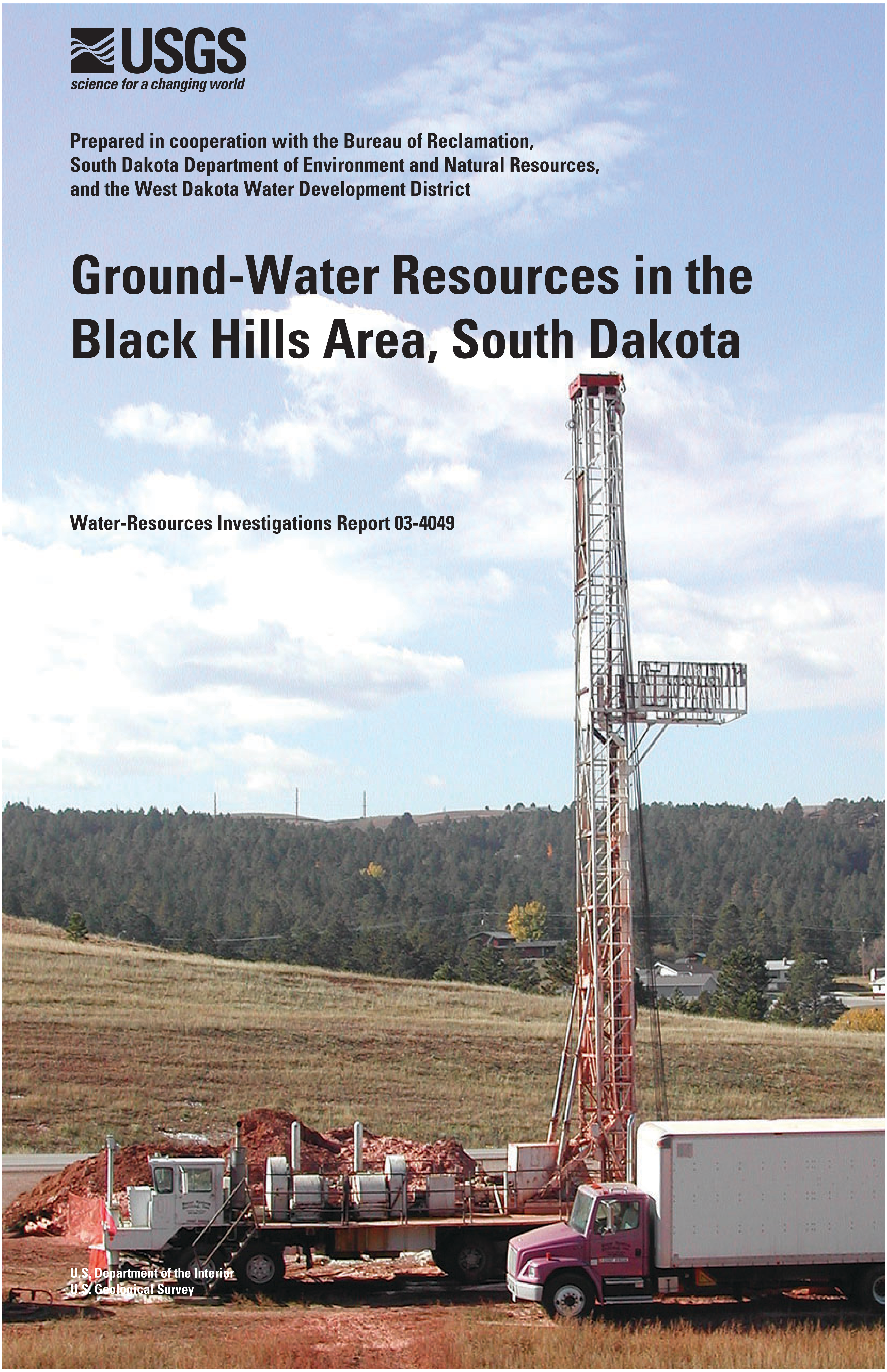

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South Dakota Department of Environment and Natural Resources,
and the West Dakota Water Development District

Ground-Water Resources in the Black Hills Area, South Dakota

Water-Resources Investigations Report 03-4049

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

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Ground-Water Resources in the Black Hills Area, South Dakota

By Janet M. Carter and Daniel G. Driscoll, U.S. Geological Survey, and
J. Foster Sawyer, South Dakota Department of Environment and Natural Resources

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GALE A. NORTON, Secretary

U.S. Geological Survey

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Rapid City, South Dakota: 2003

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CONVERSION FACTORS, VERTICAL DATUM, AND WELL-NUMBERING SYSTEM

Multiply	By	To obtain
acre-foot	1,233	cubic meter
acre-foot	0.001233	cubic hectometer
foot	0.3048	meter
gallons per minute	0.06309	liter per second
inch	2.54	centimeter
inch	25.4	millimeter
mile	1.609	kilometer
square mile	259.0	hectare
square mile	2.590	square kilometer

Temperature in degrees Fahrenheit (° F) may be converted to degrees Celsius (° C) as follows:

$$°C = (°F - 32) / 1.8$$

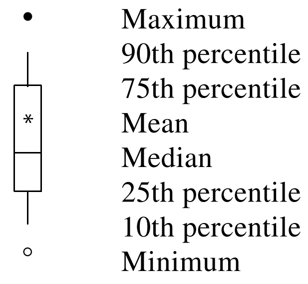
Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929).

OTHER ABBREVIATIONS, ACRONYMS, AND SYMBOLS USED

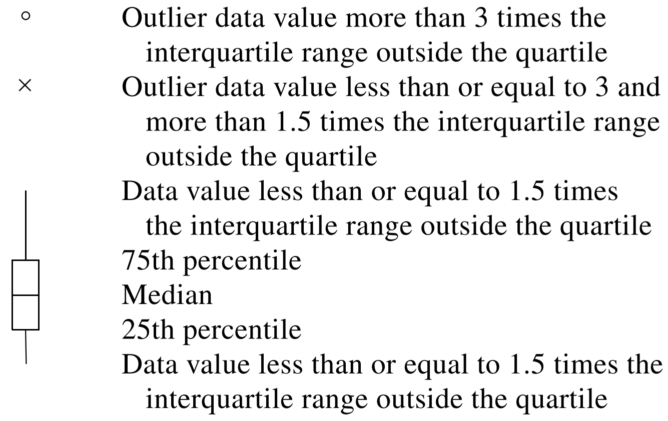
mg/L	milligrams per liter
µg/L	micrograms per liter
pCi/L	picocuries per liter

GWSI	Ground Water Site Inventory database
USEPA	U.S. Environmental Protection Agency
MCL	Maximum Contaminant Level
SMCL	Secondary Maximum Contaminant Level
USGS	U.S. Geological Survey

Boxplots are a useful and concise graphical display for summarizing the distribution of a data set. Two different types of boxplots are used in this report. In both types, the center of the data (known as the median) is shown as the center line of the box. The variation or spread of the data (known as the interquartile range) is shown by the box height.



The first type is a truncated boxplot, and is used for all boxplots that do not show water-quality data. In the truncated boxplot, the whiskers are drawn only to the 90th and 10th percentiles of the data set. Thus, values included in the largest 10 percent and the smallest 10 percent of the data are not shown. The mean, maximum, and minimum values for the data set are shown.



The second type is a standard boxplot, and is used for all boxplots that show water-quality data. In the standard boxplot, the whiskers are drawn only to the last data value that is within 1.5 times the interquartile range (height of the box). Values outside 1.5 times the interquartile range are called “outliers.” For water-quality data, these outliers are of interest when comparing to water-quality standards and general distribution of extreme values.

○	Spring
▼	Water table

Ground-Water Resources in the Black Hills Area, South Dakota

By Janet M. Carter and Daniel G. Driscoll, U.S. Geological Survey, *and*
J. Foster Sawyer, South Dakota Department of Environment and Natural Resources

ABSTRACT

The availability of ground-water resources in the Black Hills area is influenced by many factors including location, local recharge and ground-water flow conditions, and structural features. Thus, the availability of ground water can be extremely variable throughout the Black Hills area, and even when water is available, it may not be suitable for various uses depending on the water quality.

The major bedrock aquifers in the Black Hills area are the Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara aquifers. Minor bedrock aquifers occur in other hydrogeologic units, including confining units, due to fracturing and interbedded permeable layers.

