Geochemistry of the Madison and Minnelusa Aquifers in the Black Hills Area, South Dakota

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ABSTRACT

The Madison and Minnelusa aquifers are two of the most important aquifers in the Black Hills area because of utilization for water supplies and important influences on surface-water resources resulting from large springs and streamflow-loss zones. Examination of geochemical information provides a better understanding of the complex flow systems within these aquifers and interactions between the aquifers.

Major-ion chemistry in both aquifers is dominated by calcium and bicarbonate near outcrop areas, with basinward evolution towards various other water types. The most notable differences in major-ion chemistry between the Madison and Minnelusa aquifers are in concentrations of sulfate within the Minnelusa aquifer. Sulfate concentrations increase dramatically near a transition zone where dissolution of anhydrite is actively occurring.

Water chemistry for the Madison and Minnelusa aquifers is controlled by reactions among calcite, dolomite, and anhydrite. Saturation indices for gypsum, calcite, and dolomite for most samples in both the Madison and Minnelusa aquifers are indicative of the occurrence of dedolomitization. Because water in the Madison aquifer remains undersaturated with respect to gypsum, even at the highest sulfate concentrations, upward leakage into the overlying Minnelusa aquifer has potential to drive increased dissolution of anhydrite in the Minnelusa Formation.

Isotopic information is used to evaluate ground-water flowpaths, ages, and mixing conditions for the Madison and Minnelusa aquifers. Distinctive patterns exist in the distribution of stable isotopes of oxygen and hydrogen in precipitation for the Black Hills area, with isotopically lighter precipitation generally occurring at higher elevations and latitudes. Distributions of $\delta^{18}O$ in ground water are consistent with spatial patterns in recharge areas, with isotopically lighter $\delta^{18}O$ values in the Madison aquifer resulting from generally higher elevation recharge sources, relative to the Minnelusa aquifer.

Three conceptual models, which are simplifications of lumped-parameter models, are considered for evaluation of mixing conditions and general ground-water ages. For a simple slug-flow model, which assumes no mixing, measured tritium concentrations in ground water can be related through a first-order decay equation to estimated concentrations at the time of recharge. Two simplified mixing models that assume equal proportions of annual recharge over a range of years also are considered. An "immediate-arrival" model is used to conceptually represent conditions in outcrop areas and a "time-delay" model is used for locations removed from outcrops, where delay times for earliest arrival of ground water generally would be expected. Because of limitations associated with estimating tritium input and gross simplifying assumptions of equal annual recharge and thorough mixing conditions, the conceptual models are used only for general evaluation of mixing conditions and approximation of age ranges.

Headwater springs, which are located in or near outcrop areas, have the highest tritium concentrations, which is consistent with the immediate-arrival mixing model. Tritium concentrations for many wells are very low, or nondetectable, indicating general applicability of the time-delay conceptual model for locations beyond outcrop areas, where artesian conditions generally occur. Concentrations for artesian springs generally are higher than for wells, which indicates generally shorter delay times resulting from preferential flowpaths that typically are associated with artesian springs.

In the Rapid City area, a distinct division of isotopic values for the Madison aquifer corresponds with distinguishing $\delta^{18}O$ signatures for nearby streams, where large streamflow recharge occurs. Previous dye testing in this area documented rapid ground-water flow (timeframe of weeks) from a streamflow loss zone to sites located several miles away. These results are used to illustrate potential errors that may result from the simplified conceptualization of this complex ground-water setting with dual-porosity hydraulic characteristics. For Rapid City sites with time-series data, minimal variability in $\delta^{18}O$ values corresponded with tritium data indicative of dominant proportions of older water. Other sites showed response to temporal $\delta^{18}O$ trends in streamflow recharge, with tritium data indicating larger proportions of modern recharge. Several large production wells located near the isotopic transition zone had changes in $\delta^{18}O$ values indicative of changes in capture zones associated with recent production.

Evaluation of major-ion and isotope data indicates that regional flowpaths for the Madison aquifer are essentially deflected around the study area, with the possible exception of the southwestern and northwestern corners. Two wells just north of the study area clearly show influence of regional flow, and a well just within the study area shows possible influence. Large artesian springs near the northern axis of the uplift show no regional influence and are concluded to be recharged within the uplift area. Ion concentrations for wells west of the study area in Wyoming indicate deflection of regional flowpaths, with minor influence possible for several wells. The $\delta^{18}O$ values for large springs along the southern axis of the uplift essentially preclude regional influence, which also is supported by ion chemistry, and indicate potential recharge areas extending along the entire southwestern flank of the uplift. Low, but detectable, tritium concentrations in these springs along the southern axis confirm the influence of recharge from within the study area, but indicate relatively long traveltimes.

Hydrographs for 9 of 13 well pairs are fairly well separated and do not indicate direct hydraulic connection between the Madison and Minnelusa aquifers. Comparison of geochemical information provides no evidence of extensive mixing resulting from general, areal leakage between the aquifers.

Aquifer interactions can occur at artesian springs, which discharge about one-half of average recharge to the Madison and Minnelusa aquifers in the Black Hills area. Various investigators have hypothesized that the Madison aquifer is the primary source for many artesian springs, based on geochemical modeling. The Madison aquifer is inferred as the primary source for several springs where artesian conditions in the Minnelusa aquifer are precluded by nearby outcrop sections. For many springs, quantifying relative contributions from each aquifer is hampered by geochemical similarities between the Madison and Minnelusa aquifers, especially near recharge areas. For some springs, high sulfate concentrations indicate Minnelusa influence, but may result from dissolution of Minnelusa minerals by water from the Madison aquifer.

Generally higher hydraulic head in the Madison aquifer, in combination with gypsum undersaturation, is concluded to be a primary mechanism driving interactions with the Minnelusa aquifer, in areas where artesian conditions exist in the Madison aquifer. Upward leakage from the Madison aquifer probably contributes to general dissolution of anhydrite deposits in the Minnelusa aquifer and development of breccia pipes, which enhances vertical hydraulic conductivity. Breccia pipes are a likely mechanism for upward movement of large quantities of water through the Minnelusa aquifer at artesian spring locations and many exposed breccia pipes of the upper Minnelusa Formation probably are the throats of abandoned artesian springs. Dissolution processes are an important factor in a self-perpetuating process associated with development of artesian springs and preferential flowpaths, which initially develop in locations with large secondary porosity and associated hydraulic conductivity, with ongoing enhancement resulting from dissolution activity.

Outward (downgradient) migration of the artesian springs probably occurs as upgradient spring-discharge points are abandoned and new ones are occupied, keeping pace with regional erosion over geologic time. In response, hydraulic heads in the Madison and Minnelusa aquifers also have declined over geologic time. Artesian springflow and general leakage are concluded to be important factors in governing water levels in the Madison and Minnelusa aquifers. Artesian springs are especially important in acting as a relief mechanism that provides an upper limit for hydraulic head, with springflow increasing in response to increasing water levels.

INTRODUCTION

The Madison and Minnelusa aquifers are two of the most important aquifers in the Black Hills area. These aquifers are used extensively for domestic, municipal, irrigation, and industrial uses and have a major influence on the surface-water resources because of large spring discharges and large streamflow losses that occur along many stream channels.

