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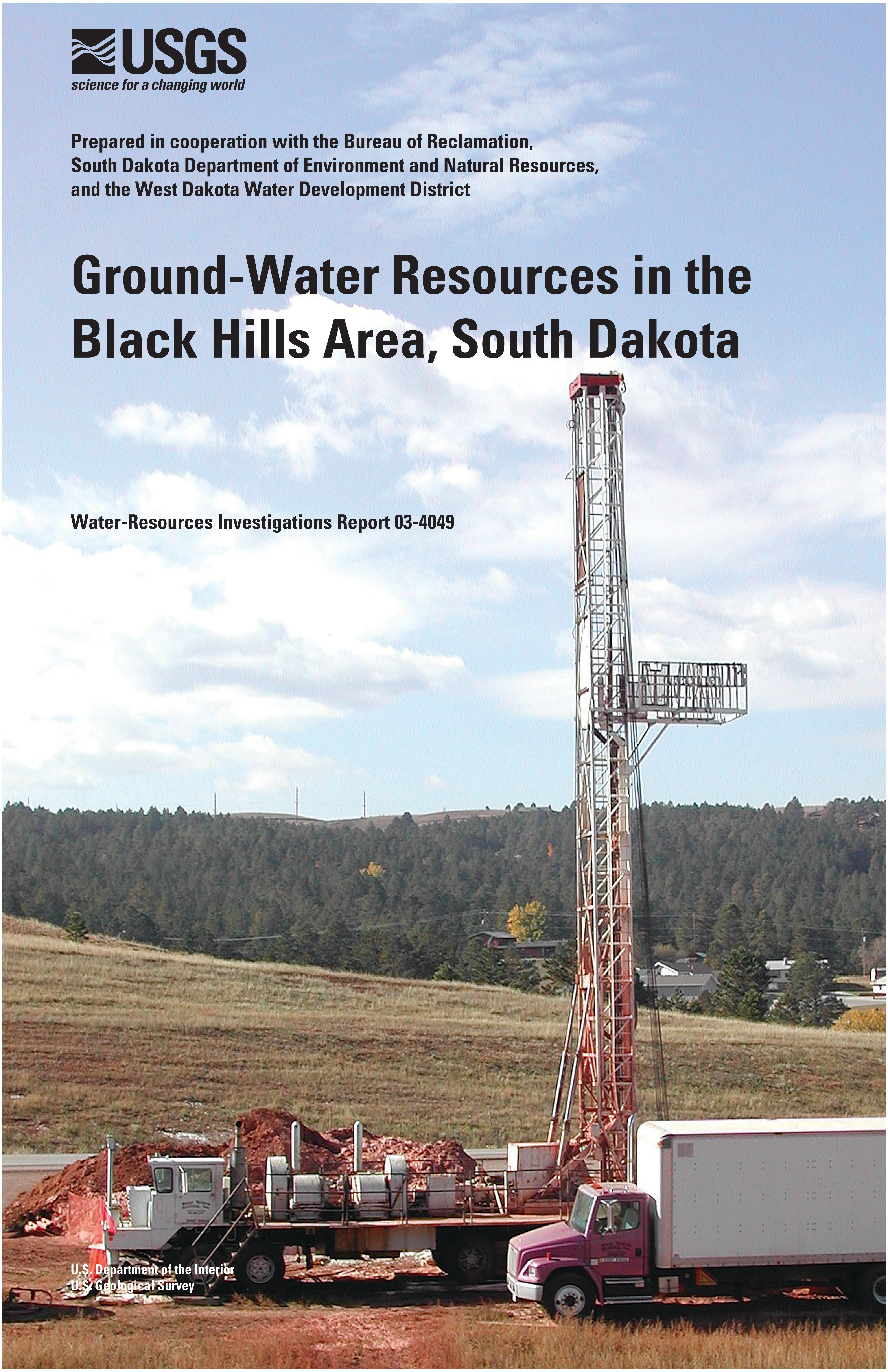
Ground-Water Resources in the Black Hills Area, South Dakota

Water-Resources Investigations Report 03-4049



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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

Charles G. Groat, Director

Rapid City, South Dakota: 2003

For additional information write to:

District Chief
U.S. Geological Survey
1608 Mt. View Road
Rapid City, SD 57702

Copies of this report can be purchased from:

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Information Services
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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:

$$°C = (°F - 32) / 1.8$$

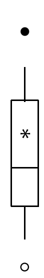
Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929).

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.



Maximum
90th percentile
75th percentile
Mean
Median
25th percentile
10th percentile
Minimum

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.

Outlier data value more than 3 times the interquartile range outside the quartile
Outlier data value less than or equal to 3 and more than 1.5 times the interquartile range outside the quartile
Data value less than or equal to 1.5 times the interquartile range outside the quartile
75th percentile
Median
25th percentile
Data value less than or equal to 1.5 times the interquartile range outside the quartile

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.

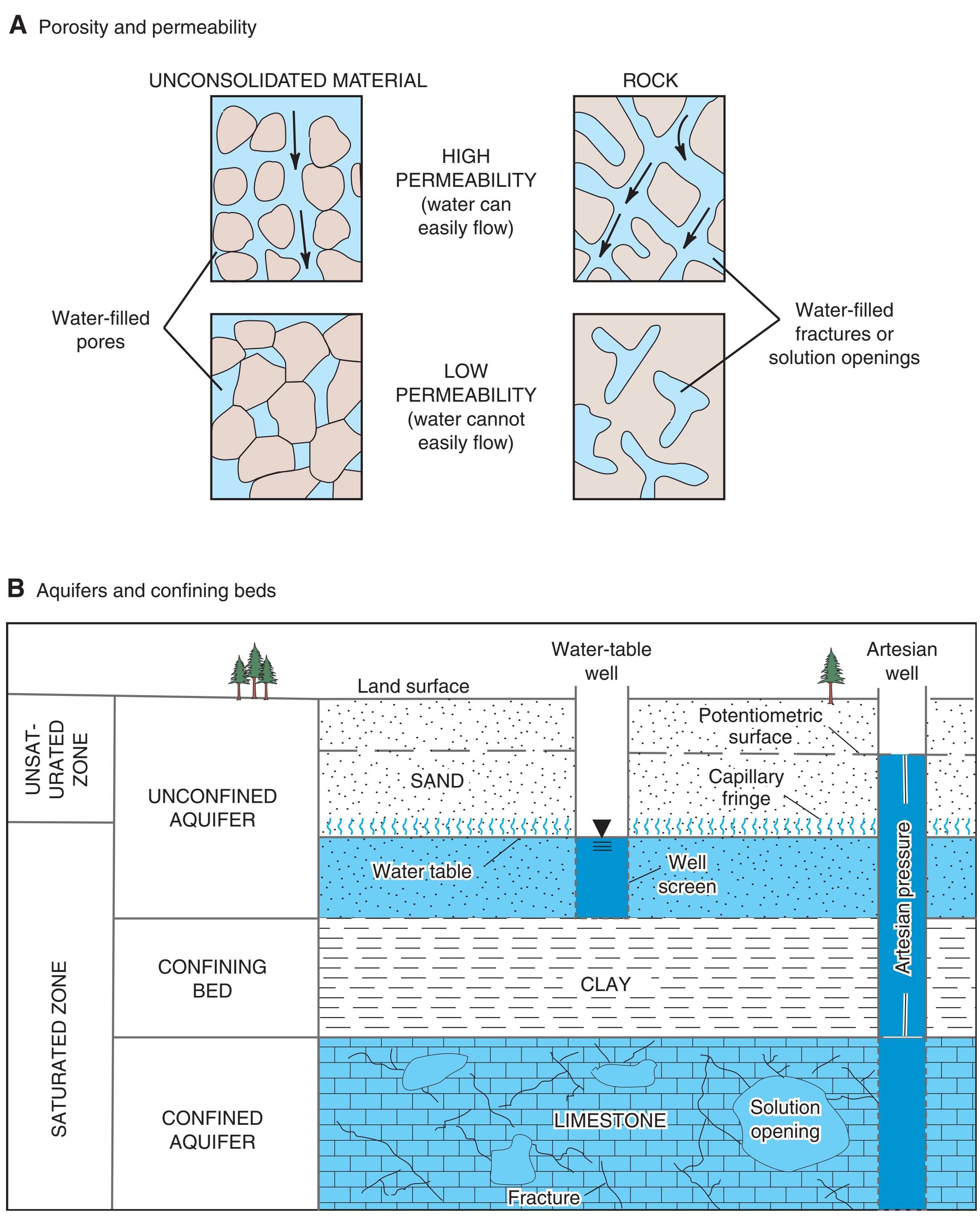


Figure 1. Schematic diagram showing (A) porosity and permeability (modified from Clark and Briar, 1993); and (B) aquifers and confining beds (modified from Heath, 1983).