Various information and maps are presented in this report that describe availability and quality of ground-water resources in the Black Hills area. However, there is no guarantee of obtaining usable water at any location due to the extreme potential variability in conditions that can affect the availability and quality of ground water in the area. Maps presented in this report include the distribution of hydrogeologic units; depth to the top of the five formations that contain major aquifers; thickness of the five formations that contain major aquifers; potentiometric maps for the five major aquifers; saturated thickness of the Madison and Minnelusa aquifers; water temperature in the Madison aquifer; specific conductance in the Madison, Minnelusa, and Inyan Kara aquifers; hardness in the Inyan Kara aquifer; sulfate concentrations in the Minnelusa aquifer; and radon concentrations in the Deadwood aquifer.

Water quality of the major aquifers generally is very good in and near outcrop areas but deteriorates progressively with distance from the outcrops. In the Minnelusa aquifer, an abrupt increase in concentrations of dissolved sulfate occurs downgradient from outcrop areas, where a zone of active anhydrite dissolution occurs.

Most limitations for the use of ground water are related to aesthetic qualities associated with hardness and high concentrations of chloride, sulfate, sodium, manganese, and iron. Very few health-related limitations exist for ground water; most limitations are for radionuclides, such as radon and uranium. In addition, high concentrations of arsenic have been measured in a few samples from the Minnelusa aquifer.

INTRODUCTION

Ground water originating in the Black Hills area is used for municipal, industrial, agricultural, and recreational purposes throughout much of western South Dakota. The Black Hills area is an important recharge area for aquifers in the northern Great Plains. About 45 percent of the recent population growth in the Black Hills area has occurred in unincorporated areas where water-supply systems are not provided by municipalities (Carter and others, 2002). Adequate water supplies for various uses can be difficult to obtain at some locations in the Black Hills area.

The Black Hills Hydrology Study was conducted by the U.S. Geological Survey (USGS) during 1990-2002 to assess the quantity, quality, and distribution of water resources within the Black Hills area. The Black Hills Water Management Study was a companion study conducted by the Bureau of Reclamation during 1992-2002 to evaluate alternatives for management of water resources in the area. Information summarized in this report was initially assembled in conjunction with these two studies. This report was produced in cooperation with the Bureau of Reclamation, South Dakota Department of Environment and Natural Resources, and West Dakota Water Development District.

The purpose of this report is to describe ground-water resources in the Black Hills area. Availability and quality of water in the major aquifers (Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara) and various minor aquifers in the Black Hills area are described. Information collected and compiled from both the Black Hills Hydrology Study and the Black Hills Water Management Study that relates to the availability of ground water in the Black Hills area is presented in this report. Specifically, this report contains maps showing: (1) distribution of hydrogeologic units; (2) depth to the top of the five formations that contain major aquifers; (3) thickness of the five formations that contain major aquifers; (4) potentiometric maps for the five major aquifers; (5) saturated thickness of the Madison and Minnelusa aquifers; (6) water temperature in the Madison aquifer; (7) specific conductance in the Madison, Minnelusa, and Inyan Kara aquifers; (8) hardness in the Inyan Kara aquifer; (9) sulfate concentrations in the Minnelusa aquifer; and (10) radon concentrations in the Deadwood aquifer. More detailed information regarding ground-water resources in the Black Hills area was summarized by Carter and others (2002) and Driscoll and others (2002) from a series of previous topical reports.

GROUND-WATER PROCESSES

Precipitation falling on the earth's surface generally infiltrates into the soil horizon, unless the soil is saturated or the infiltration capacity is exceeded. As water infiltrates into the ground, some of it clings to particles of soil or to roots of plants just below the land surface. Water not used by plants can move deeper into the ground through spaces or cracks in the soil, sand, or rocks, until it reaches a water table or a confining unit (such as clay or shale). The top of the water in the soil, sand, or rocks (top of the saturated zone) is called the water table, and the water that fills the spaces and cracks is called ground water. A confining unit is a relatively low-permeability layer of rock through which water cannot easily move. After reaching the water table or confining unit, the water then fills the spaces (voids) and cracks above the water table or above the confining unit.

The process of infiltration of water from the land surface to ground water is called recharge. Ground water is recharged from rain water and snowmelt or from water that leaks through the bottom of some lakes and streams. Water can be discharged from an aquifer by pumping from a well or by flowing naturally from a spring. An aquifer is the underground soil or rock through which ground water can easily move and which supplies usable quantities of water to wells or springs. An aquifer may be only a few feet thick to hundreds of feet thick; it may lie a few feet below the land surface to thousands of feet below; it may underlie just a few acres or as much as thousands of square miles.

Rock materials may be classified as consolidated or unconsolidated. Consolidated rocks (often called bedrock) may consist of limestone, dolomite, sandstone, siltstone, shale, or granite. Unconsolidated rock consists of granular material such as sand, gravel, silt, and clay. The amount of ground water that can flow through soil or rock depends on the size of the spaces in the soil or rock and how well the spaces are connected. Porosity is the percentage of the soil or rock volume that is occupied by pore space, which is void of material. Permeability is the measure of how well the spaces are connected (fig. 1A). An estimated one million cubic miles of the world's ground water is stored within one-half mile below the land surface (U.S. Geological Survey, 1994).

Consolidated rock may contain fractures, small cracks, pore spaces, spaces between layers, and solution openings—all of which can hold water and may be connected. Vertical fractures may intersect horizontal openings, enabling water to move from one layer to another. Water can dissolve carbonate rocks, such as limestone, to form solution openings through which water can move both horizontally and vertically. Caves, such as Wind Cave and Jewel Cave (two of the largest caves in the world; fig. 2), are examples of large solution openings.

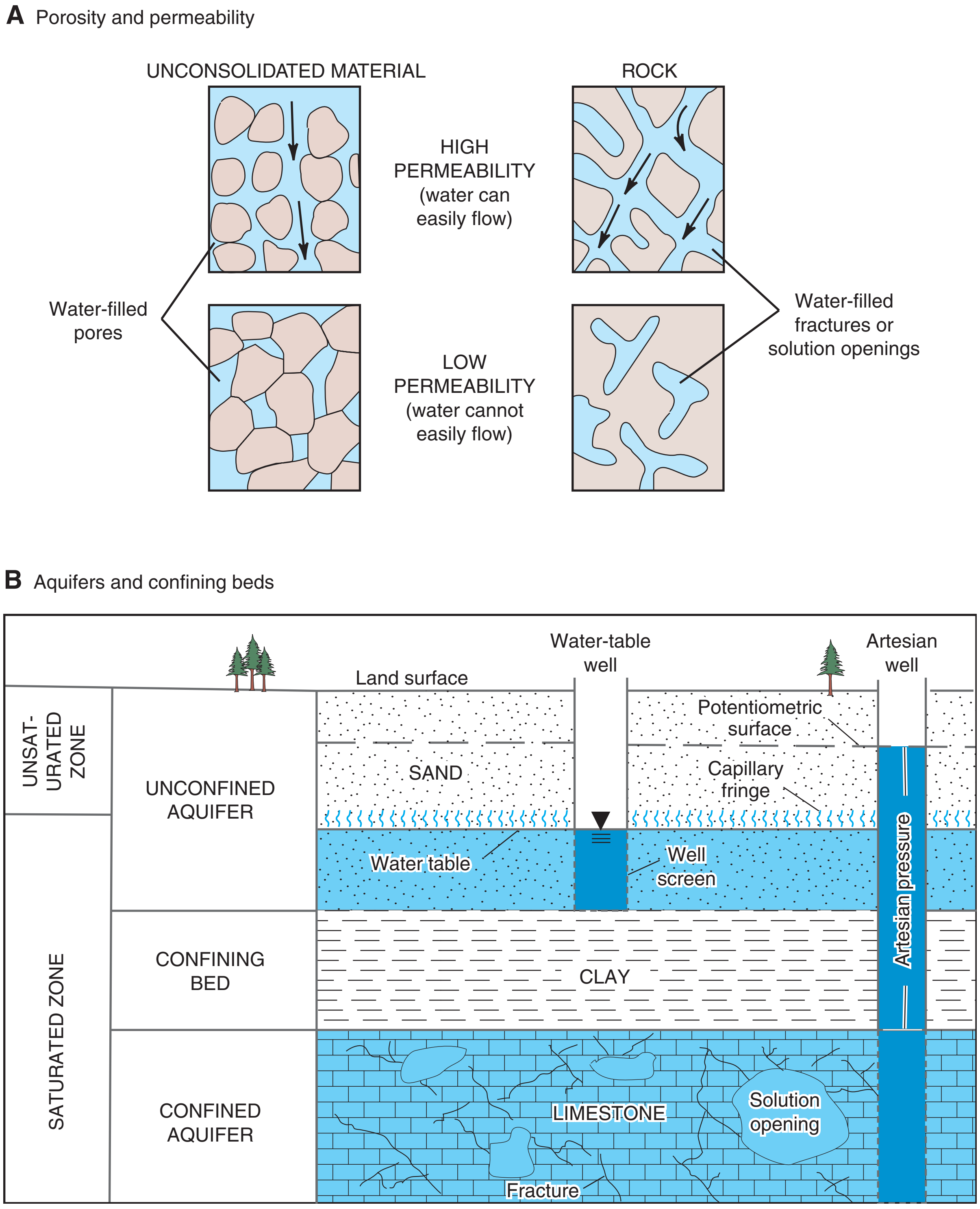


Figure 1. Schematic diagram showing (A) porosity and permeability (modified from Clark and Briar, 1993); and (B) aquifers and confining beds (modified from Heath, 1983).