Population growth, resource development, and periodic droughts have the potential to affect the quantity, quality, and availability of water within the Black Hills area. Because of this concern, the Black Hills Hydrology Study was initiated in 1990 to assess the quantity, quality, and distribution of surface and ground water in the Black Hills area of South Dakota (Driscoll, 1992). This long-term study is a cooperative effort between the U.S. Geological Survey, the South Dakota Department of Environment and Natural Resources, and the West Dakota Water Development District, which represents various local and county cooperators. The Madison and Minnelusa aquifers are the primary focus of the Black Hills Hydrology Study.

Ground-water conditions in the Madison and Minnelusa aquifers are extremely complex because of several factors. Water recharged in the uplifted Black Hills area mixes with the regional flow system at lower elevations; however, interfaces and mixing conditions are not well defined. Both aquifers are potential sources for numerous large springs in the Black Hills area, and hydraulic connections are possible in other locations because of large secondary porosity and permeability in both aquifers. Ground-water flowpaths and velocities in both aquifers are influenced by anisotropic and heterogeneous hydraulic properties caused by secondary porosity resulting from fractures, faults, and dissolution activity. Karst features, including sinkholes, collapse features, solution cavities, and caves, in the Madison aquifer, and collapse breccia associated with dissolution of interbedded evaporites in the Minnelusa aquifer, create the potential for the introduction and rapid transport of contaminants within the Madison and Minnelusa aquifers.

Geochemistry is a useful tool for better understanding the complex flow systems in the Madison and Minnelusa aquifers. The major-ion chemistry of water from these aquifers is an important water-quality consideration. Isotope information provides insights regarding recharge areas and traveltimes. Both major-ion and isotope information provide insights regarding flowpaths within the Madison and Minnelusa aquifers and potential interconnections between them.

Purpose and Scope

The purpose of this report is to present geochemical information for the Madison and Minnelusa aquifers in the Black Hills area of South Dakota, with an emphasis on information relating to understanding the ground-water flow conditions in these aquifers. The report includes discussions of major-ion and isotope chemistry of the Madison and Minnelusa aquifers, possible influences from regional flowpaths, and interactions that may occur between the two aquifers.

Previous Investigations

Previous investigations have provided various information regarding the geochemistry of the Madison and Minnelusa aquifers in the Black Hills area. The geochemical evolution of ground water in the Madison and Minnelusa aquifers has been studied by Bowles and Braddock (1963), Braddock and Bowles (1963), Back and others (1983), Busby and others (1983, 1991, 1995), Plummer and others (1990), and Naus (1999). Potential source aquifers for springs in the Black Hills area were investigated by Alexander and others (1988, 1989), Whalen (1994), Klemp (1995), and Wenker (1997). Browne (1992) studied water-quality characteristics and geochemical differentiation of the Madison and Minnelusa aquifers near Rapid City. Applications of oxygen and hydrogen isotopes to the study of ground-water source areas, flowpaths, and mixing in the Madison aquifer in the Black Hills area have been presented by Back and others (1983), Busby and others (1983), Greene (1997, 1999), and Anderson and others (1999).

Acknowledgments

The authors acknowledge the efforts of the West Dakota Water Development District for helping to develop and support the Black Hills Hydrology Study. West Dakota's coordination of various local and county cooperators has been a key element in making this study possible. The authors also recognize the numerous local and county cooperators represented by West Dakota, as well as the numerous private citizens who have helped provide guidance and support for the Black Hills Hydrology Study. The South Dakota Department of Environment and Natural Resources has provided support and extensive technical assistance to the study. David Parkhurst, U.S. Geological Survey, provided extensive guidance and numerous insights regarding this report. In addition, the authors acknowledge technical assistance from many faculty and students at the South Dakota School of Mines and Technology.

DESCRIPTION OF STUDY AREA

The study area consists of the topographically defined Black Hills and adjacent areas located in western South Dakota (fig. 1). Outcrops of the Madison Limestone and Minnelusa Formation, as well as the generalized outer extent of the Inyan Kara Group, which approximates the outer extent of the Black Hills area, also are shown in figure 1. The study area includes most of the larger communities in western South Dakota and contains about one-fifth of the State's population.

The Black Hills are a dome-shaped uplift about 125 miles long and 60 miles wide (Feldman and Heimlich, 1980). Land-surface elevations range from about 7,200 ft at the highest peaks to about 3,000 ft in the surrounding plains. The overall climate of the study area is continental, with generally low precipitation amounts, hot summers, cold winters, and extreme variations in both precipitation and temperatures (Johnson, 1933). Local climatic conditions are affected by topography, with generally lower temperatures and higher precipitation at the higher elevations.

The average annual precipitation for the study area (1931-98) is 18.61 inches, and has ranged from 10.22 inches for water year 1936 to 27.39 inches for water year 1995 (Driscoll, Hamade, and Kenner, 2000). The largest precipitation amounts typically occur in the northern Black Hills near Lead, where average annual precipitation exceeds 29 inches. Annual averages (1931-98) for counties within the study area range from 16.35 inches for Fall River County to 23.11 inches for Lawrence County. The average annual temperature is 43.9°F (U.S. Department of Commerce, 1999) and ranges from 48.7°F at Hot Springs to approximately 37°F near Deerfield Reservoir. Average annual evaporation generally exceeds average annual precipitation throughout the study area. Average pan evaporation for April through October is about 30 inches at Pactola Reservoir and about 50 inches at Oral.

Geologic Setting

The oldest geologic units in the study area are the Precambrian metamorphic and igneous rocks (fig. 2), which underlie the Paleozoic, Mesozoic, and Cenozoic rocks and sediments, except where exposed at the land surface. The Precambrian rocks range in age from about 1.7 to 2.5 billion years, and were eroded to a gentle undulating plain at the beginning of the Paleozoic era (Gries, 1996). The Paleozoic and Mesozoic rocks were deposited as nearly horizontal beds and were later uplifted during the rise of the Black Hills during the Laramide orogeny. Uplift during the Laramide orogeny and related erosion exposed the Precambrian rocks in the central core of the Black Hills with the Paleozoic and Mesozoic sedimentary rocks exposed in roughly concentric rings around the core. Deformation during the Laramide orogeny contributed to the numerous fractures, folds, and other features present throughout the Black Hills. Tertiary intrusive activity in the northern Black Hills (fig. 3) also contributed to rock fracturing.