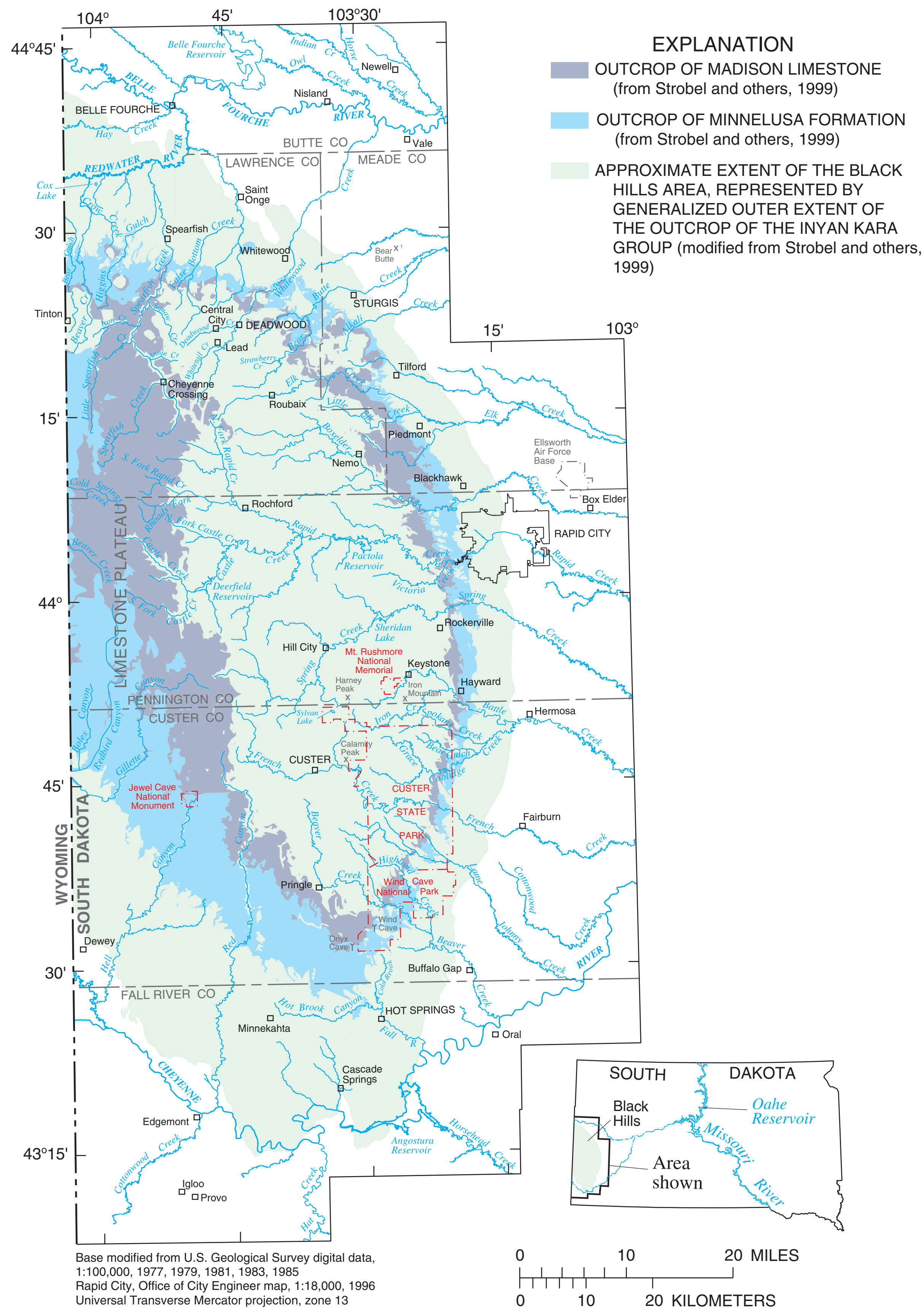


Figure 2. Area of investigation for the Black Hills Hydrology Study.

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).

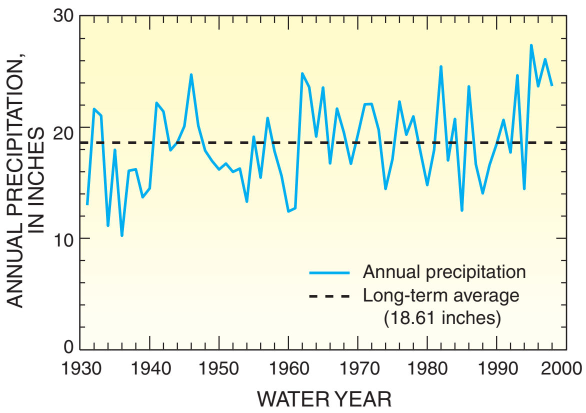


Figure 3. Long-term trends in precipitation for the Black Hills area, water years 1931-98.

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.
			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 thin-bedded, brown to reddish-brown sandstone.
			INYAN KARA GROUP: 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.
	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	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	OꞒd	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		pꞒu	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.

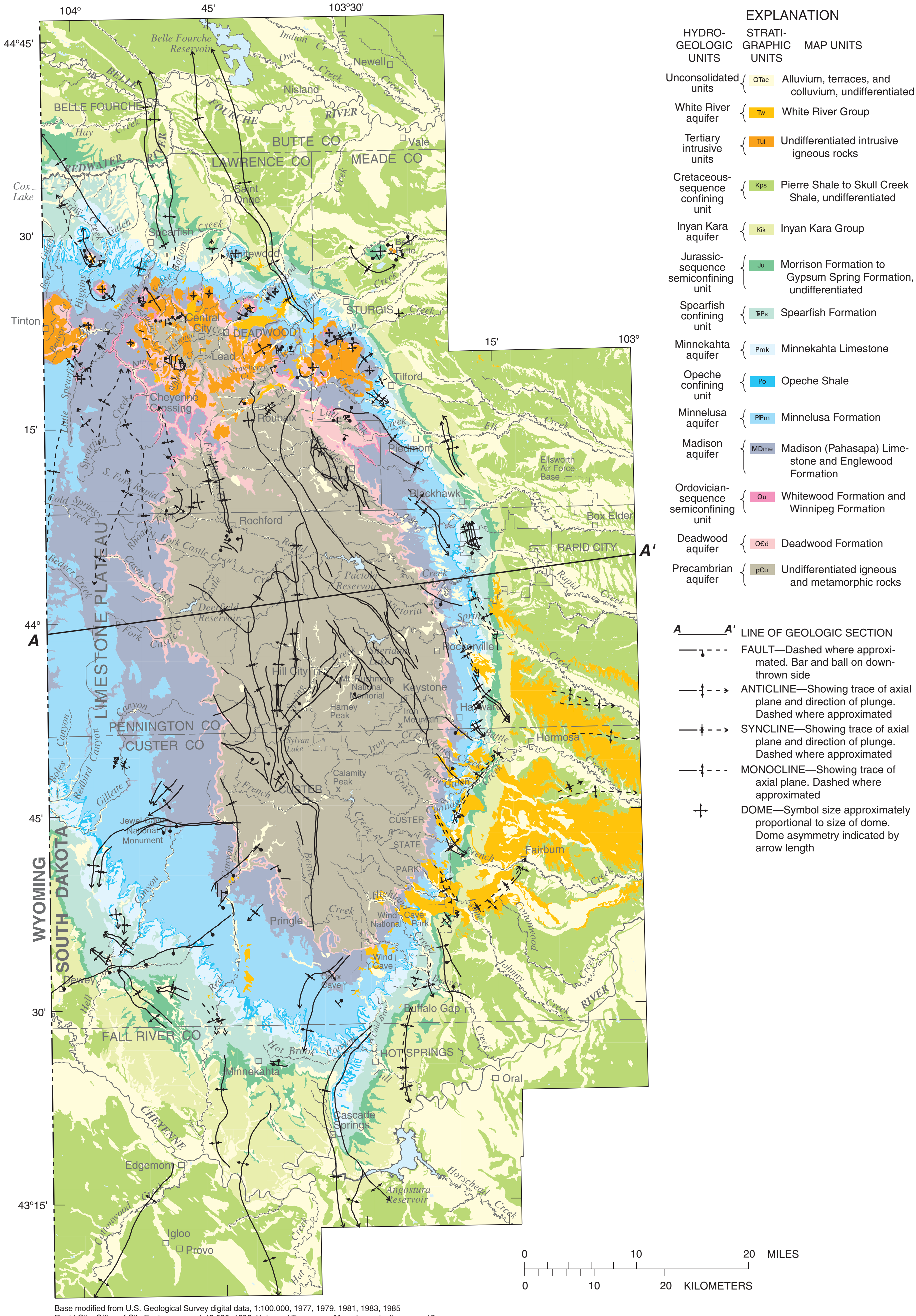


Figure 5. Distribution of hydrogeologic units in the Black Hills area (modified from Strobel and others, 1999).

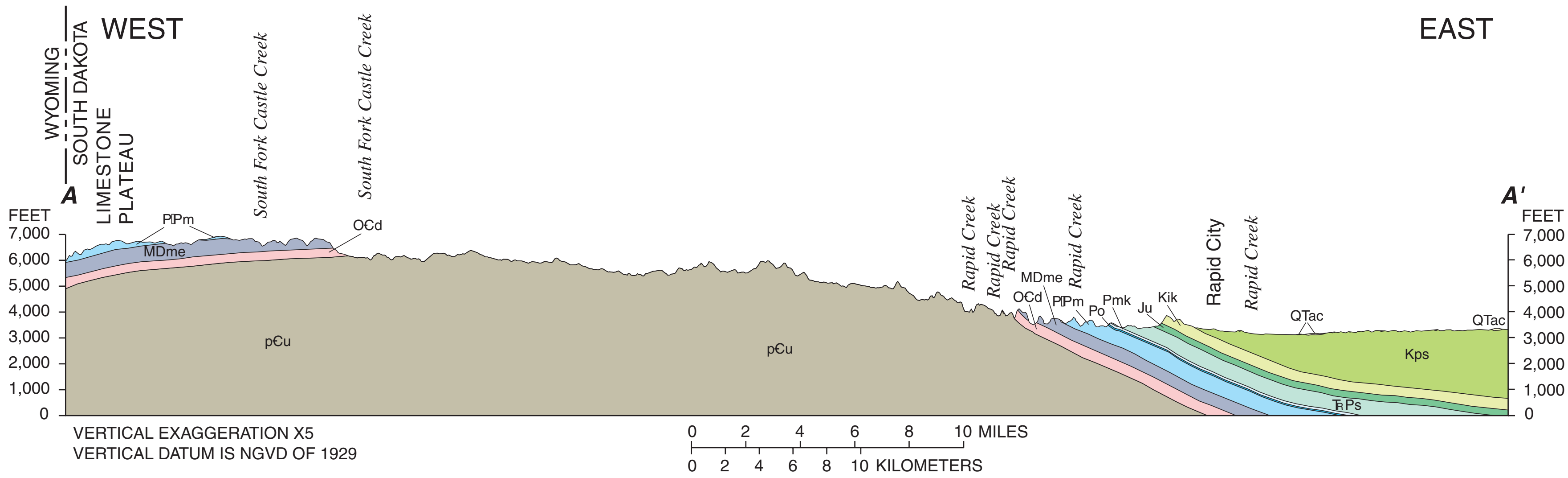


Figure 6. Geologic cross section A-A′ (modified from Strobel and others, 1999). Location of section is shown in figure 5. Abbreviations for stratigraphic intervals are explained in figure 4.

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, ground-water 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.