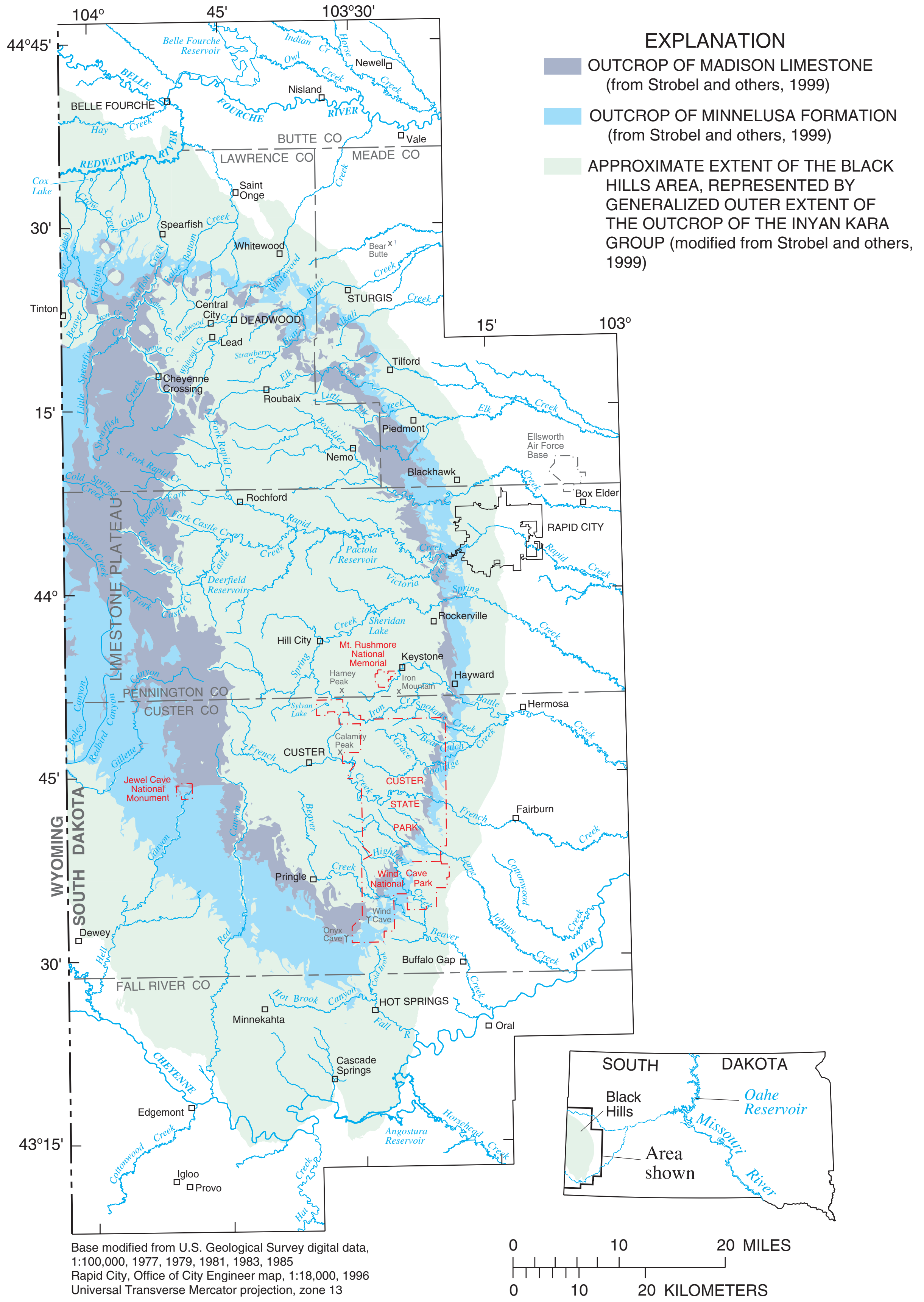


Figure 2. Area of investigation for the Black Hills Hydrology Study.

Unconsolidated materials in the Black Hills area generally consist of sand and gravel, boulders, silt, or clay deposited by streams or in lakes. Alluvial deposits (alluvium) generally are adjacent to streams in the flood plain. Well-sorted unconsolidated material can store large quantities of ground water. The coarser materials—sand and gravel—readily yield water to wells.

Ground water can occur in aquifers under two different conditions. Where water-table conditions occur, water does not fill the formation containing aquifer material all the way to the top and the aquifer is considered unconfined. Where an aquifer is completely filled with water (fully saturated) and is overlain by a confining unit, the water can be confined under pressure and can rise above the top of the aquifer in an artesian well to a level representing the potentiometric surface. In the schematic shown in figure 1B, the potentiometric surface of the confined (artesian) aquifer is higher than the water table of the unconfined aquifer overlying the confined aquifer. Artesian wells will flow where the potentiometric surface is above the land surface. Semiconfining units contain some layers with low permeability but may transmit some water to and from adjacent aquifers.

DESCRIPTION OF STUDY AREA

The study area (fig. 2) consists of the topographically defined Black Hills and adjacent areas located in western South Dakota. The Black Hills are situated between the Cheyenne and Belle Fourche Rivers. The study area includes most of the larger communities in western South Dakota and contains about one-fifth of the State's population.

Outcrops of the Madison Limestone and Minnelusa Formation, which are areas where these geologic formations occur at the land surface, are shown in figure 2. The generalized outer extent of the outcrop of the Inyan Kara Group, which approximates the outer extent of the Black Hills area, also is shown in figure 2.

Climate

The overall climate of the Black Hills area is continental, which is characterized generally by low precipitation amounts, hot summers, cold winters, and extreme variations in both precipitation and temperatures. Local climatic conditions are affected by topography, with generally lower temperatures and higher precipitation at the higher altitudes.

Long-term trends in precipitation for water years 1931-98 for the study area are shown in figure 3; a water year is the 12-month period, October 1 through September 30, and is designated by the calendar year in which it ends. Annual precipitation for the study area averaged 18.61 inches and has ranged from 10.22 inches in water year 1936 to 27.39 inches in water year 1995 (Driscoll, Hamade, and Kenner, 2000).