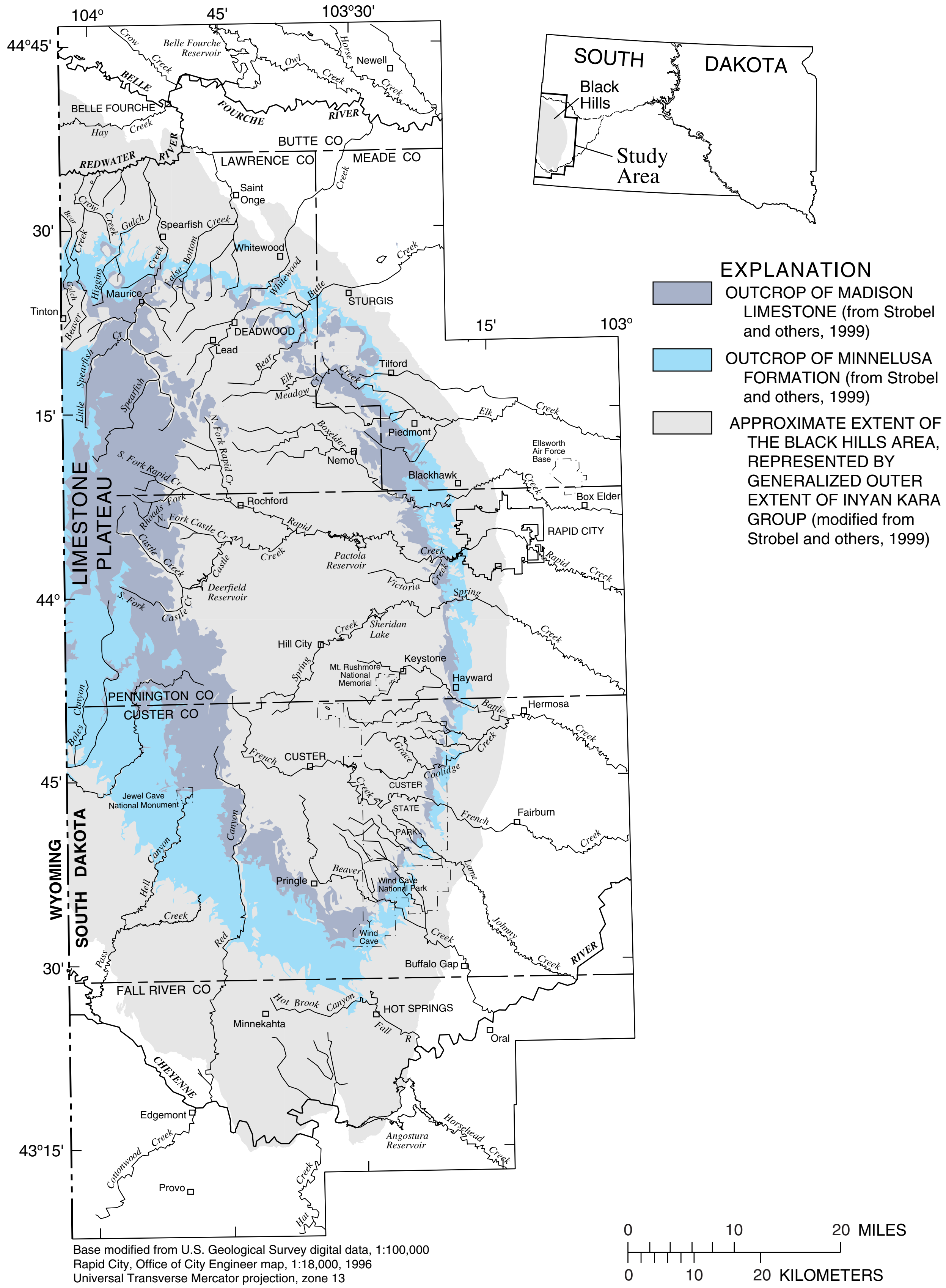

Figure 1. Generalized outcrops of Madison Limestone, Minnelusa Formation, and outer extent of Inyan Kara Group within the study area for Black Hills Hydrology Study.

ERATHEM	SYSTEM	ABBREVIATION FOR STRATIGRAPHIC INTERVAL	STRATIGRAPHIC UNIT	THICKNESS IN FEET	DESCRIPTION
CENOZOIC	QUATERNARY & TERTIARY (?)	QTac	UNDIFFERENTIATED SANDS AND GRAVELS	0-50	Alluvial and colluvial materials.
		Tw	WHITE RIVER GROUP	0-300	Light colored clays with sandstone channel fillings and local limestone lenses.
	TERTIARY	Tui	INTRUSIVE IGNEOUS ROCKS	--	Includes rhyolite, latite, trachyte, and phonolite.
MESOZOIC	CRETACEOUS	Kps	PIERRE SHALE	1,200-2,700	Principal horizon of limestone lenses giving teepee buttes. Dark-gray shale containing scattered concretions. Widely scattered limestone masses, giving small teepee buttes. Black fissile shale with concretions.
			NIOBRARA FORMATION	[1]80-300	Impure chalk and calcareous shale.
			CARLILE SHALE: Turner Sandy Member; Wall Creek Member	[1]350-750	Light-gray shale with numerous large concretions and sandy layers. Dark-gray shale.
			GREENHORN FORMATION	225-380	Impure slabby limestone. Weathers buff. Dark-gray calcareous shale, with thin Orman Lake limestone at base.
			GRANEROS GROUP: BELLE FOURCHE SHALE	150-850	Gray shale with scattered limestone concretions. Clay spur bentonite at base.
			GRANEROS GROUP: MOWRY SHALE	125-230	Light-gray siliceous shale. Fish scales and thin layers of bentonite.
			GRANEROS GROUP: MUDDY SANDSTONE / NEWCASTLE SANDSTONE	0-150	Brown to light-yellow and white sandstone.
			GRANEROS GROUP: SKULL CREEK SHALE	150-270	Dark-gray to black siliceous shale.
		Kik	INYAN KARA GROUP: FALL RIVER FORMATION	10-200	Massive to slabby sandstone.
			INYAN KARA GROUP: LAKOTA FM: Fuson Shale; Minnewaste Limestone; Chilson Member	10-190 0-25 25-485	Coarse gray to buff cross-bedded conglomeratic sandstone, interbedded with buff, red, and gray clay, especially toward top. Local fine-grained limestone.
	JURASSIC	Ju	MORRISON FORMATION	0-220	Green to maroon shale. Thin sandstone.
			UNKPAPA SS	0-225	Massive fine-grained sandstone.
			SUNDANCE FORMATION: Redwater Member; Lak Member; Hulett Member; Stockade Beaver Mem.; Canyon Spr Member	250-450	Greenish-gray shale, thin limestone lenses. Glauconitic sandstone; red sandstone near middle.
			GYPSUM SPRING FORMATION	0-45	Red siltstone, gypsum, and limestone.
	TRIASSIC	ŦPs	SPEARFISH FORMATION: Goose Egg Equivalent	375-800	Red sandy shale, soft red sandstone and siltstone with gypsum and thin limestone layers. Gypsum locally near the base.
PALEOZOIC	PERMIAN	Pmk	MINNEKAHTA LIMESTONE	[1]25-65	Thin to medium-bedded fine-grained, purplish-gray laminated limestone.
		Po	OPECHE SHALE	[1]25-150	Red shale and sandstone.
	PERMIAN / PENNSYLVANIAN	PIPm	MINNELUSA FORMATION	[1]375-1,175	Yellow to red cross-bedded sandstone, limestone, and anhydrite locally at top. Interbedded sandstone, limestone, dolomite, shale, and anhydrite. Red shale with interbedded limestone and sandstone at base.
	MISSISSIPPIAN	MDm	MADISON (PAHASAPA) LIMESTONE	[1]250-1,000	Massive light-colored limestone. Dolomite in part. Cavernous in upper part.
	DEVONIAN		ENGLEWOOD FORMATION	30-60	Pink to buff limestone. Shale locally at base.
	ORDOVICIAN	Ou	WHITEWOOD (RED RIVER) FORMATION	[1]0-235	Buff dolomite and limestone.
			WINNIPEG FORMATION	[1]0-150	Green shale with siltstone.
	CAMBRIAN	O€d	DEADWOOD FORMATION	[1]0-500	Massive to thin-bedded buff to purple sandstone. Greenish glauconitic shale, flaggy dolomite, and flat-pebble limestone conglomerate. Sandstone, with conglomerate locally at the base.
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.