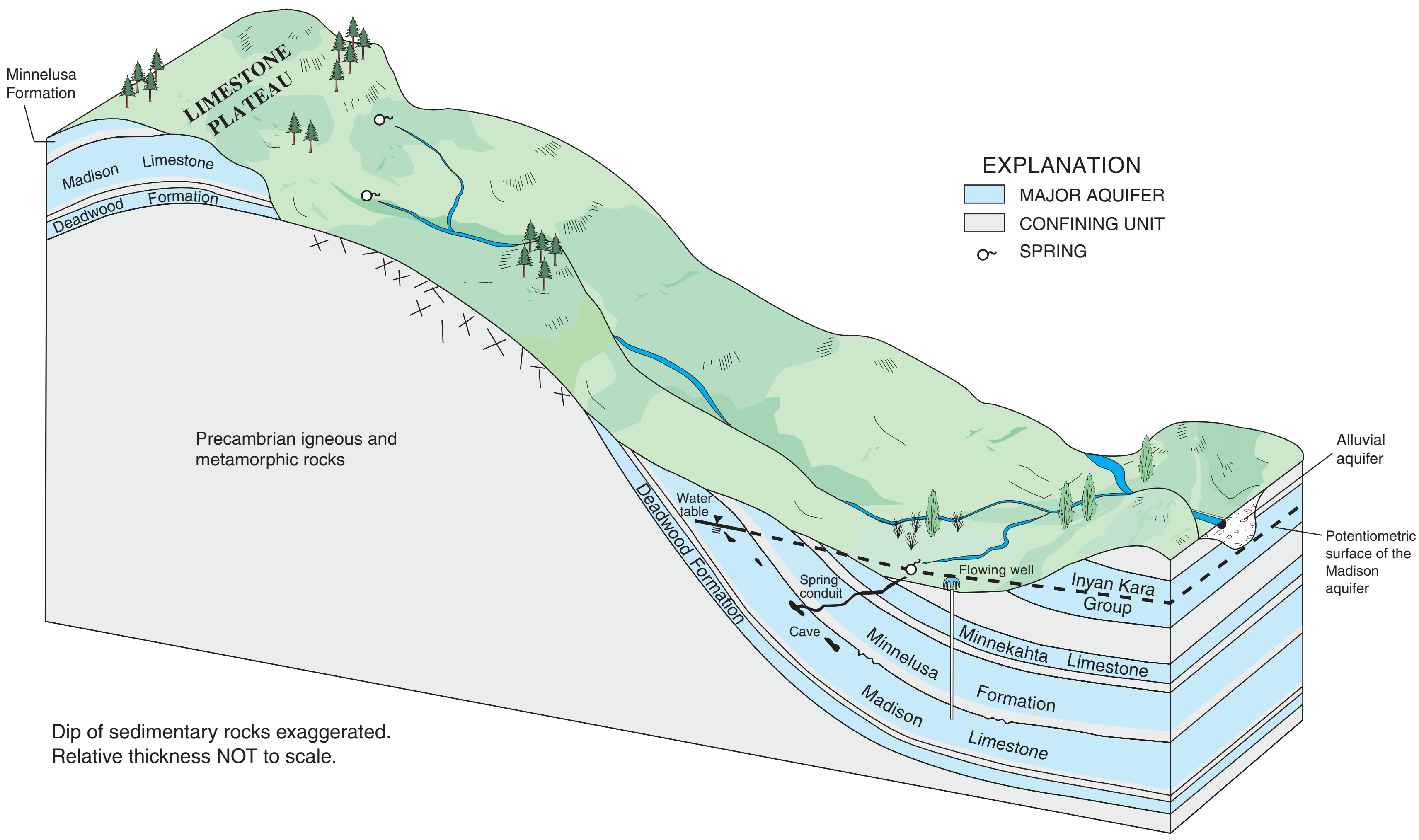


Figure 7. Schematic diagram showing simplified hydrologic setting of the Black Hills area. Schematic diagram generally corresponds with geologic cross section shown in figure 5.

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.

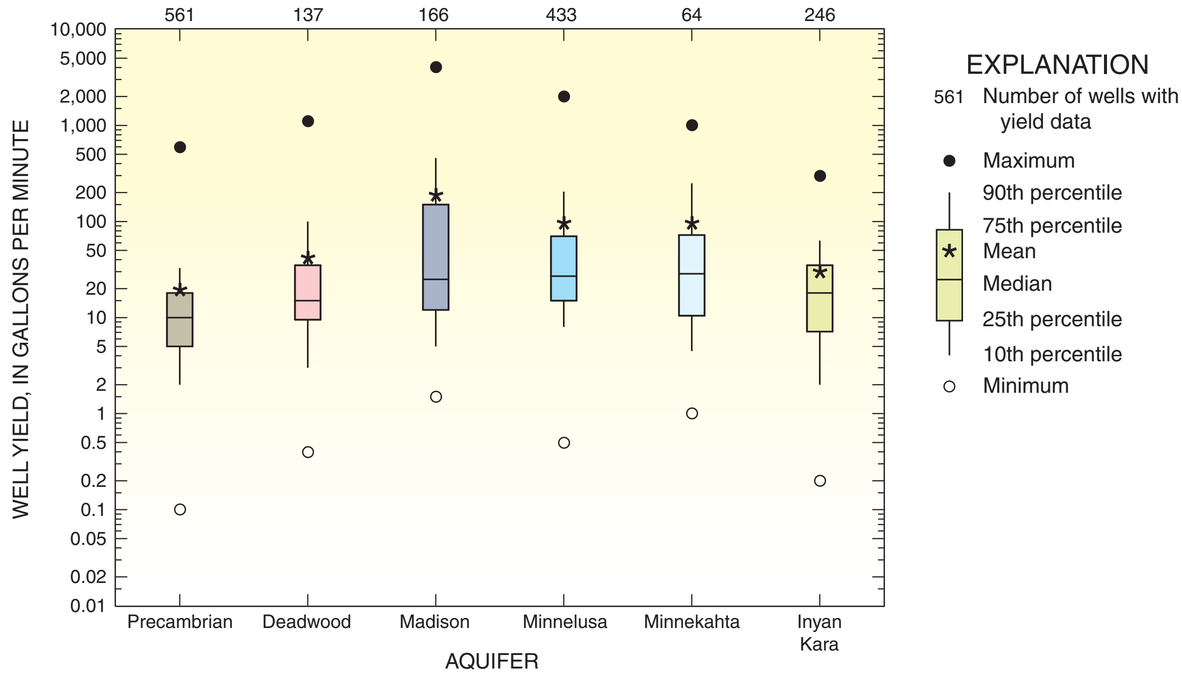


Figure 8. Distribution of well yields from selected aquifers (data obtained from U.S. Geological Survey Ground Water Site Inventory database).

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.

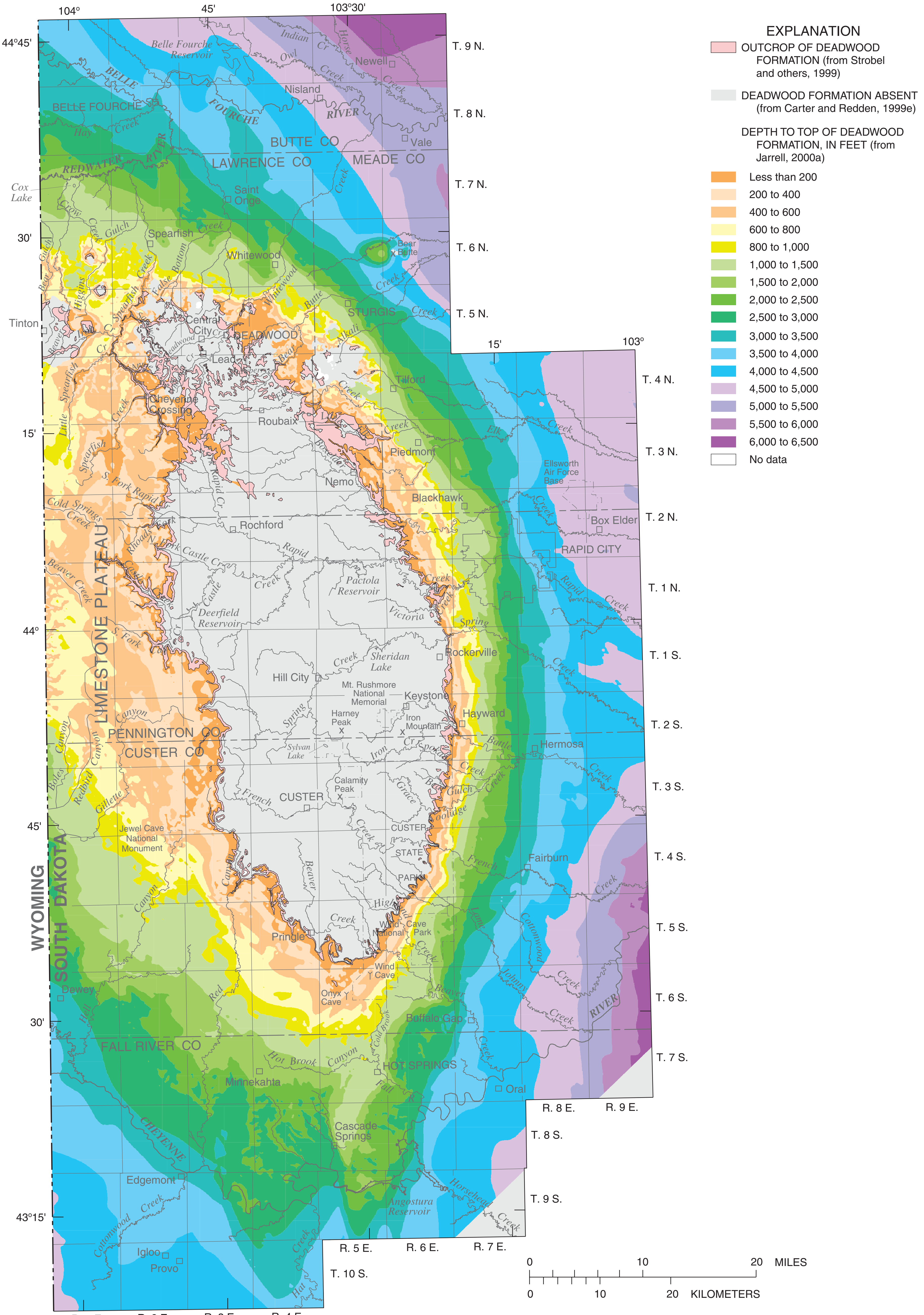
Characteristics of Minor Aquifers

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.