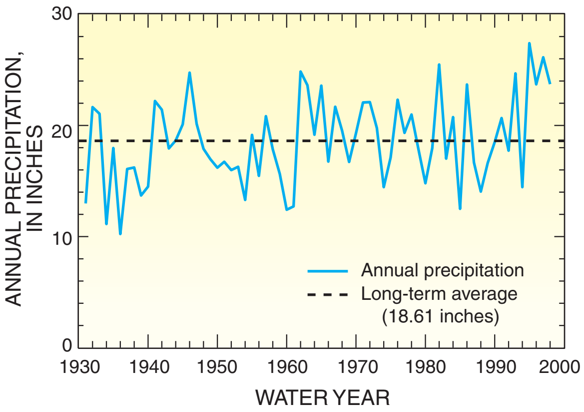


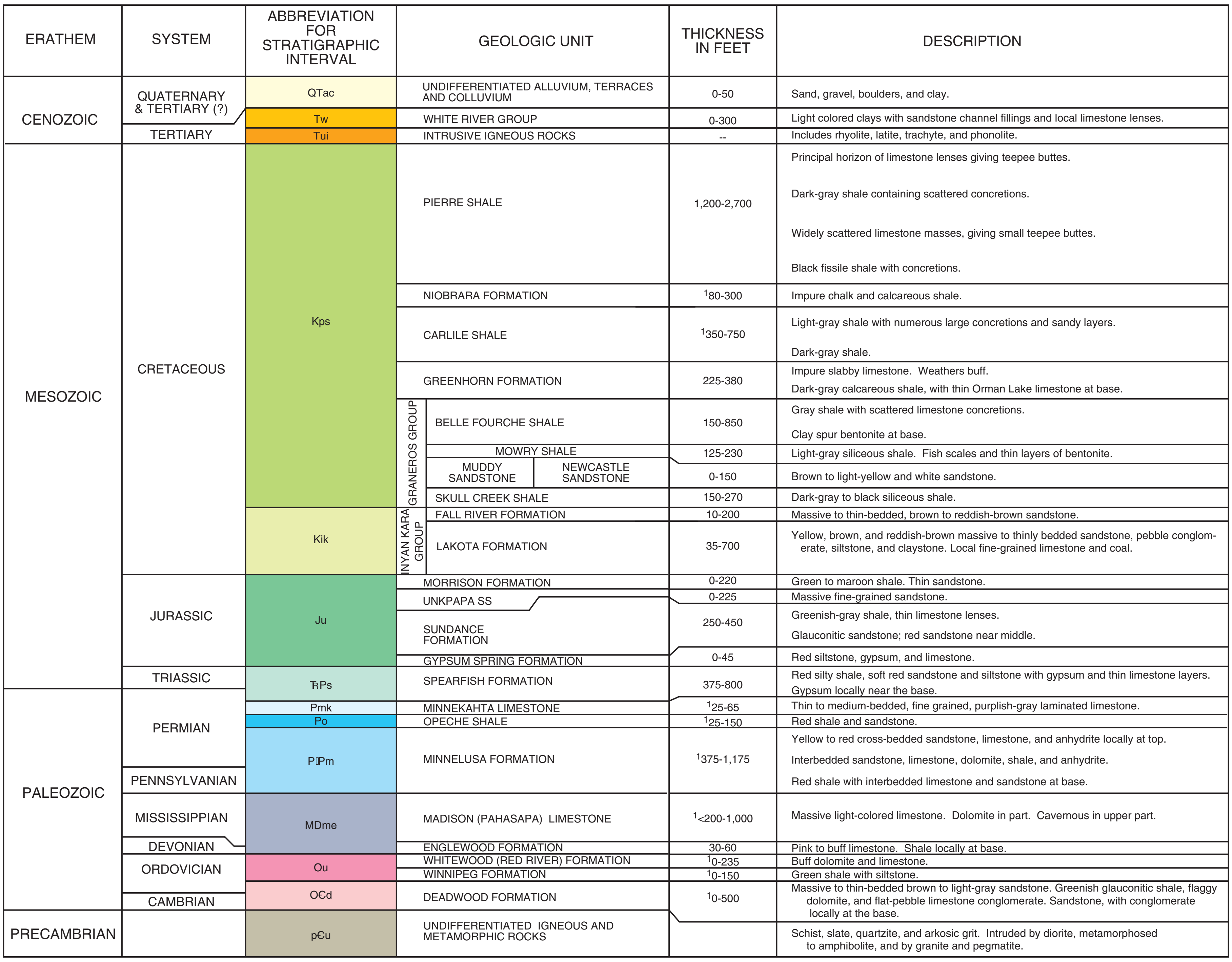
Figure 3. Long-term trends in precipitation for the Black Hills area, water years 1931-98.

Geology

Throughout geologic time, the Black Hills area has experienced frequent periods of inundation by seas, extended erosion, mountain building, and intrusion by igneous rocks; thus, the geology of the study area is very complex. The Black Hills uplift formed as an elongated dome about 60 to 65 million years ago. Numerous structural features, such as folds and fractures, were created by the deformation and displacement of rocks during the uplift. Pairs of large anticlines (folds in which the strata dip away from the axis like an arch) and synclines (folds in which the strata dip toward the axis like a trough) occur on the northern and southern flanks of the Black Hills and plunge away from the uplift into the surrounding plains. Numerous smaller anticlines, synclines, and domes, along with numerous faults and monoclines, occur throughout the Black Hills area. Igneous intrusions, such as Bear Butte, were emplaced on the northern flanks of the uplift during the Tertiary period.

The geologic time scale is divided into four eras and spans from the Precambrian Era (earliest) to the Cenozoic Era (latest). A stratigraphic column, which portrays the vertical (or chronological) sequence of geologic units of the Black Hills, is shown in figure 4. The geologic units are grouped into stratigraphic intervals representing hydrogeologic units comprising various aquifers, confining units, and semiconfining units, as shown in the explanation for figure 5. Figure 5 shows outcrops of the hydrogeologic units and locations of numerous structural features in the study area.

The oldest geologic units in the study area are the Precambrian-age crystalline (igneous and metamorphic) rocks, which are exposed in the central core of the Black Hills (fig. 5). Surrounding the Precambrian-age crystalline core is a layered series of sedimentary rocks including limestones, sandstones, and shales that are exposed in roughly concentric rings around the uplifted flanks of the Black Hills, as shown in figure 5. The bedrock sedimentary units generally dip away from the flanks of the Black Hills as shown in the geologic cross section (fig. 6), which shows the geologic units in a vertical cut along the line A-A′ in figure 5. Following are descriptions for the Paleozoic- and Mesozoic-age sedimentary units in the Black Hills area.