[1]Modified based on drill-hole data

Modified from information furnished by the Department of Geology and Geological Engineering, South Dakota School of Mines and Technology (written commun., January 1994)

Figure 2. Stratigraphic section for the Black Hills.

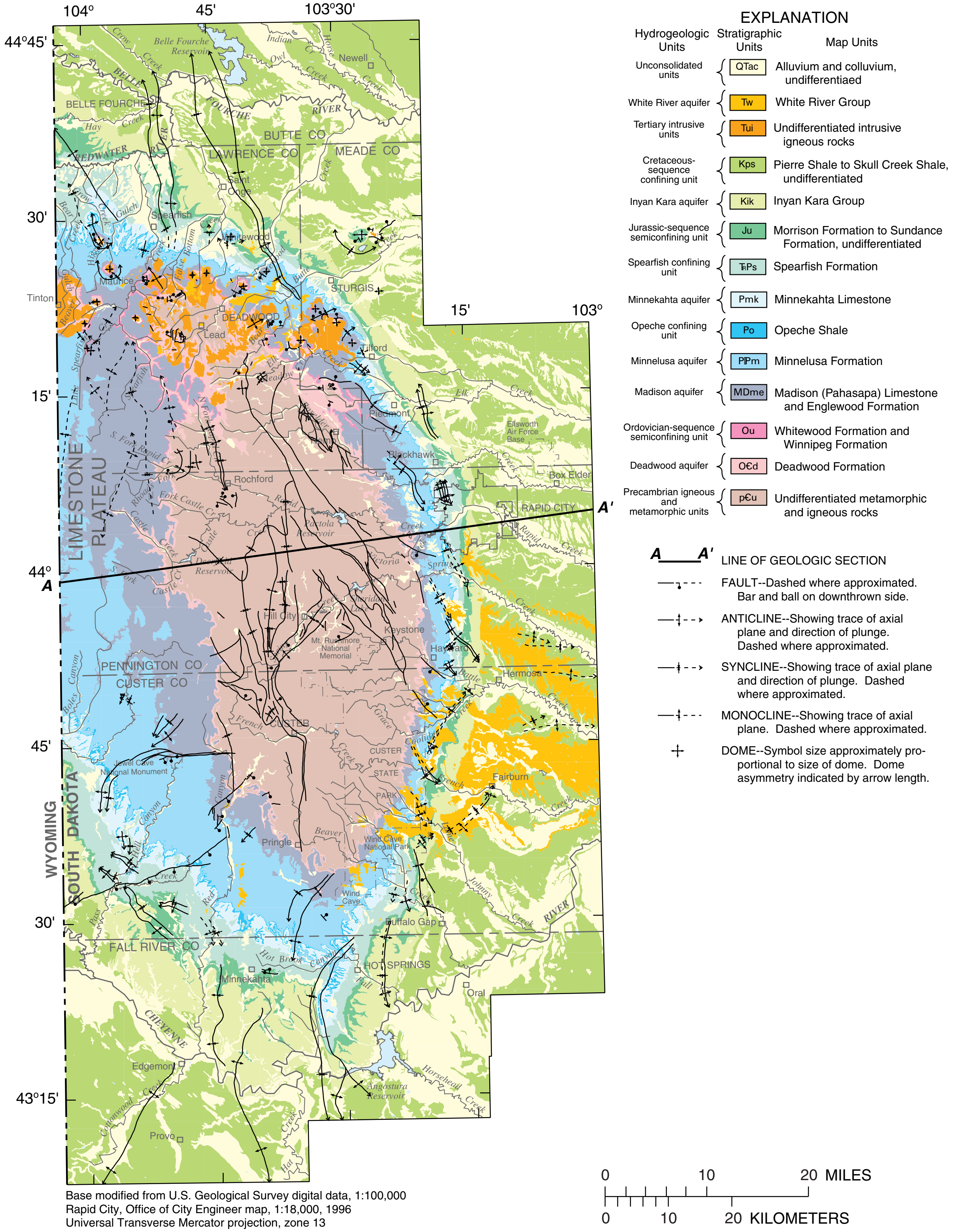

Figure 3. Distribution of hydrogeologic units in the Black Hills area (modified from Strobel and others, 1999).

Surrounding the central core is a layered series of sedimentary rocks including outcrops of the Madison Limestone (also locally known as the Pahasapa Limestone) and the Minnelusa Formation (fig. 3). The bedrock sedimentary units typically dip away from the uplifted Black Hills at angles that can approach or exceed 15 to 20 degrees near the outcrops, and decrease with distance from the uplift to less than 1 degree (Carter and Redden, 1999a, 1999b, 1999c, 1999d, 1999e) (fig. 4). Following are descriptions for selected bedrock formations from the Deadwood Formation through the Inyan Kara Group.

The oldest sedimentary unit in the study area is the Cambrian- and Ordovician-age Deadwood Formation, which is composed primarily of brown to light-gray glauconitic sandstone, shale, limestone, and local basal conglomerate (Strobel and others, 1999). These sediments were deposited on top of a generally horizontal plain of Precambrian rocks in a coastal to near-shore environment (Gries, 1975). The thickness of the Deadwood Formation increases from south to north in the study area and ranges from 0 to 500 ft (Carter and Redden, 1999e). In the northern and central Black Hills, the Deadwood Formation is disconformably overlain by Ordovician rocks, which include the Whitewood and Winnipeg Formations. The Winnipeg Formation is absent in the southern Black Hills, and the Whitewood Formation has eroded to the south and is not present south of the approximate latitude of Nemo (DeWitt and others, 1986). In the southern Black Hills, the Deadwood Formation is unconformably overlain by the Devonian- and Mississippian-age Englewood Formation because of the absence of the Ordovician sequence.

The Mississippian-age Madison Limestone is a massive, gray to buff limestone that is locally dolomitic (Strobel and others, 1999). The Madison Limestone, which was deposited as a marine carbonate, was exposed at land surface for approximately 50 million years. During this period, significant erosion, soil development, and karstification occurred (Gries, 1996). There are numerous caves and fractures within the upper part of the formation (Peter, 1985). The thickness of the Madison Limestone increases from south to north in the study area and ranges from almost zero in the southeast corner of the study area (Rahn, 1985) to 1,000 ft east of Belle Fourche (Carter and Redden, 1999d). Local variations in thickness are due largely to the karst topography that developed before the deposition of the overlying formations (DeWitt and others, 1986). Because the surface of the Madison Limestone was exposed to weathering and karstification for millions of years, the formation is unconformably overlain by the Pennsylvanian- and Permian-age Minnelusa Formation. The Madison Limestone is underlain by the Englewood Formation, which Gries (1996) included as an impure basal phase of the Madison Limestone but Fahrenbach (1995) described as a separate unit from the Madison Limestone. The Madison Limestone and equivalent units are regionally extensive throughout the northern Great Plains area and pinch out in southern and eastern South Dakota.