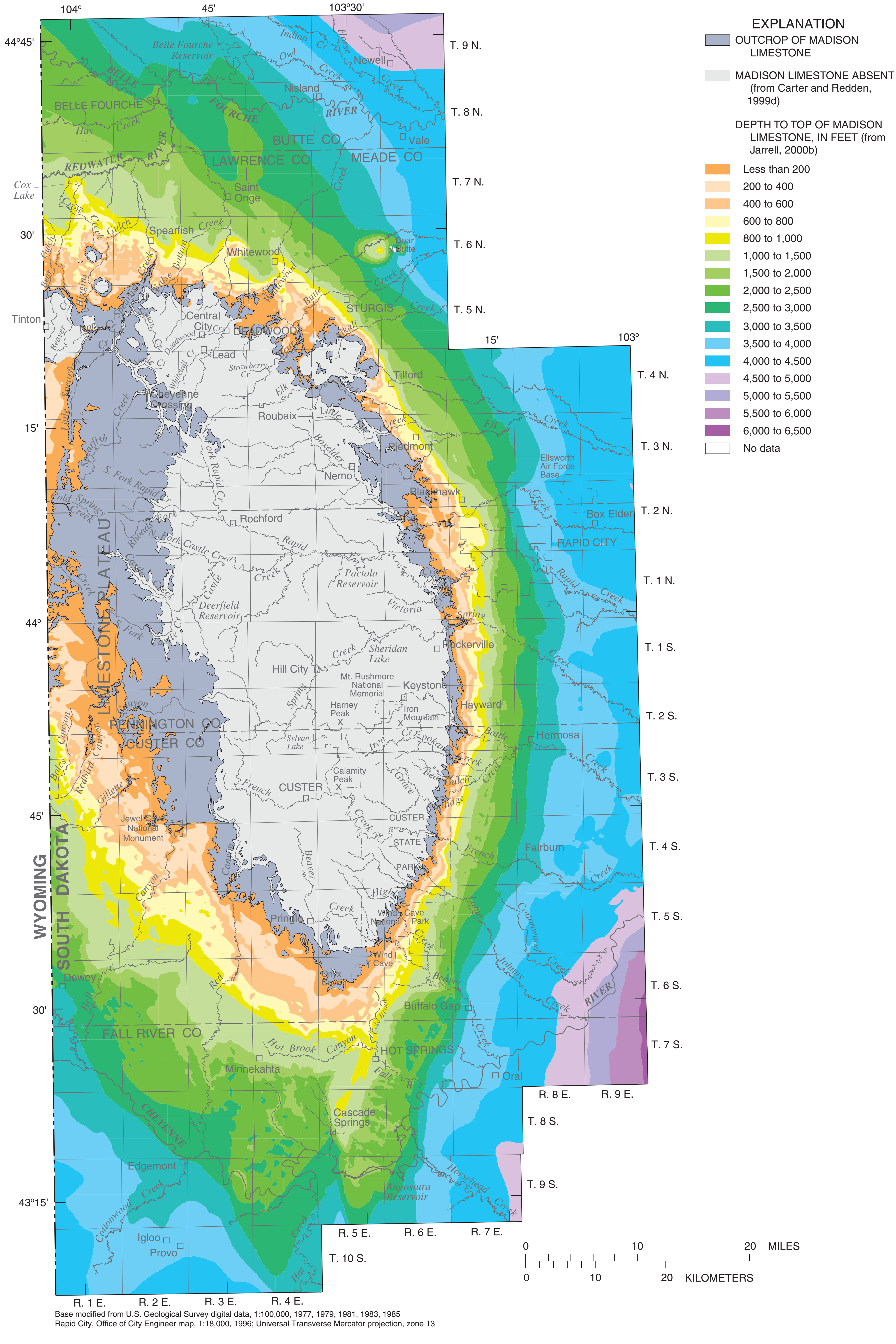
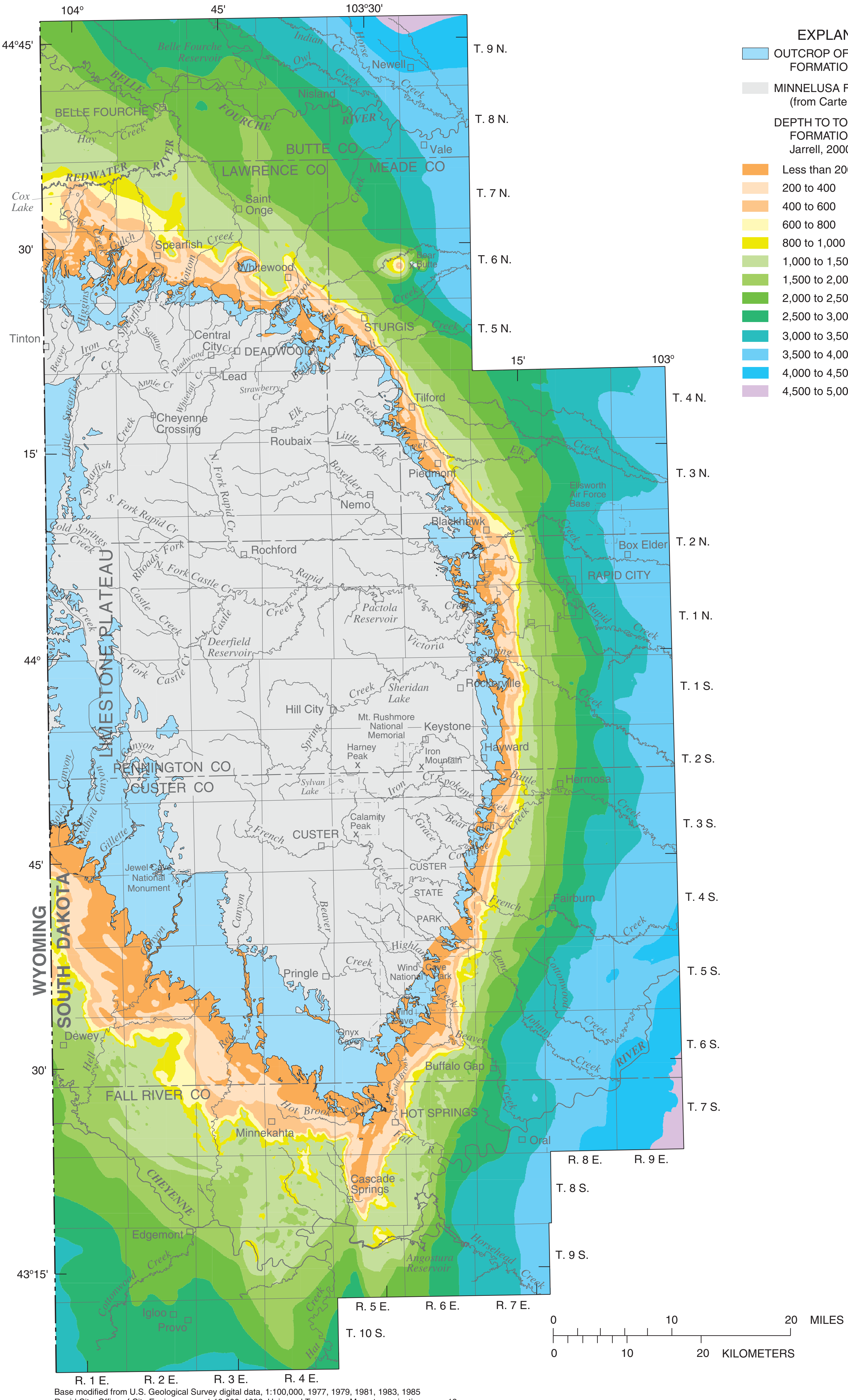


Figure 10. Depth to top of Madison Limestone.



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Rapid City, Office of City Engineer map, 1:18,000, 1996; Universal Transverse Mercator projection, zone 13

Figure 11. Depth to top of Minnelusa Formation.