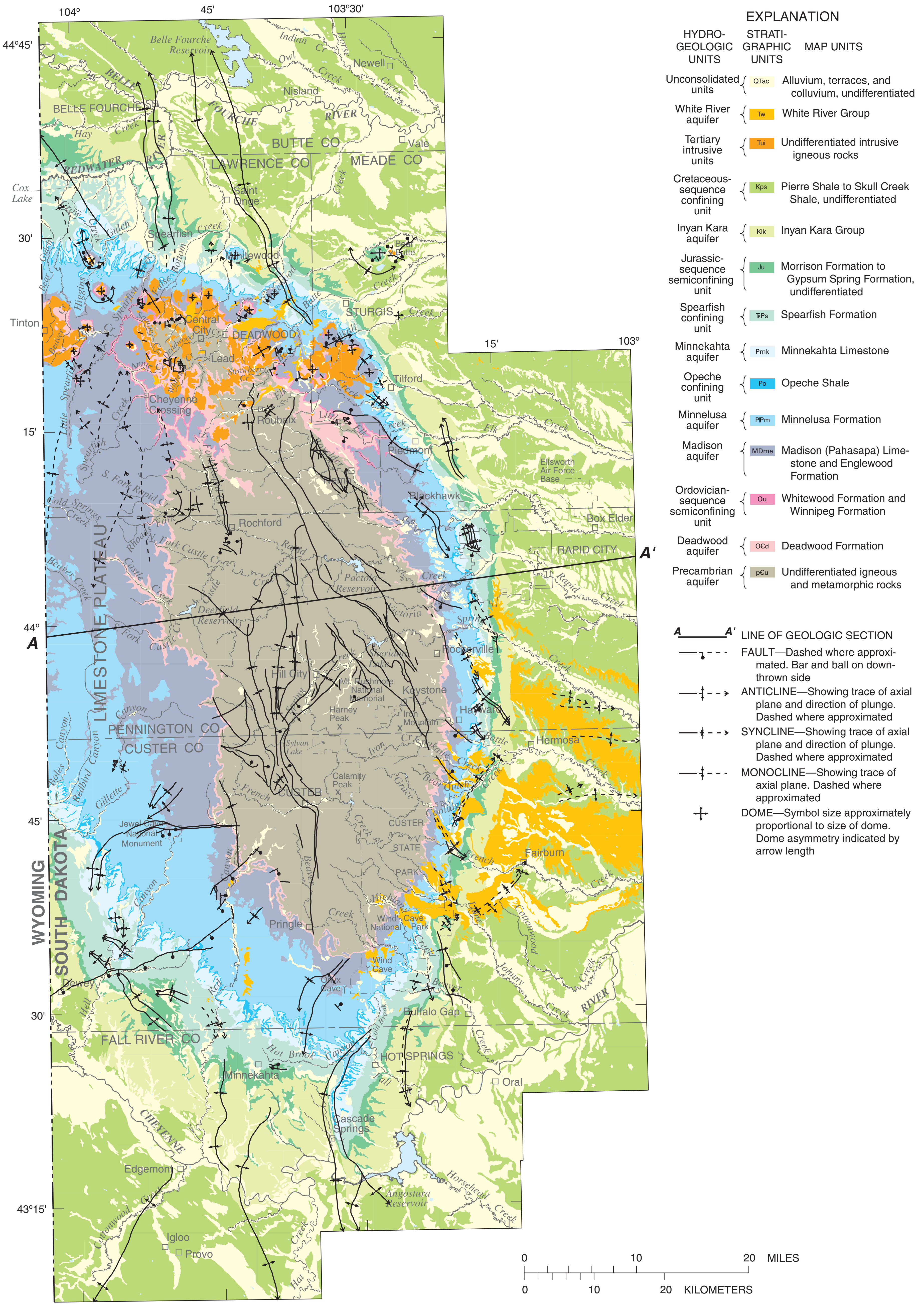


ERATHEM	SYSTEM	ABBREVIATION FOR STRATIGRAPHIC INTERVAL	GEOLOGIC UNIT	THICKNESS IN FEET	DESCRIPTION
CENOZOIC	QUATERNARY & TERTIARY (?)	QTac	UNDIFFERENTIATED ALLUVIUM, TERRACES AND COLLUVIUM	0-50	Sand, gravel, boulders, and clay.
		Tw	WHITE RIVER GROUP	0-300	Light colored clays with sandstone channel fillings 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	[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.
			MOWRY SHALE	125-230	Light-gray siliceous shale. Fish scales and thin layers of bentonite.
			MUDDY SANDSTONE NEWCASTLE SANDSTONE	0-150	Brown to light-yellow and white sandstone.
			SKULL CREEK SHALE	150-270	Dark-gray to black siliceous shale.
		Kik	INYAN KARA GROUP FALL RIVER FORMATION	10-200	Massive to thin-bedded, brown to reddish-brown sandstone.
			LAKOTA FORMATION	35-700	Yellow, brown, and reddish-brown massive to thinly bedded sandstone, pebble conglomerate, siltstone, and claystone. Local fine-grained limestone and coal.
	JURASSIC	Ju	MORRISON FORMATION	0-220	Green to maroon shale. Thin sandstone.
			UNKPAPA SS	0-225	Massive fine-grained sandstone.
			SUNDANCE FORMATION	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	TRPs	SPEARFISH FORMATION	375-800	Red silty 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.
	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	MDme	MADISON (PAHASAPA) LIMESTONE	[1]<200-1,000	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	OЄd	DEADWOOD FORMATION	[1]0-500	Massive to thin-bedded brown to light-gray sandstone. Greenish glauconitic shale, flaggy dolomite, and flat-pebble limestone conglomerate. Sandstone, with conglomerate locally at the base.
PRECAMBRIAN		pЄu	UNDIFFERENTIATED IGNEOUS AND METAMORPHIC 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 4. Stratigraphic column for the Black Hills.



Base modified from U.S. Geological Survey digital data, 1:100,000, 1977, 1979, 1981, 1983, 1985
Rapid City, Office of City Engineer map, 1:18,000, 1996; Universal Transverse Mercator projection, zone 13

Figure 5. Distribution of hydrogeologic units in the Black Hills area (modified from Strobel and others, 1999).

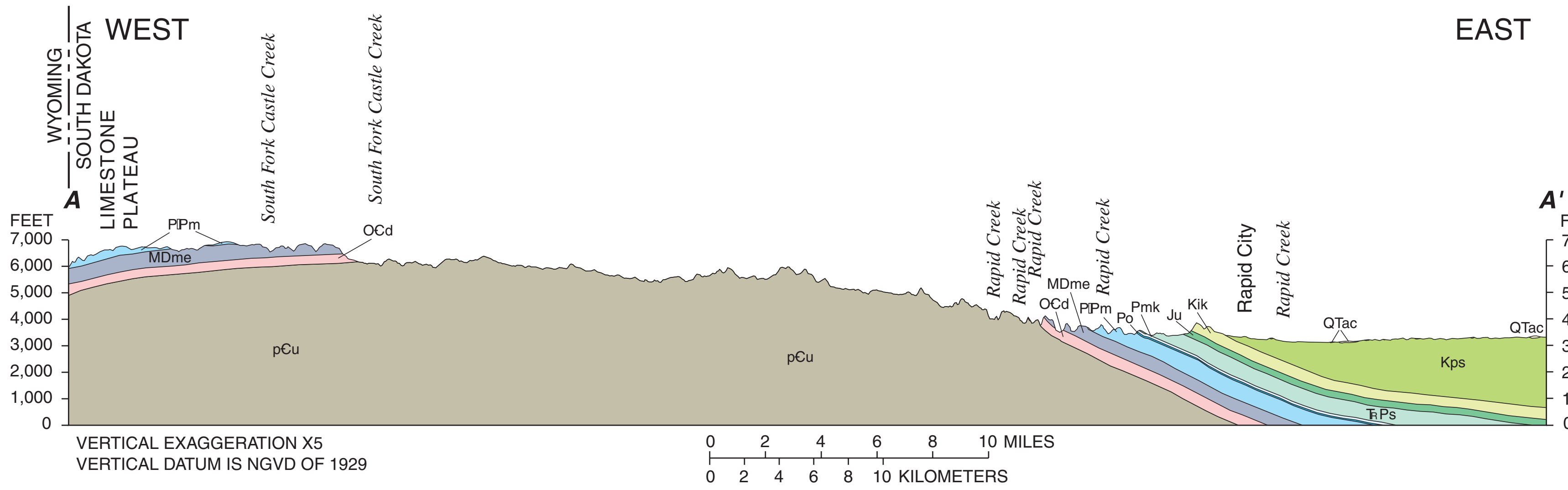


Figure 6. Geologic cross section A-A′ (modified from Strobel and others, 1999). Location of section is shown in figure 5. Abbreviations for stratigraphic intervals are explained in figure 4.

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 sandstone, shale, limestone, dolomite, and local basal conglomerate (Strobel and others, 1999). In the northern and central Black Hills, the Deadwood Formation is overlain by Ordovician-age rocks, which include the Whitewood and Winnipeg Formations. In the southern Black Hills, where the Whitewood and Winnipeg Formations are absent, the Deadwood Formation is overlain by the Englewood Formation, which generally is present throughout the Black Hills area except in the crystalline core. The Englewood Formation is overlain by the Madison Limestone.

The Mississippian-age Madison Limestone is a massive, gray to buff limestone with some dolomite (Strobel and others, 1999). The Madison Limestone was deposited by shallow seas and subsequently was exposed at land surface for approximately 50 million years. During this period of extensive erosion, rainwater, made slightly acidic during its passage through the air, infiltrated slowly down through the limestone, dissolving the limestone and forming caves in the rocks (Gries, 1996). The process of dissolving mineral and rock materials is called dissolution. As the caves collapsed, many of them broke through to the land surface, creating sinkholes. This process is called karstification, which results in a type of topography (with caves and sinkholes) called karst. Numerous caves and fractures occur within the upper part of the Madison Limestone (Peter, 1985). The Madison Limestone is overlain by the Minnelusa Formation.

The Pennsylvanian- and Permian-age Minnelusa Formation consists mostly of yellow to red sandstone, limestone, dolomite, and shale (Strobel and others, 1999). In addition to sandstone and dolomite, the middle part of the formation contains anhydrite, which can be easily dissolved by water, and shale (DeWitt and others, 1986). The upper part of the Minnelusa Formation also may contain anhydrite, which generally has been dissolved in or near the outcrop areas, occasionally forming collapse features. The Minnelusa Formation is overlain by the Opeche Shale, which is overlain by the Minnekahta Limestone.

The Permian-age Minnekahta Limestone is a fine-grained, purple to gray laminated limestone (Strobel and others, 1999). The Minnekahta Limestone is overlain by the Spearfish Formation.

The Spearfish Formation is a red, silty shale with interbedded red sandstone and siltstone (Strobel and others, 1999). Massive gypsum deposits are scattered throughout the Spearfish Formation. Because gypsum is easily dissolved by water, numerous sinkholes in the Spearfish Formation have developed, especially in the northern Black Hills (Epstein, 2000). Overlying the Spearfish Formation are Mesozoic-age units that are composed primarily of shale, siltstone, and sandstone deposits. These units include the Cretaceous-age Inyan Kara Group.

The Inyan Kara Group consists of the Lakota Formation and overlying Fall River Formation. A resistant ridge of Cretaceous-age sandstones, mostly of the Lakota Formation, completely encircles the Black Hills and stands hundreds of feet above the surrounding prairie. This ridge, known as the Cretaceous hogback, forms the general boundary between the Black Hills and the prairie (Gries, 1996). The Lakota Formation consists of yellow, brown, and reddish-brown, massive to thinly bedded sandstone, pebble conglomerate, siltstone, and claystone that were deposited by rivers (Gott and others, 1974); locally there are lenses of limestone and coal. The Fall River Formation is a brown to reddish-brown, fine-grained sandstone, thin bedded at the top and massive at the bottom (Strobel and others, 1999). The Inyan Kara Group is overlain by a thick sequence of various shale units with some interbedded sandstone and limestone units.

Ground Water

The hydrologic setting of the Black Hills area is schematically illustrated in figure 7. The major bedrock aquifers are the Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara aquifers. Minor bedrock aquifers occur in other units, including confining units, due to fracturing and interbedded permeable layers. In general, groundwater flow in these aquifers is radially away from the central core of the Black Hills. The bedrock aquifers primarily receive recharge from infiltration of precipitation on outcrops, and the Madison and Minnelusa aquifers also receive substantial recharge from streamflow losses. The unconsolidated units, which include alluvium, terraces, and colluvium, are considered aquifers where saturated. Alluvial deposits along streams commonly are used as local aquifers.