The Pennsylvanian- and Permian-age Minnelusa Formation consists mostly of yellow to red cross-stratified sandstone, limestone, dolomite, and shale (Strobel and others, 1999). Anhydrite cements are prevalent in many layers within the subsurface, but generally have been removed by dissolution at or near outcrop areas (DeWitt and others, 1986). Collapse features filled with breccia (breccia pipes) occur within the upper part of the Minnelusa Formation in many locations (Braddock, 1963; Long and others, 1999; Epstein, 2000). The thickness of the Minnelusa Formation in the study area increases from north to south in the study area and ranges from about 375 ft near Belle Fourche to 1,175 ft near Edgemont (Carter and Redden, 1999c). The Minnelusa Formation was deposited in a coastal environment, and dune structures at the top of the formation may represent beach sediments (Gries, 1996). Along the northeastern flank of the Black Hills, there is little anhydrite in the subsurface due to a change in the depositional environment (Carter and Redden, 1999c). On the south and southwest side of the study area, there is a considerable increase in thickness of clastic units as well as a thick section of anhydrite. The Minnelusa Formation disconformably is overlain by the Permian-age Opeche Shale, which is overlain by the Minnekahta Limestone. The Minnelusa Formation and equivalent units are regionally extensive throughout the northern Great Plains area and pinch out in eastern South Dakota.

The Permian-age Minnekahta Limestone is a fine-grained, purple to gray laminated limestone (Strobel and others, 1999), which ranges in thickness from 25 to 65 ft in the study area. The Minnekahta Limestone is overlain by the Triassic- and Permian-age Spearfish Formation.

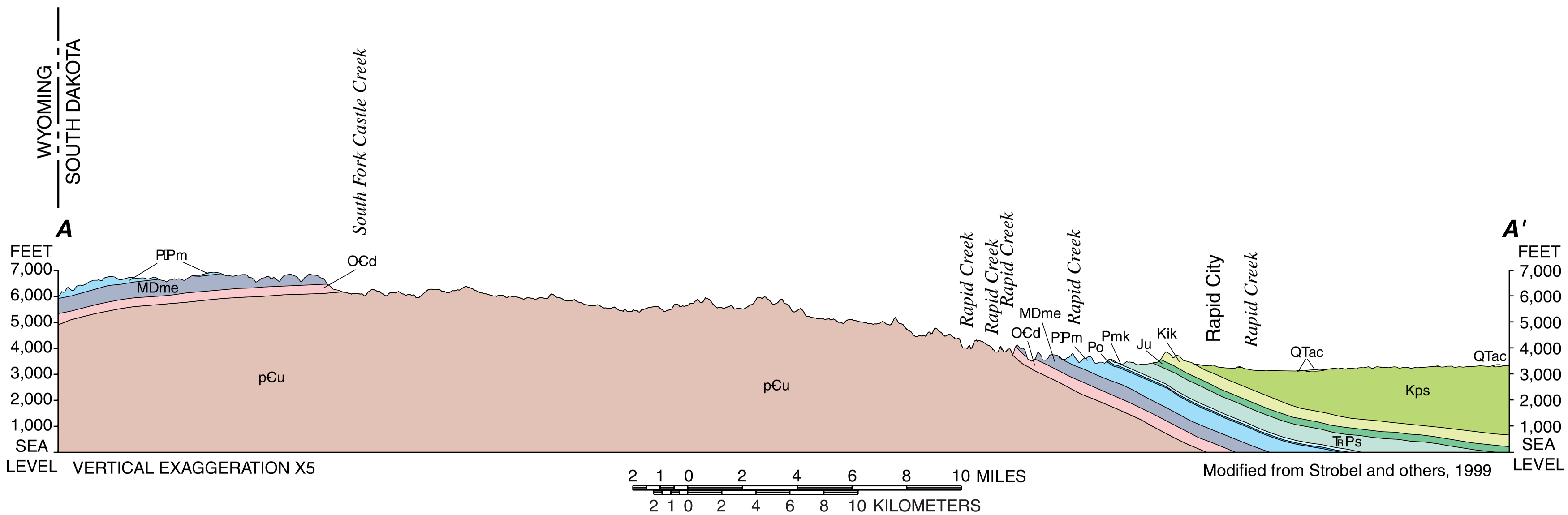

Figure 4. Geologic cross section A-A' (Location of section is shown in figure 3. Abbreviations for stratigraphic intervals are explained in figure 2.).

The Spearfish Formation is a red, silty shale with interbedded red sandstone and siltstone, which ranges in thickness from about 375 to 800 ft (Strobel and others, 1999). The Spearfish Formation contains massive gypsum throughout. The overlying Mesozoic-age units are composed primarily of shale, siltstone, and sandstone deposits, and include the Cretaceous-age Inyan Kara Group. The thickness of the Inyan Kara Group ranges from about 135 to 900 ft in the study area (Carter and Redden, 1999a).

Hydrologic Setting

The hydrologic setting of the Black Hills area is schematically illustrated in figure 5, and the areal distribution of hydrogeologic units is shown in figure 3. Four of the major bedrock aquifers in the Black Hills area (Deadwood, Madison, Minnelusa, and Inyan Kara aquifers) are regionally extensive and are discussed in the following sections in the context of both regional and local hydrologic settings. A fifth major aquifer (Minnekahta) generally is used only locally, as are aquifers in the metamorphic and igneous rocks within the central core area.

Regional Setting

The Paleozoic aquifers underlie parts of Montana, North Dakota, South Dakota, Wyoming, and Canada (Downey, 1984). The Canadian part of the regional aquifer system is not described or shown in this report. For the description of the regional setting (a large part of the northern Great Plains), it is convenient to use aquifer names of Downey and Dinwiddie (1988) and Whitehead (1996). The Paleozoic aquifers include the Cambrian-Ordovician aquifer (or Deadwood aquifer in the Black Hills), Mississippian aquifer (or Madison aquifer in the Black Hills), and the Pennsylvanian aquifer (or Minnelusa aquifer in the Black Hills). The Paleozoic aquifers are recharged in outcrop areas around major uplifts (fig. 6).