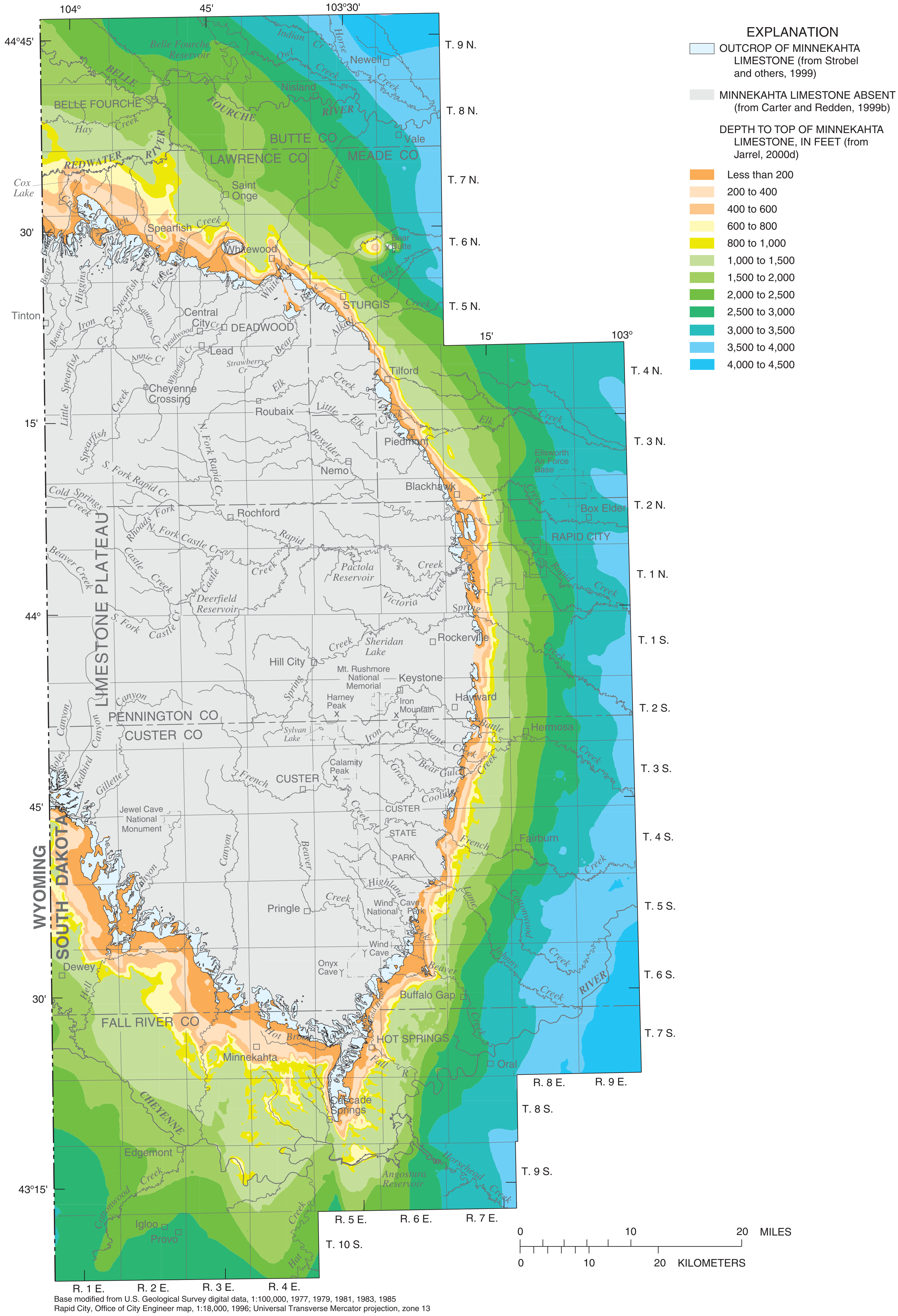


Figure 12. Depth to top of Minnekahta Limestone.

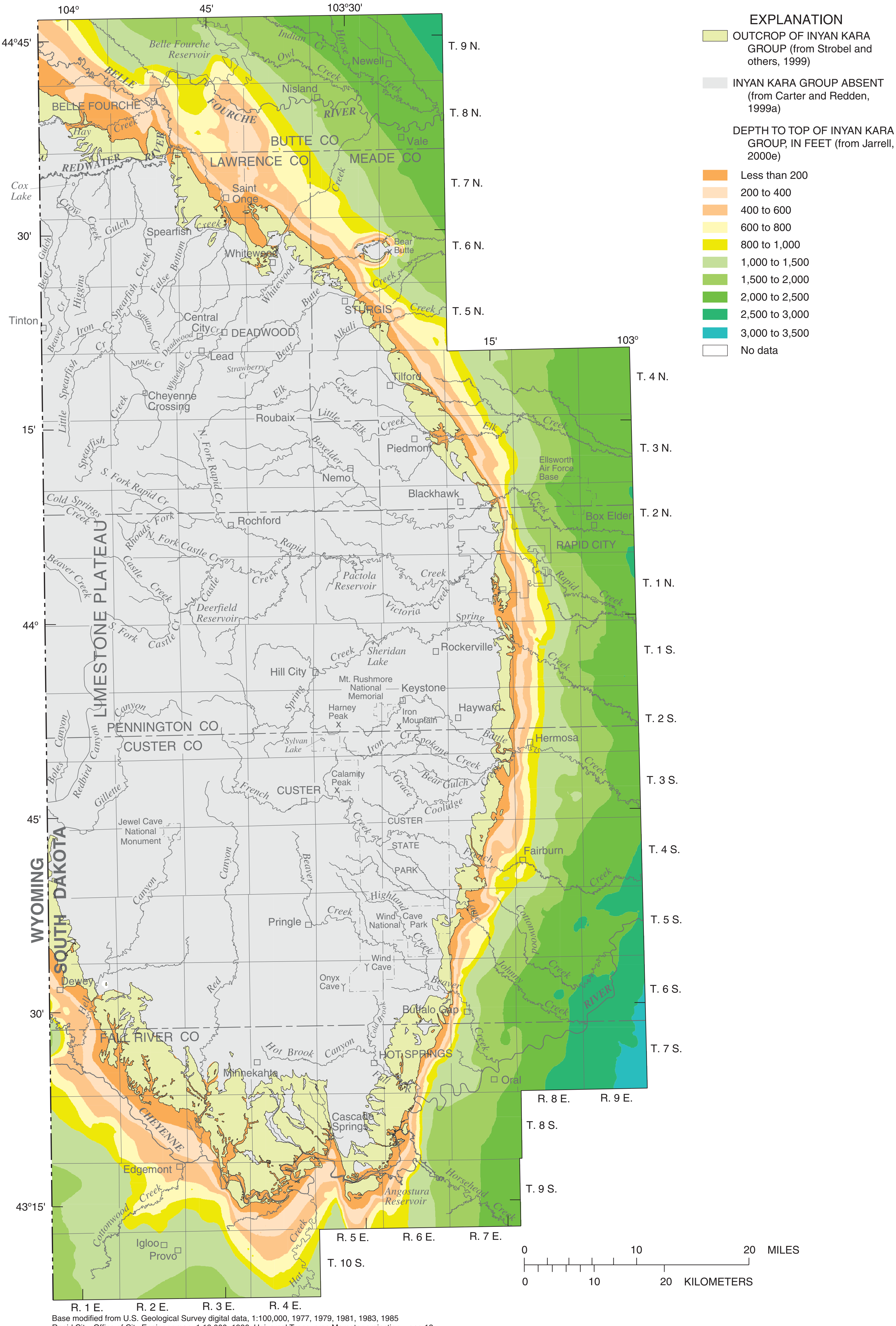
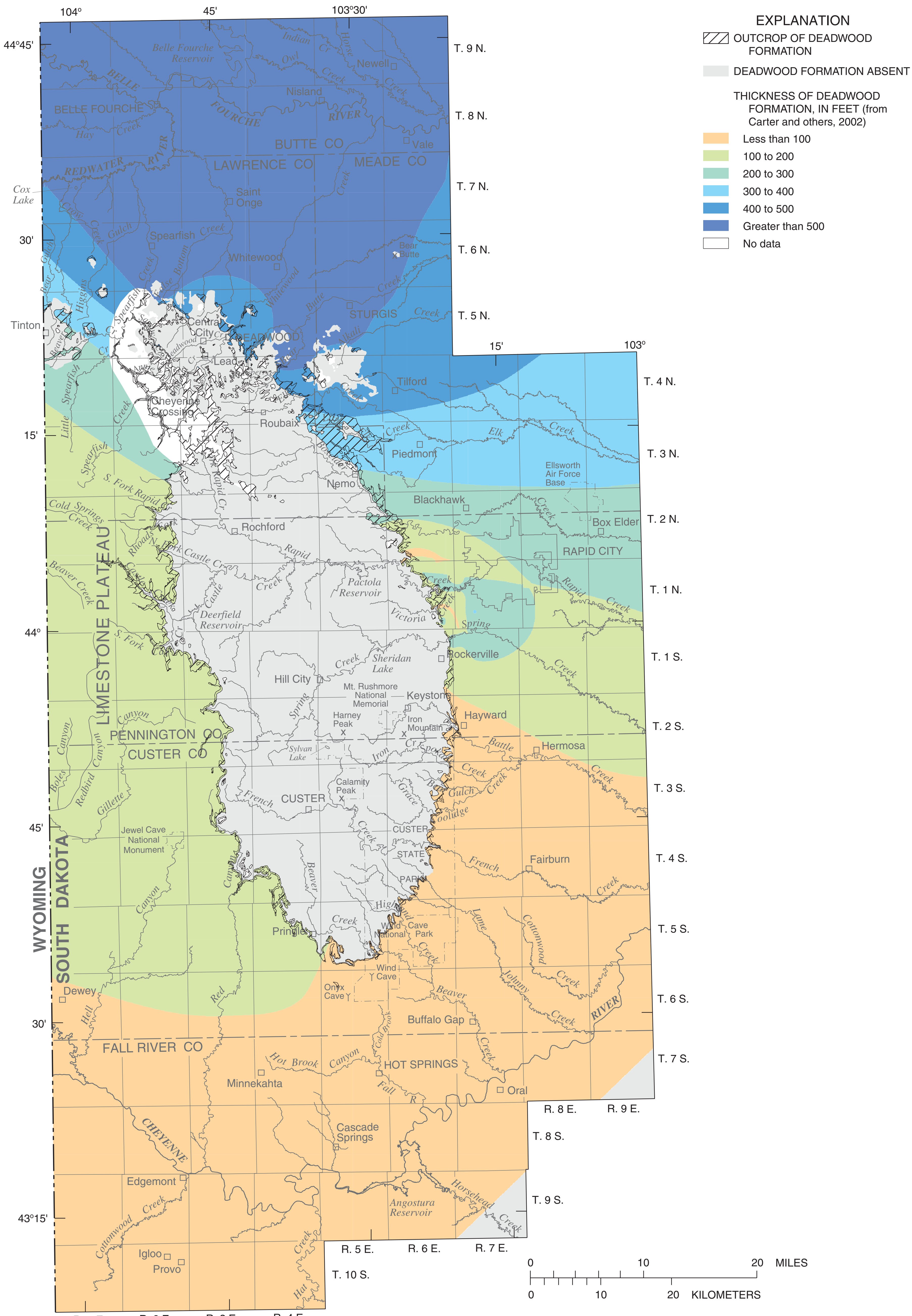


Figure 13. Depth to top of Inyan Kara Group.



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Rapid City, Office of City Engineer map, 1:18,000, 1996; Universal Transverse Mercator projection, zone 13

Figure 14. Generalized thickness of the Deadwood Formation.