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

Confined (artesian) conditions generally exist within the bedrock aquifers in locations where an upper confining layer is present except in areas close to the formation outcrop. Under confined 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 (level to which water will rise) is above the land surface. Flowing wells and artesian springs that originate from confined aquifers are common around the periphery of the Black Hills.

The Precambrian-age basement rocks generally have low permeability and form the lower confining unit for the series of sedimentary aquifers (fig. 7). However, localized aquifers occur in many locations in the crystalline core of the Black Hills where secondary permeability (developed after the rock was formed) has resulted from weathering and fracturing. Water-table (unconfined) conditions generally occur in these localized aquifers, and topography can strongly influence ground-water flow directions.

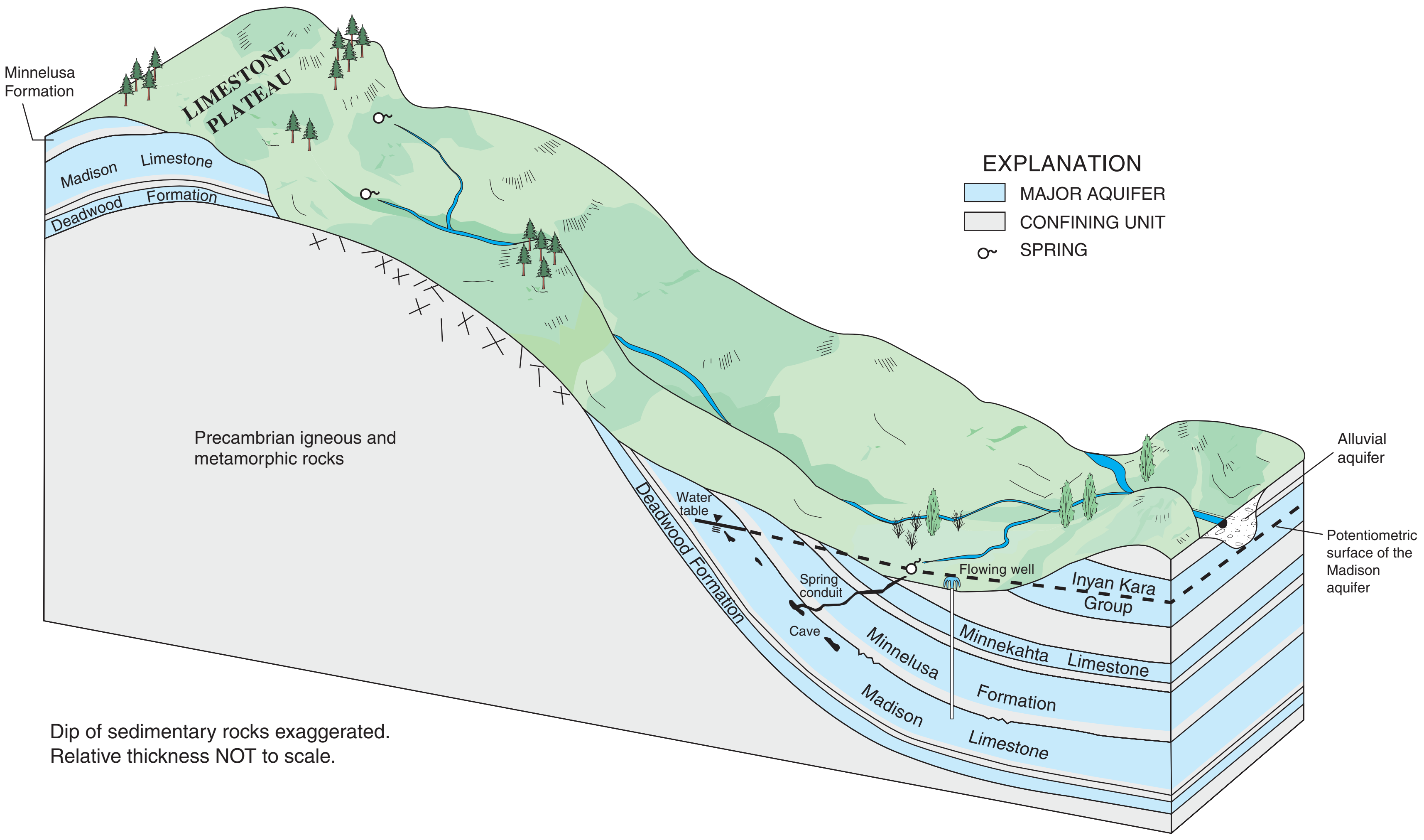


Figure 7. Schematic diagram showing simplified hydrologic setting of the Black Hills area. Schematic diagram generally corresponds with geologic cross section shown in figure 5.

Overlying the Precambrian-age rocks is the Deadwood aquifer, which is contained within the Deadwood Formation and is used primarily near outcrop areas. Regionally, the Precambrian-age rocks act as an underlying 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 in contact with the overlying Englewood Formation, which is considered similar in hydrologic characteristics to the lower Madison Limestone.

The Madison aquifer generally occurs within the karstic upper part of the Madison Limestone, where numerous fractures and solution openings have created extensive secondary porosity and permeability. The entire Madison Limestone and Englewood Formation were included in the delineation of the Madison aquifer for this study. Thus, in this report, outcrops of the Madison Limestone and Englewood Formation (fig. 5) are referred to as the outcrop of the Madison Limestone for simplicity. The Madison aquifer receives recharge from streamflow losses and precipitation on the outcrop. Low-permeability layers in the lower part of the Minnelusa Formation generally act as an upper confining unit to the Madison aquifer. However, collapse related to karst features in the top of the Madison Limestone and fracturing related to the Black Hills uplift may have reduced the effectiveness of the overlying confining unit in some locations.

The Minnelusa aquifer occurs within layers of sandstone, dolomite, and anhydrite in the lower portion of the Minnelusa Formation and sandstone and anhydrite in the upper portion. Shales in the lower portion of the Minnelusa Formation act as confining layers to the underlying Madison aquifer; however, the extent of hydraulic separation between the two aquifers varies greatly between locations and is not well defined. Collapse breccia associated with dissolution of interbedded anhydrite in the Minnelusa Formation may enhance secondary porosity to the aquifer (Long and others, 1999). The Minnelusa aquifer receives substantial recharge from streamflow losses and precipitation on the outcrop. Streamflow recharge to the Minnelusa aquifer generally is less than to the Madison aquifer because much streamflow 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 Madison and Minnelusa aquifers are distinctly different aquifers, but are connected hydraulically in some areas. Many of the artesian springs have been interpreted as originating at least partially from upward leakage from the Madison aquifer; however, the overlying Minnelusa aquifer and other aquifers probably contribute to artesian springflow in many locations. Although the confining layers in the lower parts of the Madison and Minnelusa aquifers generally do not transmit water at a high rate, their capacity to store water could influence how these aquifers respond to stress (Long and Putnam, 2002).

The Minnekahta aquifer, which overlies the Opeche Shale, is contained within the Minnekahta Limestone. The Minnekahta aquifer typically is very permeable, but well yields can be limited by the small aquifer thickness. The Minnekahta aquifer receives recharge primarily from precipitation on the outcrop and some additional recharge from streamflow losses. The overlying Spearfish Formation acts as a confining unit to the Minnekahta aquifer and to other aquifers in the underlying Paleozoic-age rock interval. Hence, most of the artesian springs occur near the outcrop of the Spearfish Formation.

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

AVAILABILITY OF GROUND-WATER RESOURCES

The availability of ground-water resources in the Black Hills area is influenced by many factors including location, local recharge and ground-water flow conditions, and structural features. Thus, the availability of ground water can be extremely variable throughout the Black Hills area. The suitability of available water supplies also can be limited by water quality, as discussed later in this report. This section of the report provides information and maps that describe potential availability of ground-water resources in the Black Hills area. Readers are cautioned that there is no guarantee of obtaining usable water at any location due to the extreme potential variability in conditions that can affect the availability and quality of ground water in the area.

Characteristics of Major Aquifers

General descriptions of aquifer characteristics and ground-water levels, with emphasis on the major aquifers, are presented in this section of the report. A series of maps showing the depth and thickness of selected geologic formations, and the potentiometric surface and saturated thickness of selected aquifers, also is presented.