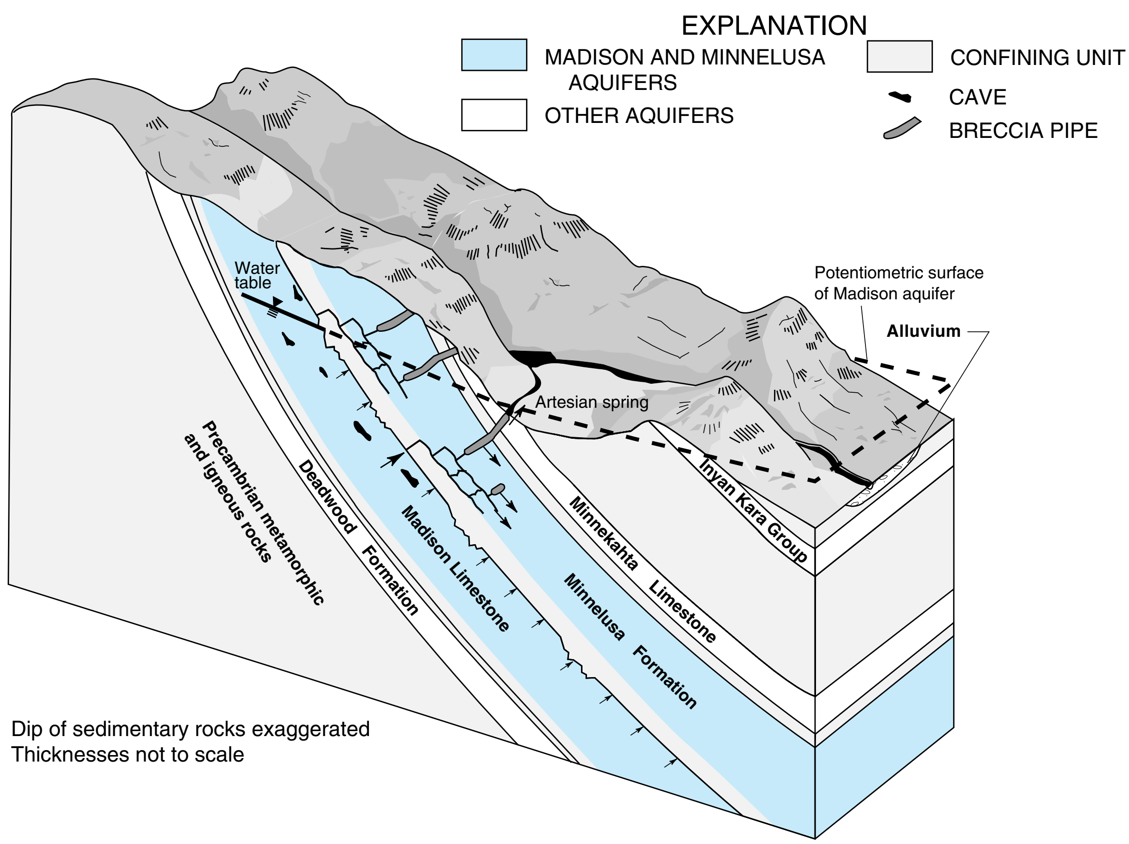

Figure 5. Schematic showing hydrogeologic setting of the Black Hills area. Figure also shows caves and breccia pipes, which contribute to secondary porosity in the Madison and Minnelusa aquifers. Breccia pipes may result from upward leakage from the Madison aquifer, creating conduits for artesian springs.

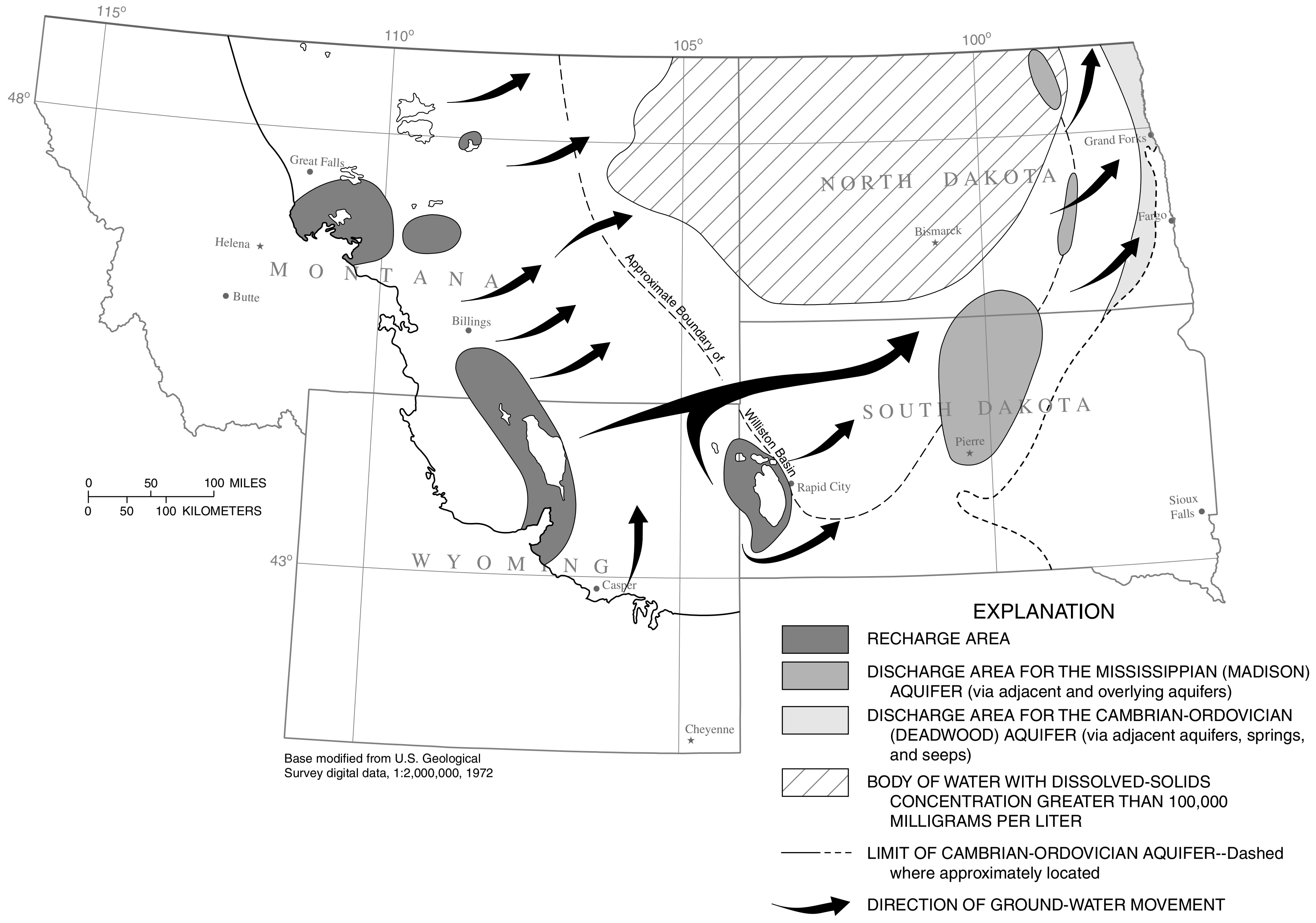

Figure 6. General direction of ground-water flow in Paleozoic aquifers in the northern Great Plains (modified from Downey and Dinwiddie, 1988 and Whitehead, 1996).

The Cambrian-Ordovician (or Deadwood) aquifer consists of sandstones of Cambrian age (Deadwood Formation and equivalents) and limestones of Ordovician age. The Cambrian-Ordovician aquifer contains freshwater, with dissolved solids concentrations less than 1,000 mg/L (milligrams per liter), only in an area surrounding the Black Hills and in a small area in north-central Wyoming (Whitehead, 1996).

The Mississippian (or Madison) aquifer is contained within the limestones, siltstones, sandstones, and dolomite of the Madison Limestone and equivalent units. Generally, water in the Mississippian aquifer is confined except in outcrop areas. Flow in the Mississippian aquifer generally is from the recharge areas to the northeast (fig. 6). Discharge from the Mississippian aquifer occurs by upward leakage to the lower Cretaceous aquifer in central South Dakota and eastern flow to the Cambrian-Ordovician aquifer in eastern North Dakota (Downey, 1984). Water in the Mississippian aquifer is fresh only in small areas near recharge areas and becomes slightly saline to saline as it moves downgradient. The water is a brine with dissolved solids concentrations greater than 300,000 mg/L in the deep parts of the Williston basin (Whitehead, 1996).

The Pennsylvanian (or Minnelusa) aquifer is comprised of sandstones and limestones of the Minnelusa Formation and equivalent units of Pennsylvanian age. Water in the Pennsylvanian aquifer moves from recharge areas to discharge areas in eastern South Dakota (Downey and Dinwiddie, 1988). Some water discharges by upward leakage to the lower Cretaceous aquifer (Swenson, 1968; Gott and others, 1974).