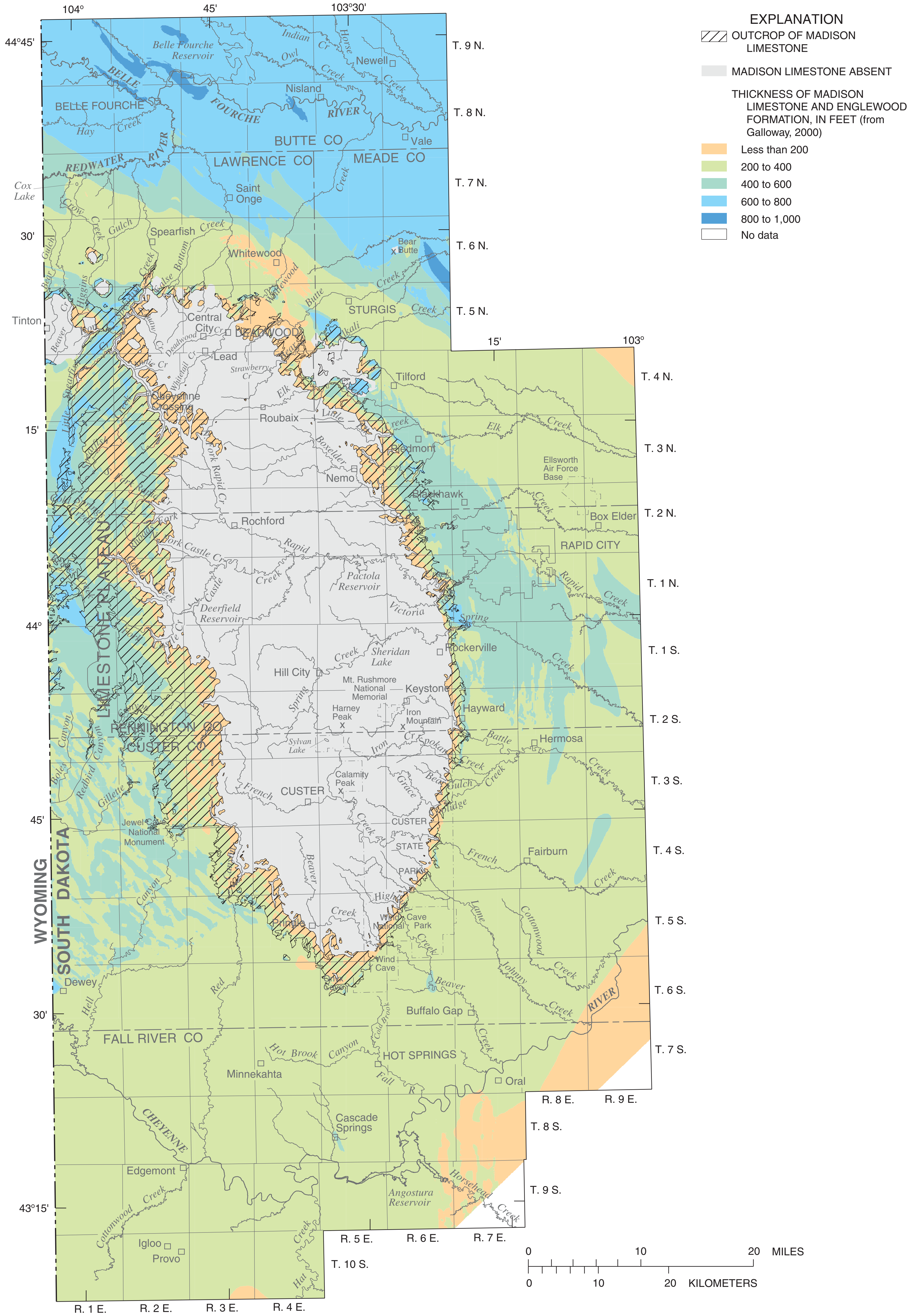


Figure 15. Generalized thickness of the Madison Limestone and Englewood Formation.

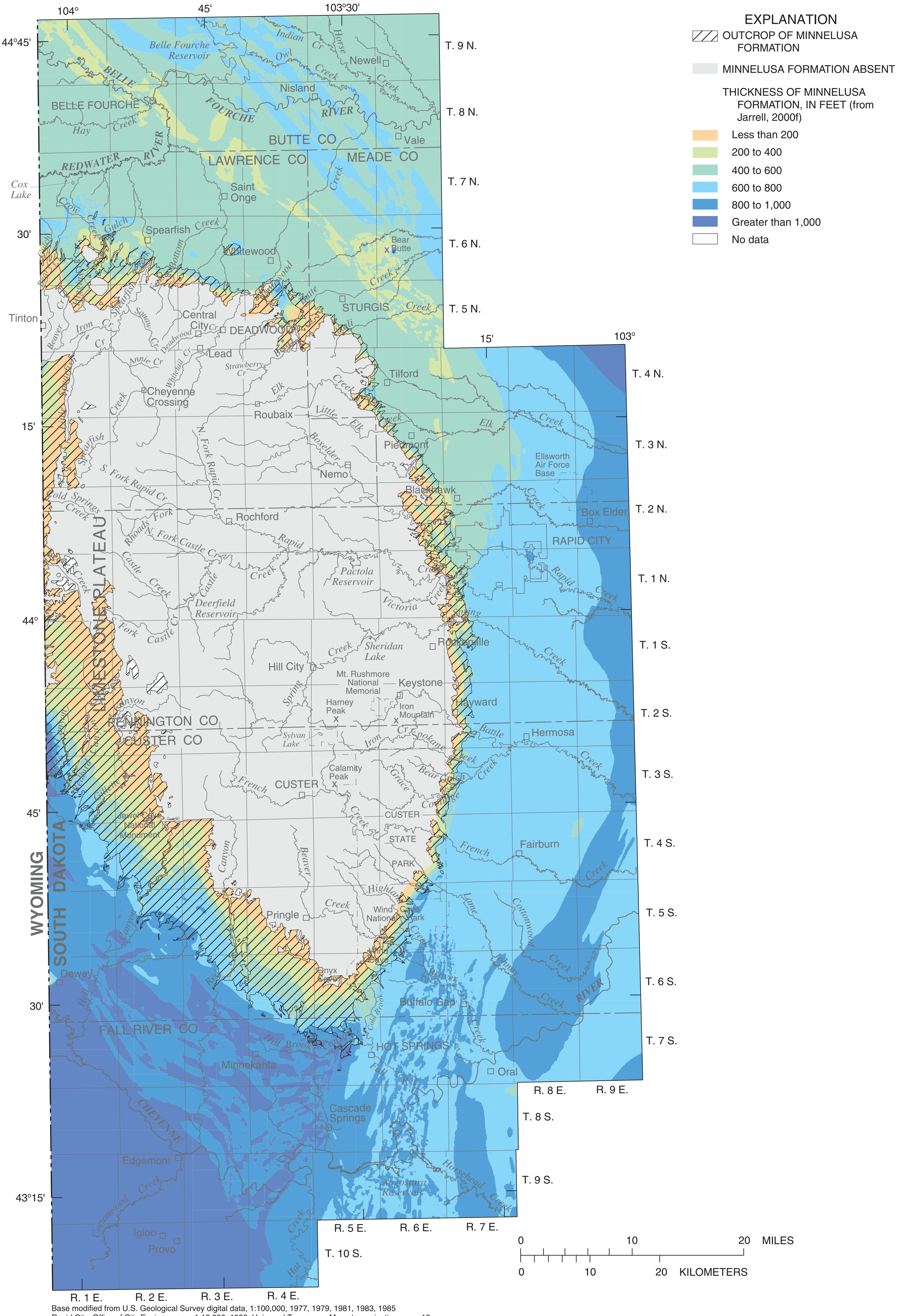


Figure 16. Generalized thickness of the Minnelusa Formation.

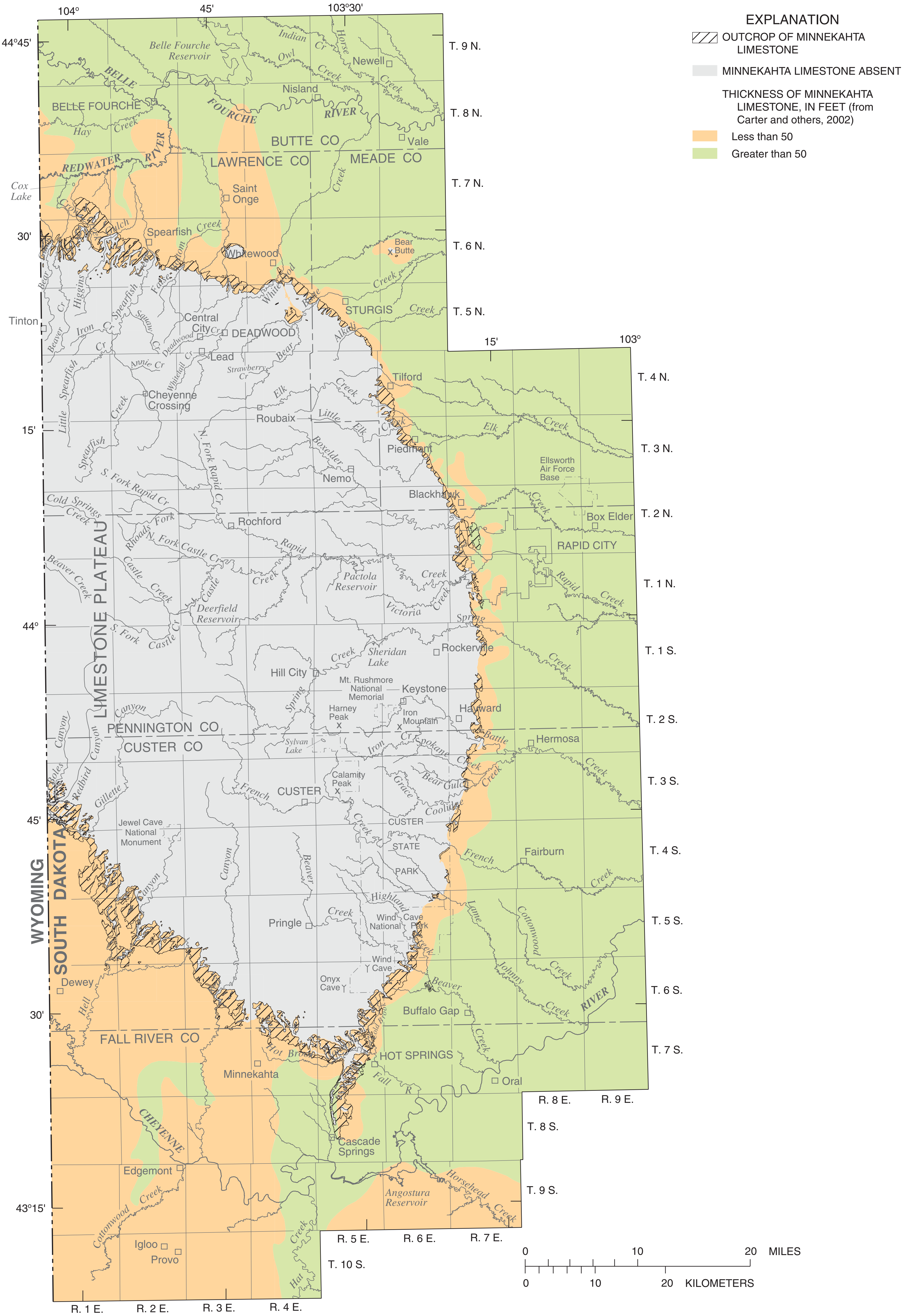


Figure 17. Generalized thickness of the Minnekahta Limestone.