General Characteristics

Aquifer characteristics, including area, thickness, and storage volume, are presented in table 1 for the major aquifers in the study area. Aquifer characteristics for the Precambrian aquifer also are presented with the major aquifers because numerous wells are completed in this aquifer in the crystalline core of the Black Hills.

Localized aquifers occur in the igneous and metamorphic rocks that make up the crystalline core of the Black Hills and are referred to collectively as the Precambrian aquifer. The Precambrian aquifer is not continuous and ground-water conditions are controlled mainly by secondary permeability caused by fracturing and weathering. The aquifer is considered to be contained in the area where the Precambrian-age rocks are exposed in the central core, which has an area of approximately 825 square miles in the study area. The thickness of the Precambrian aquifer has been estimated by Rahn (1985) to be generally less than 500 feet, which was considered the average saturated thickness for calculations of the estimated amount of recoverable water in storage (table 1). Wells in the Custer area have been completed at depths greater than 1,000 feet, indicating that localized aquifers are thicker in some locations. The Precambrian aquifer is mostly unconfined, but may have locally confined conditions.

Large amounts of water are stored within the major aquifers, but not all of it is recoverable because some of the water is contained in unconnected pore spaces. Thus, effective porosity, which is the porosity of a rock that consists of interconnected voids, was used in estimating the amount of recoverable water in storage (table 1). Where aquifer units are not fully saturated (generally in and near outcrop areas), the saturated thickness is less than the formation thickness and the aquifer is unconfined. For the Madison and Minnelusa aquifers, it was possible to delineate the saturated thickness of the unconfined portions of these aquifers, as discussed later in this report. Average saturated thicknesses of the unconfined and confined portions of the Madison and Minnelusa aquifers were used in storage estimates for these aquifers. For the other major aquifers, full saturation was assumed because more detailed information was not available.

The total volume of recoverable water stored in the major aquifers (including the Precambrian aquifer) within the study area is estimated as 256 million acre-feet, which is slightly more than 10 times the maximum storage of Oahe Reservoir, a large reservoir on the Missouri River northeast of the study area (fig. 2). Although the volume of stored ground water is very large, the water quality may not be suitable for all uses in some parts of the study area, as discussed in a following section of this report. The largest storage volume is for the Inyan Kara aquifer because of the large effective porosity (0.17). Storage in the Minnelusa aquifer is larger than in the Madison aquifer, primarily because of larger average saturated thickness.

Well yields (fig. 8) for wells completed in the major aquifers were obtained from the USGS Ground Water Site Inventory (GWSI) database. The mean well yields for the aquifers generally are much higher than the median well yields because some well yields are very high. Well yields generally are lower for wells completed in the Precambrian aquifer than for the major aquifers (fig. 8) because the Precambrian aquifer is not continuous and most of the available water is stored in fractures. The Madison aquifer has the potential for high well yields, and the mean well yield is higher in the Madison aquifer than the other major aquifers. The Minnelusa aquifer also has the potential for high well yields. The Deadwood and Minnekahta aquifers could have well yields as high as 1,000 gallons per minute in localized areas. Low well yields are possible in some locations for all the major aquifers.

Maps showing estimated depths to tops of formations that contain the major aquifers (Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara) are presented in figures 9-13. The depths shown are to the top of the formations, which are not necessarily the depths to the tops of the water-bearing layers. In fact, water-bearing layers in any given formation may be minimal or absent at many locations, especially in areas on or near the outcrops. Readers are cautioned that relatively large errors in estimated depths can occur because of large potential uncertainties in estimated altitudes for tops of formations especially in areas with limited well and test-hole data.

Maps showing generalized thicknesses of the formations that contain major aquifers are presented in figures 14-18. Thicknesses shown are estimated formation thicknesses and are not necessarily indicative of saturated thicknesses at any given location. In fact, the formations may have little saturation or may even be dry at many locations, especially in areas on or near outcrops. Readers are again cautioned that relatively large errors in estimated thicknesses can occur.

Maps showing estimated potentiometric surfaces for the major aquifers are presented in figures 19-23. The potentiometric contours on the maps show the approximate altitude to which water would rise in tightly cased, nonpumping wells. In general, the direction of ground-water flow is perpendicular to the potentiometric contours and in the direction of the hydraulic gradient (water flows from higher hydraulic head to lower hydraulic head). In general, ground-water flow in the major aquifers is radially outward from the uplifted area. However, structural features, such as folds and faults, and other factors may have sufficiently large local influences on ground-water flow directions. Flow directions may be nearly parallel to potentiometric contours in some locations, especially in the Madison aquifer (Long, 2000). Readers are again cautioned that relatively large errors in mapped potentiometric contours can occur due to insufficient data.

Table 1. Summary of the characteristics of major aquifers in the study area
[--, no data]

Aquifer	Area (square miles)	Maximum formation thickness (feet)	Average saturated thickness (feet)	Effective porosity[1]	Estimated amount of recoverable water in storage[2] (million acre-feet)
Precambrian	[3]5,041	--	[1]500	0.01	2.6
Deadwood	4,216	500	226	.05	30.5
Madison	4,113	1,000	[4]521	.05	[5]62.7
Minnelusa	3,623	1,175	[6]736	.05	[5]70.9
Minnekahta	3,082	65	50	.05	4.9
Inyan Kara	2,512	900	310	.17	84.7
Combined storage for major aquifers					256.3

[1] From Rahn (1985).
[2] Storage estimated by multiplying area times average saturated thicknesses times effective porosity.
[3] The area used in storage calculation was the area of the exposed Precambrian-age rocks, which is 825 square miles.
[4] Average saturated thickness of the confined area of the Madison aquifer. The unconfined area had an average saturated thickness of 300 feet.
[5] Storage values are the summation of storage in the confined and unconfined areas.
[6] Average saturated thickness of the confined area of the Minnelusa aquifer. The unconfined area had an average saturated thickness of 142 feet.

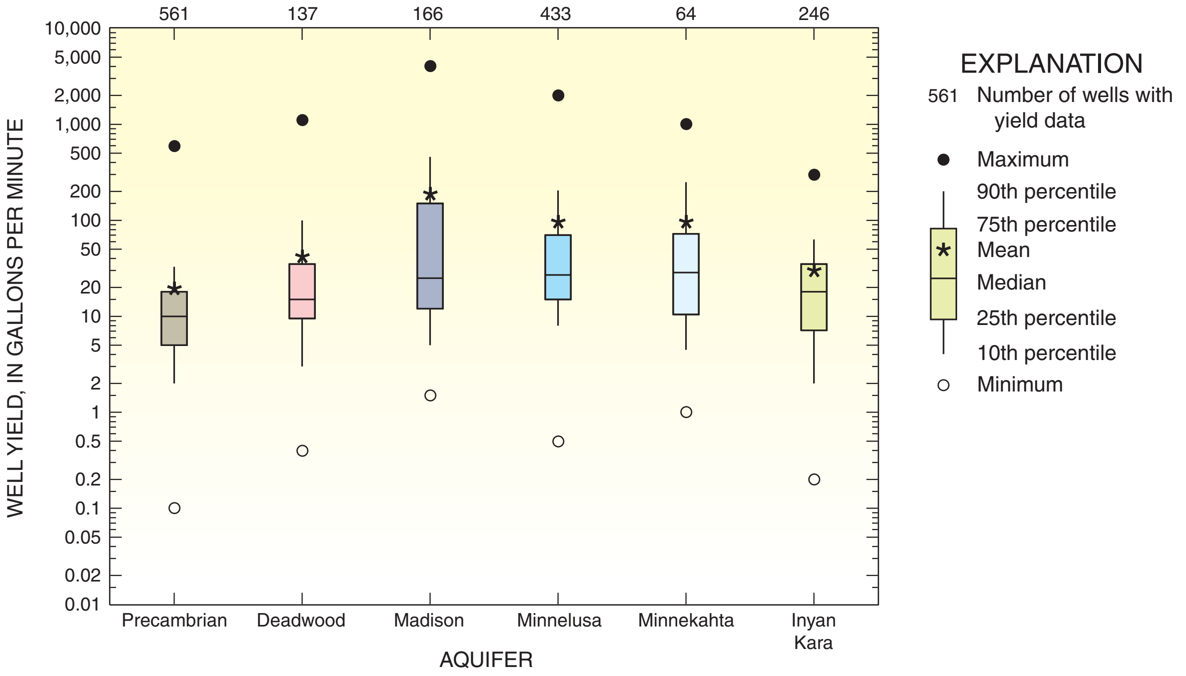


Figure 8. Distribution of well yields from selected aquifers (data obtained from U.S. Geological Survey Ground Water Site Inventory database).