Several sandstone units compose the lower Cretaceous aquifer, which generally is known as the Inyan Kara aquifer in South Dakota and the Dakota aquifer in North Dakota. Generally, water in the lower Cretaceous aquifer is confined by several thick shale layers except in aquifer outcrop areas around structural uplifts, such as the Black Hills. Water in the lower Cretaceous aquifer generally moves northeasterly from high-elevation recharge areas to discharge areas in eastern North Dakota and South Dakota (Whitehead, 1996). Although the aquifer is widespread, it contains little freshwater. Much of the saline water is believed to be from upward leakage of mineralized water from the Paleozoic aquifers (Whitehead, 1996).

Local Setting

Many of the sedimentary units in the Black Hills area contain aquifers, both within and beyond the study area. Within the Paleozoic rock interval, aquifers in the Deadwood Formation, Madison Limestone, Minnelusa Formation, and Minnekahta Limestone are used extensively. These aquifers are collectively confined by the underlying Precambrian rocks (fig. 5) and the overlying Spearfish Formation (fig. 2). Individually, these aquifers are separated by minor confining units or by relatively impermeable layers within the individual units. Extremely variable leakage can occur between these aquifers (Peter, 1985; Greene, 1993).

Artesian (confined) conditions generally exist within the sedimentary aquifers where an upper confining unit is present. Under artesian conditions, water in a well will rise above the top of the aquifer in which it is completed. Flowing wells will result when drilled in areas where the potentiometric surface is above the land surface. Flowing wells and artesian springs that originate from confined aquifers are common around the periphery of the Black Hills.

Numerous headwater springs from the Paleozoic units on the western side of the study area (fig. 3) provide base flow for many streams. These streams flow across the central core of the Black Hills, and most Black Hills streams lose all or part of their flow as they cross outcrops of the Madison Limestone and Minnelusa Formation (Hortness and Driscoll, 1998). Karst features of the Madison Limestone, including sinkholes, collapse features, solution cavities, and caves are responsible for the Madison aquifer's capacity to accept streamflow recharge. Large streamflow losses also occur in many locations within the outcrop of the Minnelusa Formation (Hortness and Driscoll, 1998). Large artesian springs occur in many locations downgradient from these loss zones, most commonly within or near the outcrop of the Spearfish Formation, providing an important source of base flow in many streams beyond the periphery of the Black Hills (Rahn and Gries, 1973; Miller and Driscoll, 1998).

Although the Precambrian basement rocks generally have low permeability and form the lower confining unit for the series of overlying aquifers, localized aquifers occur in many locations in the central core of the Black Hills, where enhanced secondary permeability has resulted from weathering and fracturing. Where the Precambrian-rock aquifers are saturated, water-table (unconfined) conditions generally occur and land-surface topography can strongly control ground-water flow directions.

Overlying the Precambrian rocks is the Deadwood aquifer, which is contained within the Deadwood Formation and is utilized primarily near its outcrop area. Regionally, the Precambrian rocks act as a lower confining unit to the Deadwood aquifer, and the Whitewood and Winnipeg Formations, where present, act as overlying semiconfining units (Strobel and others, 1999). Where the Whitewood and Winnipeg Formations are absent, the Deadwood aquifer is overlain by the Englewood Formation, which Strobel and others (1999) included as part of the Madison aquifer.

The Madison aquifer generally is considered to consist primarily of the karstic upper part of the Madison Limestone, where numerous fractures and solution openings provide extensive secondary porosity. Strobel and others (1999) included the entire Madison Limestone and the Englewood Formation in their delineation of the Madison aquifer, which receives recharge from streamflow losses and precipitation on its outcrop. In this report, outcrops of the Madison Limestone and Englewood Formation (fig. 3) are referred to as the outcrop of the Madison Limestone for simplicity. Low-permeability layers in the lower part of the Minnelusa Formation generally act as an upper confining unit to the Madison aquifer. However, karst features in the top of the Madison Limestone may contribute to reduced competency of the overlying confining unit in some locations.

The potentiometric surface of the Madison aquifer is shown in figure 7. In many locations, ground-water flow in the Madison aquifer follows the bedding dip, which generally is radially away from the central core of the Black Hills. Ground-water flowpaths and velocities also are heavily influenced by anisotropic and heterogeneous hydraulic properties of the Madison aquifer. Flowpaths are not necessarily orthogonal to potentiometric contours because of highly variable directional transmissivities and may be further influenced by vertical flow components between the Madison and Minnelusa aquifers. Long (2000) described anisotropy in the Madison aquifer in the Rapid City area that causes ground-water flow to be nearly parallel to the potentiometric contours in some cases. Regional ground-water flow from the west may influence the potentiometric surface in the northern and southwestern parts of the study area.

The Minnelusa aquifer is contained within the thin layers of sandstone, dolomite, and anhydrite in the lower portion of the Minnelusa Formation and within sandstone and anhydrite in the upper portion. Shales in the lower portion of the Minnelusa Formation act as a confining unit to the underlying Madison aquifer; however, the extent of hydraulic separation is spatially variable and is not well defined, as discussed in a subsequent section of this report. The Minnelusa aquifer may have enhanced vertical hydraulic conductivity in areas of collapse breccia (breccia pipes in fig. 5) associated with dissolution of interbedded evaporites (Long and others, 1999). Hayes (1999) concluded that upward leakage of relatively fresh water from the Madison aquifer is a probable agent for dissolution of anhydrite within the Minnelusa Formation, which is a likely mechanism for development of breccia pipes within the Minnelusa Formation. Exposed breccia pipes, which are common in many areas, were hypothesized to be conduits for abandoned springs, which migrate outwards from the flanks of the Black Hills over geologic time, keeping pace with regional erosion.

The Minnelusa aquifer receives recharge from streamflow losses and precipitation on its outcrop. Streamflow losses to the Minnelusa aquifer generally are less than to the Madison aquifer (Carter, Driscoll, and Hamade, 2001) because most of the flow is lost to the Madison aquifer before reaching the outcrop of the Minnelusa Formation. The Minnelusa aquifer is confined by the overlying Opeche Shale.

The potentiometric surface of the Minnelusa aquifer is shown in figure 8. Ground-water flow in the Minnelusa aquifer in the study area generally follows the bedding dip, but may be affected by structural features. Regional ground-water flow from the west may influence the potentiometric surface in the northern and southwestern parts of the study area.

The Minnekahta aquifer, which overlies the Opeche Shale, is contained within the Minnekahta Limestone. The Minnekahta aquifer typically is very permeable, but well yields are limited by the aquifer thickness. The overlying Spearfish Formation acts as a confining unit to the Minnekahta aquifer.

Within the Mesozoic rock interval, the Inyan Kara aquifer is used extensively and various other aquifers are used locally to lesser degrees. The Inyan Kara aquifer receives recharge primarily from precipitation on its outcrop and also may receive recharge from leakage from the underlying Paleozoic aquifers (Swenson, 1968; Gott and others, 1974). As much as 4,000 ft of Cretaceous strata (primarily shales) act as the upper confining unit to aquifers in the Mesozoic rock interval.