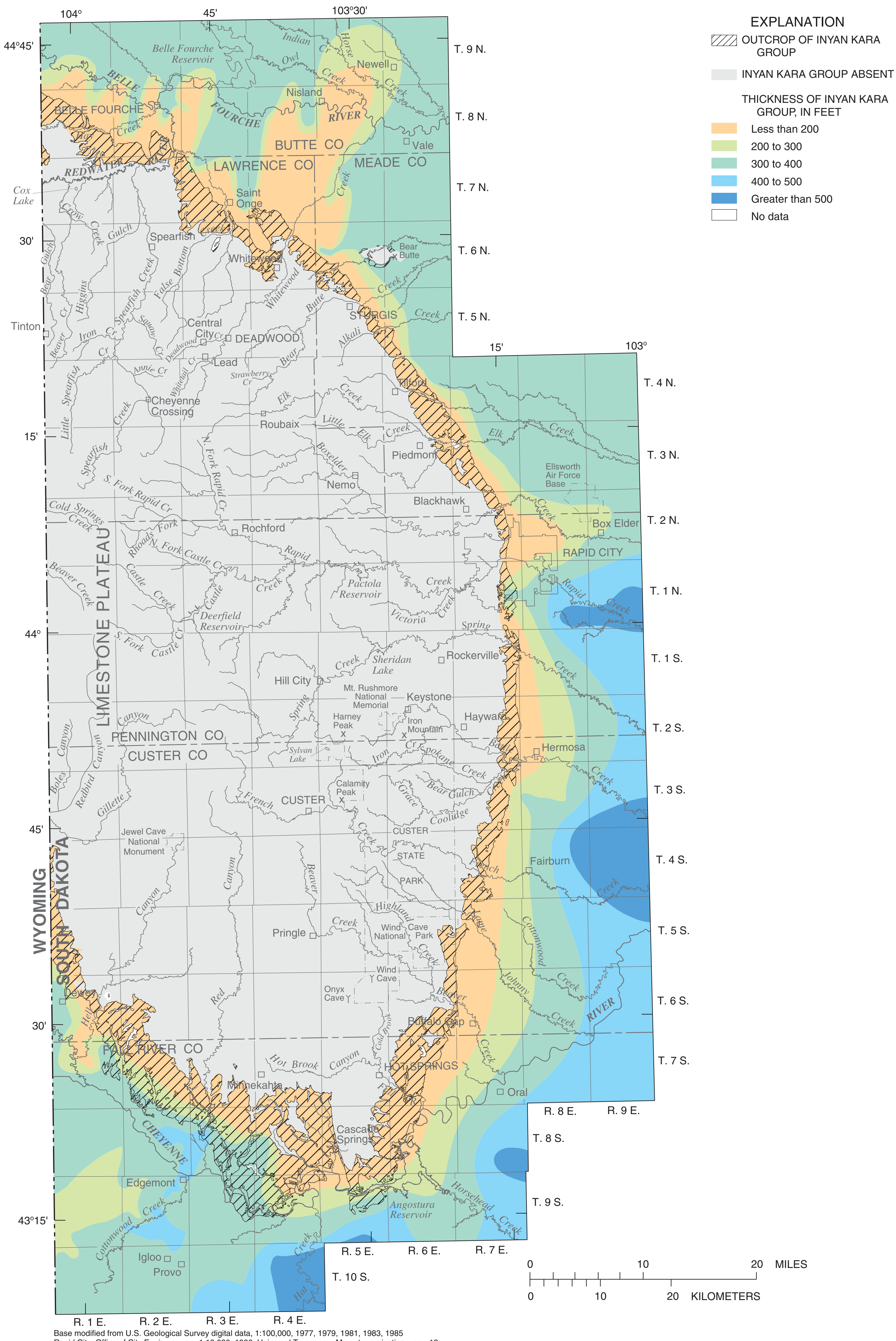
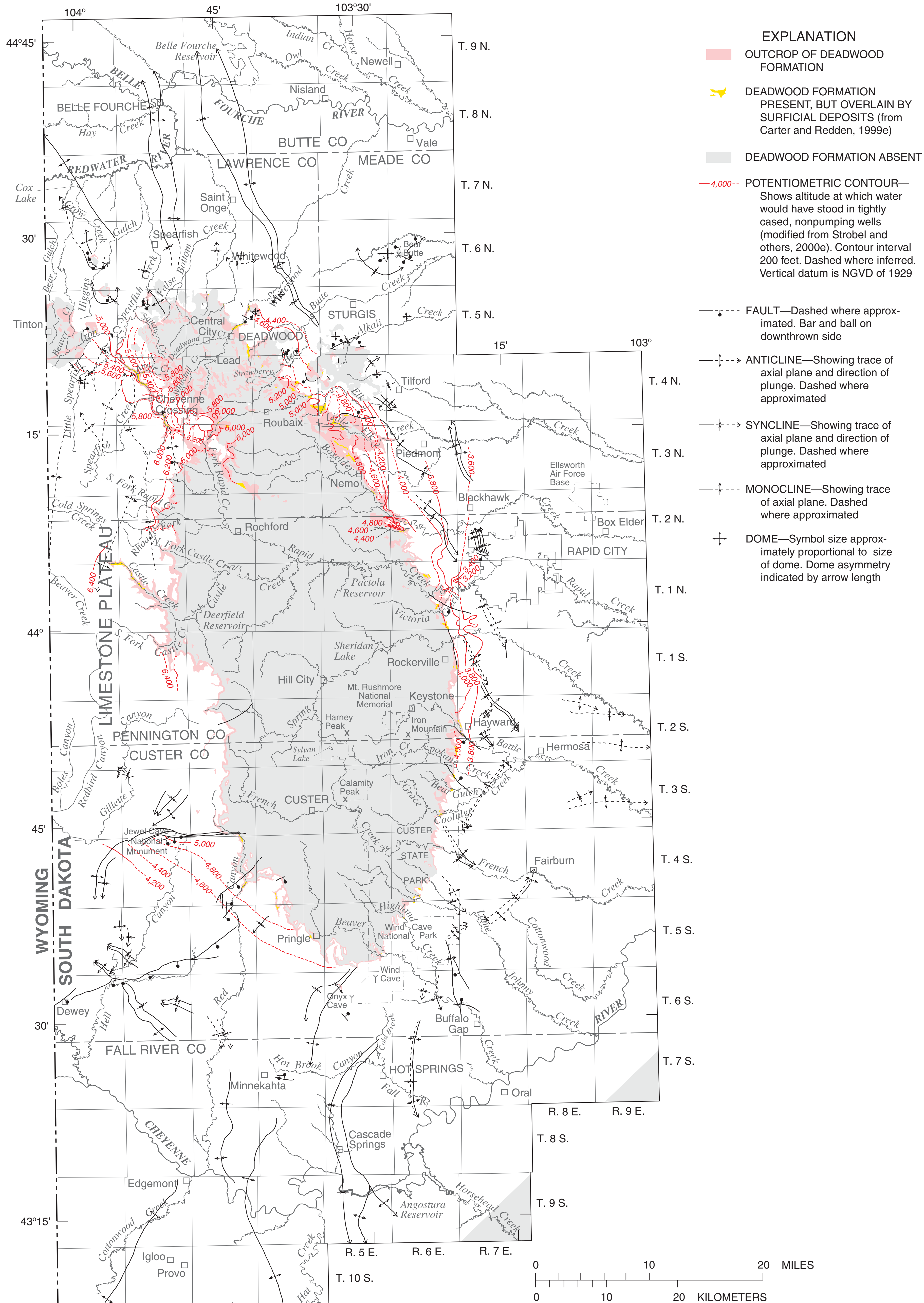


Figure 18. Generalized thickness of the Inyan Kara Group.



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Rapid City, Office of City Engineer map, 1:18,000, 1996; Universal Transverse Mercator projection, zone 13

Figure 19. Potentiometric surface of the Deadwood aquifer.

