2394984	Madison	1.57	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
28	Dupree	45.01827248	-101.6112176	Madison	1.17	--	--	--	^{14}C age dating	Groundwater-flow path[e]	Busby and others, 1991
29[f]	Dickey	44.487857	-103.868805	Madison	113.62[c]	--	41,700	0.0003	Interference test	1000-2000 ft	Greene and others, 1998
29[f]	Dickey	44.487857	-103.868805	Madison	61.85[c]	--	22,700	0.0001	Specific-capacity test	Tens of feet around borehole	Greene and others, 1998
30	LC	44.079545	-103.272278	Madison	2.74[c]	0.0068	1,600	0.0001	Multiple well pumping	1000-2000 ft	Greene, 1993
31	SP-2	44.074982	-103.269781	Madison	3.87[c]	0.016	2,600	0.0001	Multiple well pumping	1000-2000 ft	Greene, 1993
32	BHPL	44.087475	-103.266354	Madison	9.52[c]	0.011	5,200	0.0001	Multiple well pumping	1000-2000 ft	Greene, 1993
33	CL-2	44.060691	-103.293405	Madison	74.91[c]	0.0091	40,000	0.00033	Multiple well pumping	1000-2000 ft	Greene, 1993
34	CHLN-2	44.048947	-103.295524	Madison	74.07[c]	0.0053	40,000	0.00033	Multiple well pumping	1000-2000 ft	Greene, 1993
35	CQ-2	44.093532	-103.294187	Madison	34.21[c]	--	17,000	0.002	Multiple well pumping	1000-2000 ft	Greene, 1993
36	Madison no. 1	44.933185	-104.643616	Madison	1.90	--	--	--	Single well Test	--	Blankennagel and others, 1977
38	College	44.495872	-103.872694	Madison	16.24[c]	--	5,100	0.00001	Specific-capacity test	Tens of feet around borehole	Greene and others, 1998
39	Ellingson	44.485494	-103.852112	Madison	6.76[c]	--	2,900	0.000001	Specific-capacity test	Tens of feet around borehole	Greene and others, 1998
40	Nevin	44.479208	-103.849439	Madison	--	--	--	0.0000001	Specific-capacity test	Tens of feet around borehole	Greene and others, 1998
41	ETSI	43.143968	-104.202162	Madison	0.32[c]	--	455	0.00012	Multiple well pumping	--	Rahn, 1979

[a]- In decimal degrees, North American Datum, 1983 (NAD83)
[b]- As described in source publication
[c]- K_h calculated from transmissivity estimates from previous investigations, divided by thickness derived from structure tops made as part of this project.
[d]- Well is located outside of study area
[e]- K_h calculated from ^{14}C age correlation along approximate groundwater-flow path from recharge area
[f]- Duplicate entry because estimates exist from two types of aquifer tests

Vita

Jonathan Dennis Roger George McKaskey was born on 28 October 1984 to Dennis and Catherine McKaskey. He grew up in Charlotte, North Carolina and graduated high school from Northwest School of the Arts in 2003, where his education had an emphasis on jazz performance on trombone.

Jonathan attended South Dakota School of Mines and Technology during the fall 2003 and spring 2004 semesters. From April 2005 to April 2007, Jonathan volunteered as a full-time church missionary for the Church of Jesus Christ of Latter-day Saints in western Ukraine. Jonathan returned to South Dakota School of Mines and Technology for the fall 2007 semester and graduated with a Bachelor of Sciences degree in Geological Engineering in May, 2011.

Jonathan graduated with a Master of Science degree in Geological Engineering from the South Dakota School of Mines and Technology in the summer semester of 2013 under the direction of major advisor, Dr. Arden Davis. Jonathan's thesis work was a direct result of his work for the U.S. Geological Survey South Dakota Water Science Center from June 2010 to May 2013 under the supervision of research hydrologist Dr. Andrew J. Long. While working for the U.S. Geological survey, Jonathan co-authored Scientific Investigations Report 2011-5235, "Groundwater Flow, Quality (2007-10), and Mixing in the Wind Cave National Park Area, South Dakota".

Jonathan is married to Christie L. B. McKaskey and, at the time of this report, has one child, Miles Girard McKaskey.