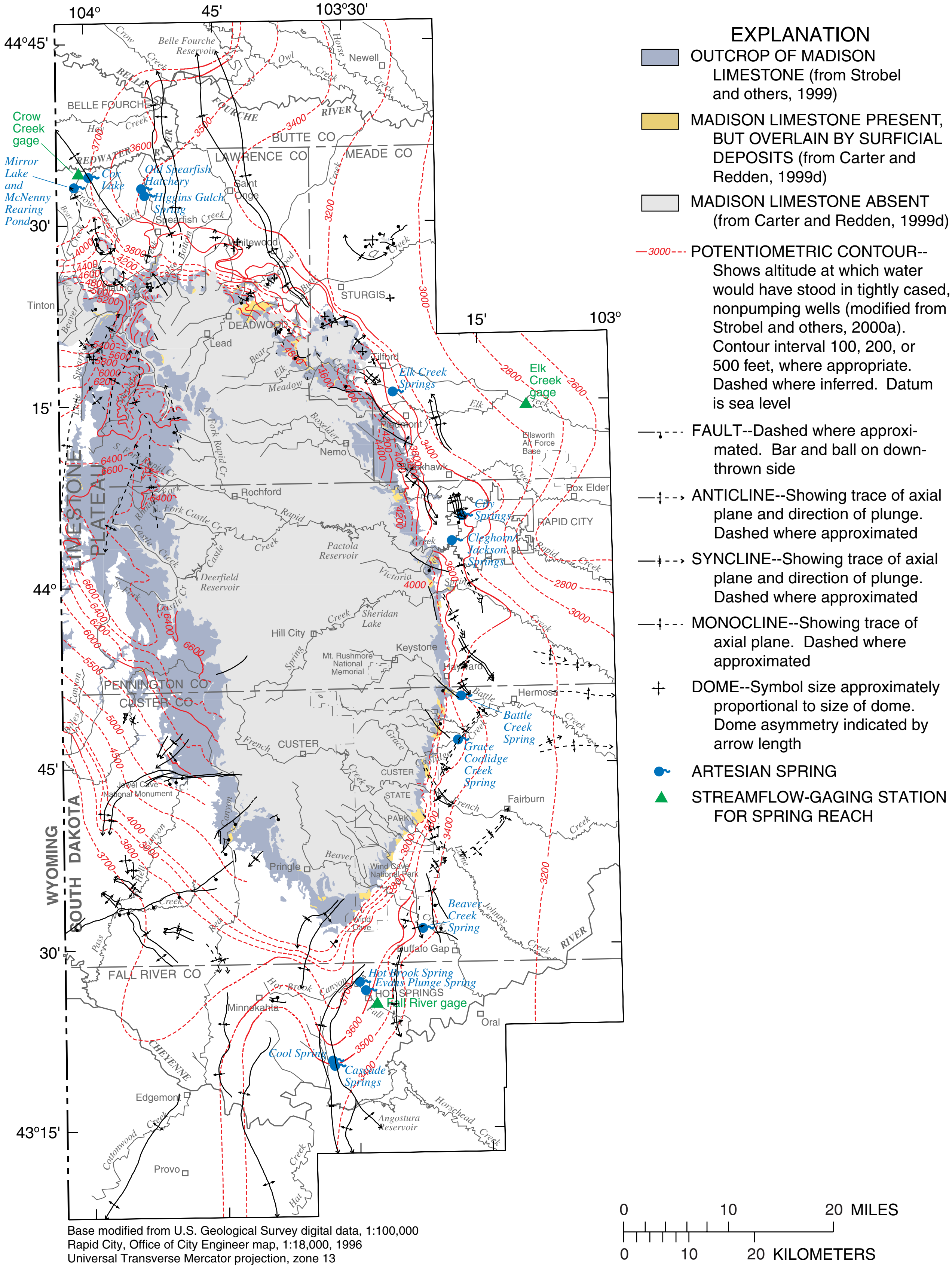

Figure 7. Potentiometric surface of the Madison aquifer and locations of major artesian springs.

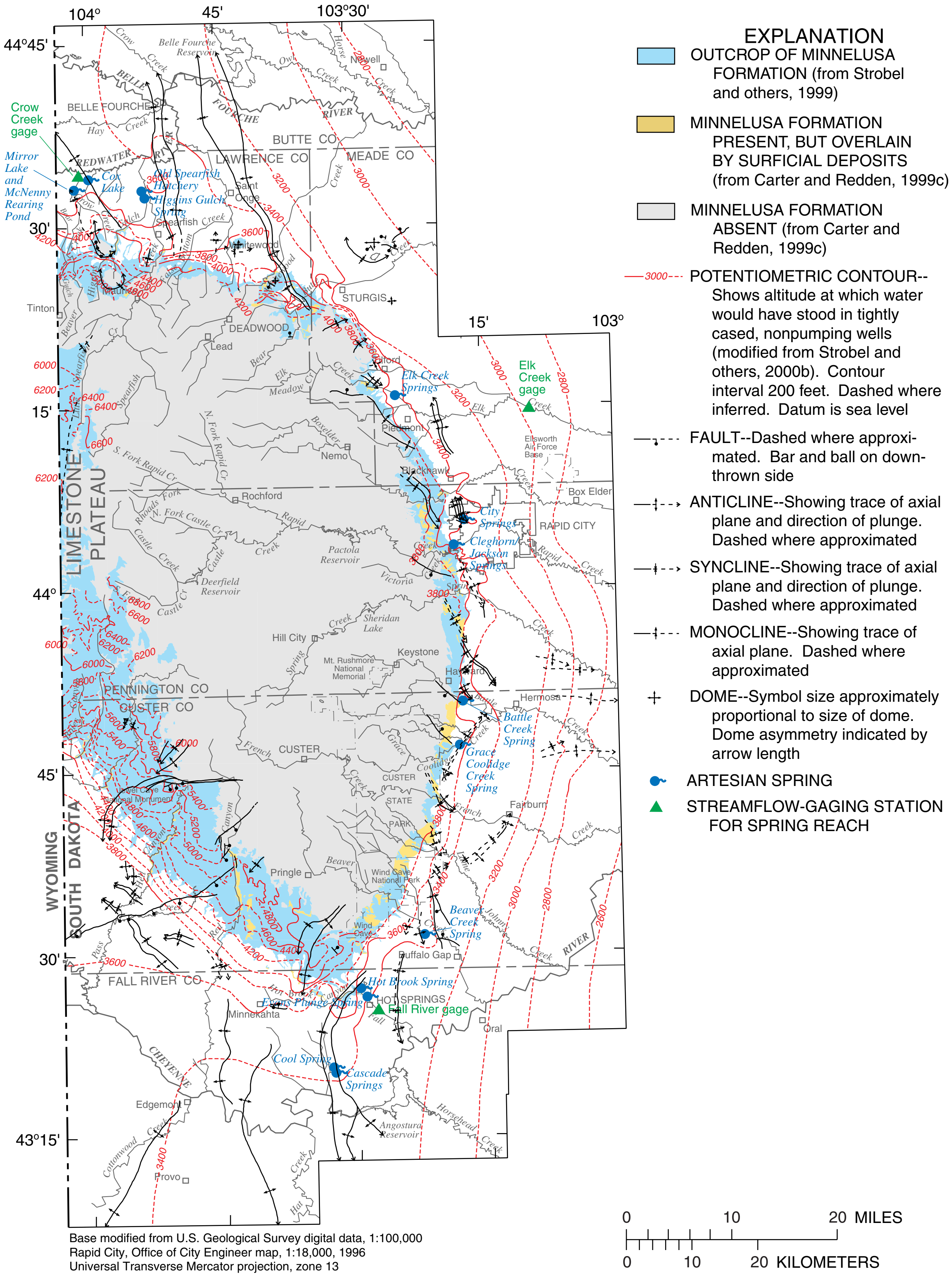

Figure 8. Potentiometric surface of the Minnelusa aquifer and locations of major artesian springs.