Maps showing estimated saturated thicknesses of the unconfined areas of the Madison and Minnelusa aquifers are shown in figures 24 and 25, respectively. Both the Madison and Minnelusa aquifers are unconfined in and near outcrop areas, but generally are confined (fully saturated) at some distance away from outcrops. In general, saturated thicknesses are estimated as less than 200 feet for most outcrop areas. These areas may be especially susceptible to water-level fluctuations resulting from drought conditions, and these formations may be predominantly dry in many of these areas regardless of precipitation conditions. In most areas, the Madison and Minnelusa aquifers are fully saturated within a short distance downgradient of the outcrops. However, in the southwest part of the study area, neither aquifer is fully saturated for a distance of about 6 miles downgradient of the respective outcrops.

Ground-Water Levels

Daily water-level data were collected for 71 observations wells for the Black Hills Hydrology Study. Hydrographs for these wells through water year 1998 were presented by Driscoll, Bradford, and Moran (2000). Hydrographs for four of these wells are presented in figure 26 to illustrate the fluctuations in water levels that can occur in bedrock aquifers in the Black Hills area. For the hydrographs presented in this report, solid lines indicate continuous records and dashed lines indicate periods with discontinuous records, which may be based only on periodic manual measurements in some cases.

Water levels can be affected by several factors including pumping of nearby wells and climatic conditions. Long-term water-level declines could have various effects, including changes in ground-water flow patterns, reduction in springflow, increased pumping costs, and dry wells. A large percentage of the observations wells completed in the Madison and Minnelusa aquifers respond quickly to climatic conditions. Nearly all of the hydrographs for these aquifers (Driscoll, Bradford, and Moran, 2000) show a downward water-level trend prior to 1993, as illustrated in the example hydrographs for a well pair completed in the Madison and Minnelusa aquifers (fig. 26A). This downward trend can be partially attributed to dry climatic conditions in the Black Hills area during this period. Precipitation amounts generally were above average after 1993 (fig. 3), and water levels increased rapidly (fig. 26A). In general, there is very little indication of long-term water-level declines from ground-water withdrawals in any of the bedrock aquifers in the Black Hills area (Carter and others, 2002), as shown by the long-term hydrograph for the Redwater Minnelusa well (fig. 26B).

Of the hydrographs for the 71 observation wells presented by Driscoll, Bradford, and Moran (2000), the Reptile Gardens Madison well showed the largest water-level fluctuation of about 111 feet (fig. 26C). Larger water-level fluctuations at other locations in the Black Hills area may be possible. Such fluctuations could result in dry wells or reduced pumping capacity during periods of declining water levels.

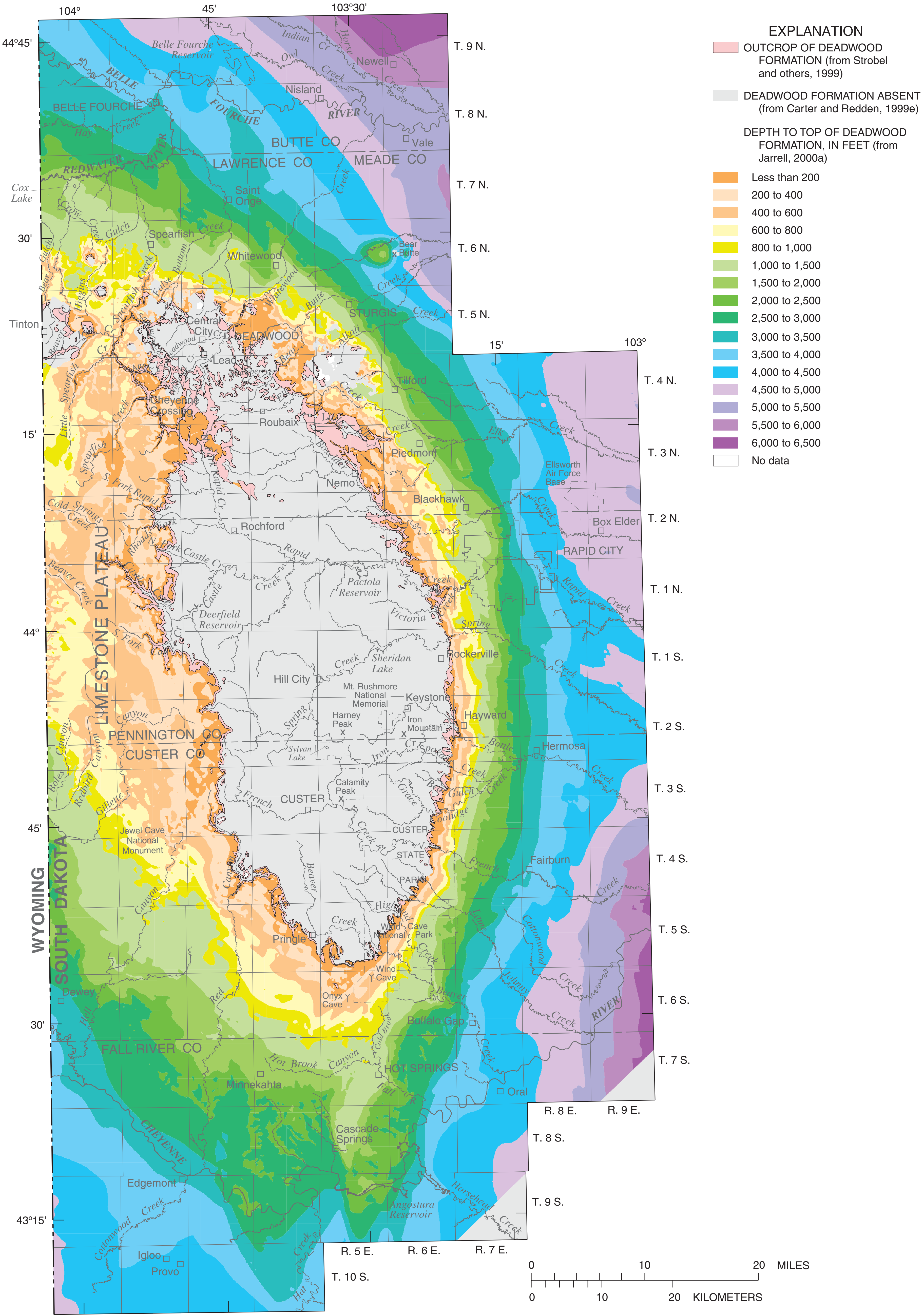
Characteristics of Minor Aquifers

In addition to the major aquifers, many other aquifers are used in the study area. The Newcastle Sandstone, White River Group, and the unconsolidated units are considered to contain aquifers where saturated (Strobel and others, 1999). In addition, many of the semiconfining and confining units shown in figure 5 may contain local aquifers. This section of the report provides a brief overview from Strobel and others (1999) of other aquifers in the study area that are contained in various units from oldest to youngest.

The Whitewood Formation, where present, can contain a local aquifer that seldom is used because of generally more reliable sources in the adjacent Madison or Deadwood aquifers. Local aquifers can exist in the Spearfish confining unit where gypsum and anhydrite have been dissolved, causing increased porosity and permeability; these aquifers are referred to as the Spearfish aquifer in this report. The Jurassic-sequence semiconfining unit consists of shales and sandstones. Overall, this unit is semiconfining because of the low permeability of the interbedded shales; however, local aquifers exist in some formations such as the Sundance and Morrison Formations. These aquifers are referred to as the Sundance and Morrison aquifers in this report.

The Cretaceous-sequence confining unit mainly includes shales of low permeability, such as the Pierre Shale; local aquifers in the Pierre Shale are referred to as the Pierre aquifer in this report. Within the Graneros Group, the Newcastle Sandstone contains an important minor aquifer referred to as the Newcastle aquifer. Because water-quality characteristics (discussed in a subsequent section of this report) are very different between the Newcastle aquifer and the other units in the Graneros Group, data are presented for the Newcastle aquifer separately from the other units in the Graneros Group, known as the Graneros aquifer in this report.

Tertiary intrusive units are present only in the northern Black Hills, and generally are relatively impermeable, although “perched” ground water often is associated with intrusive sills. The White River aquifer consists of various discontinuous units of sandstone and channel sands along the eastern flank of the Black Hills; local aquifers can exist where saturated conditions occur. Unconsolidated units of Tertiary or Quaternary age, including alluvium, terraces, colluvium, and wind-blown deposits, all have the potential to be local aquifers where they are saturated.



Base modified from U.S. Geological Survey digital data, 1:100,000, 1977, 1979, 1981, 1983, 1985
Rapid City, Office of City Engineer map, 1:18,000, 1996; Universal Transverse Mercator projection, zone 13

Figure 9. Depth to top of Deadwood Formation.