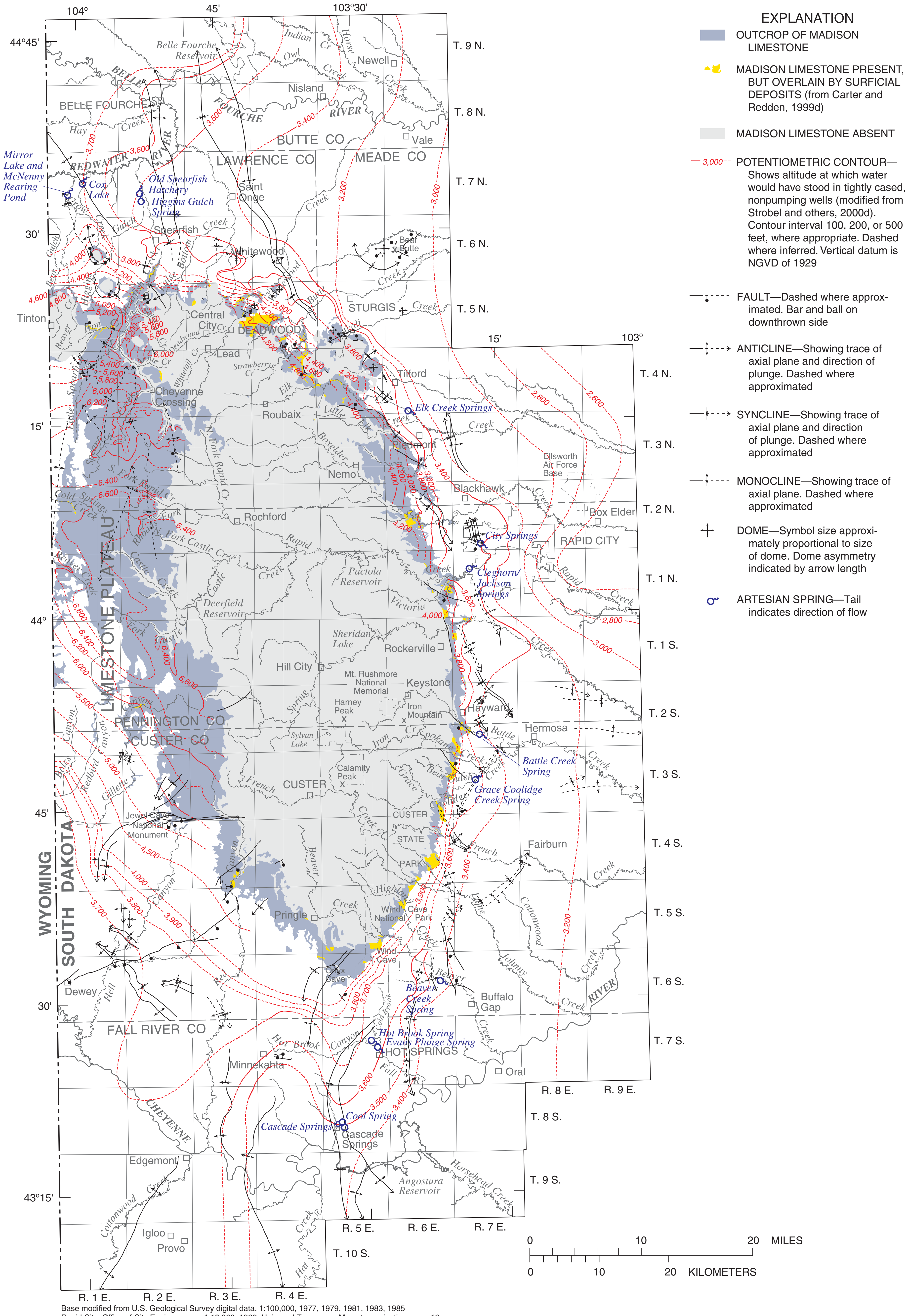

Figure 20. Potentiometric surface of the Madison aquifer and locations of major artesian springs.

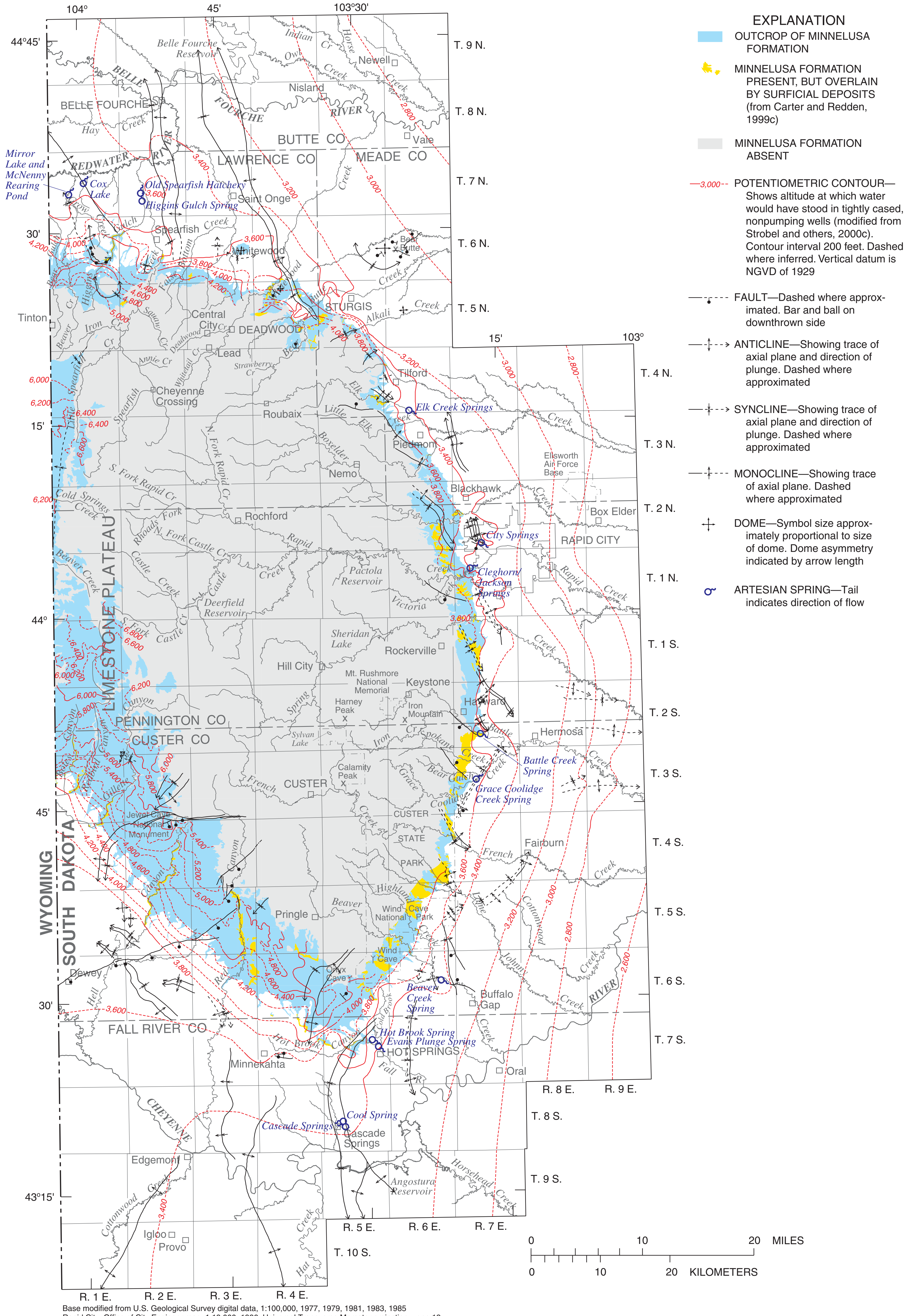

Figure 21. Potentiometric surface of the Minnelusa aquifer and locations of major artesian springs.

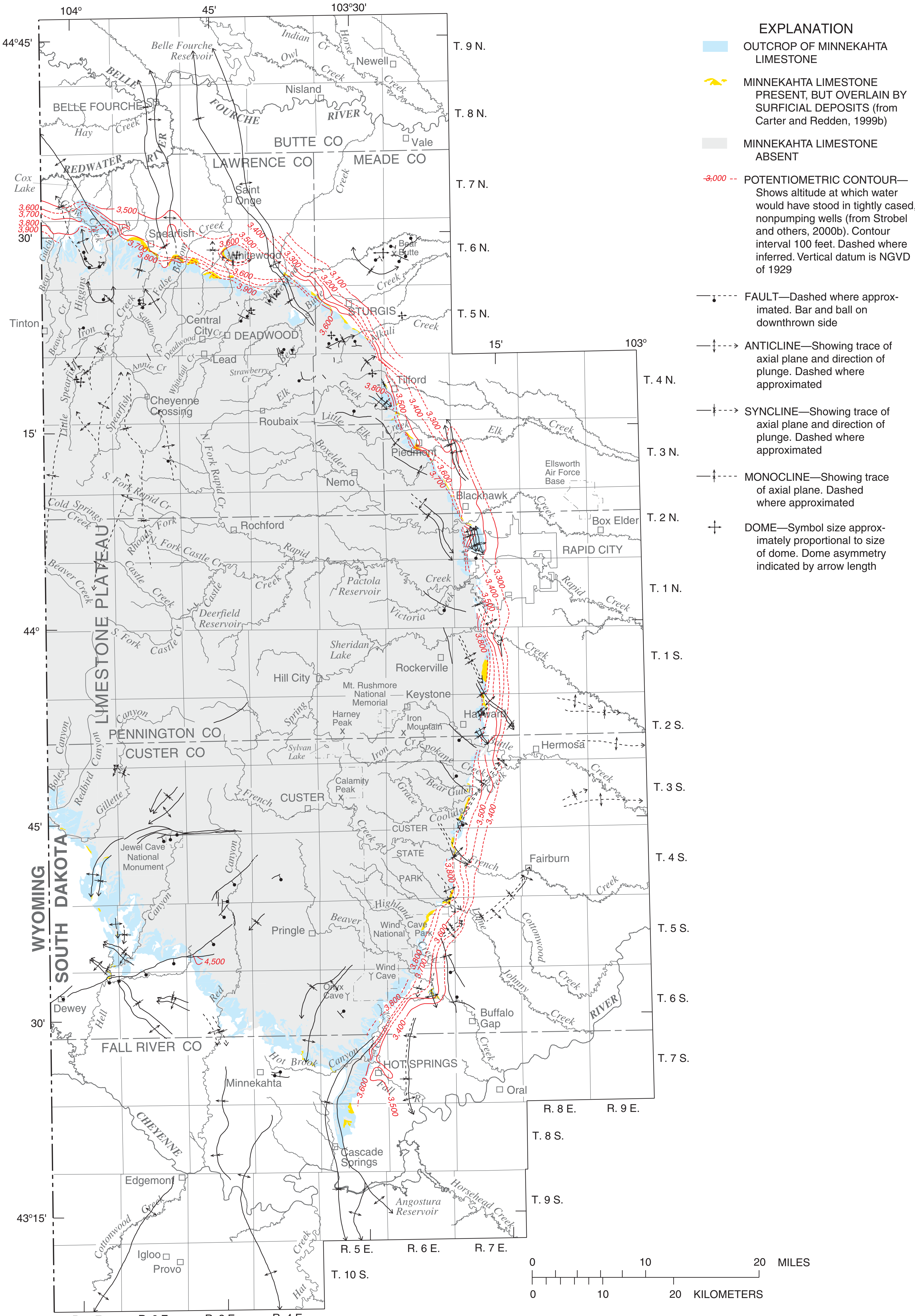

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Figure 22. Potentiometric surface of the Minnekahta aquifer.

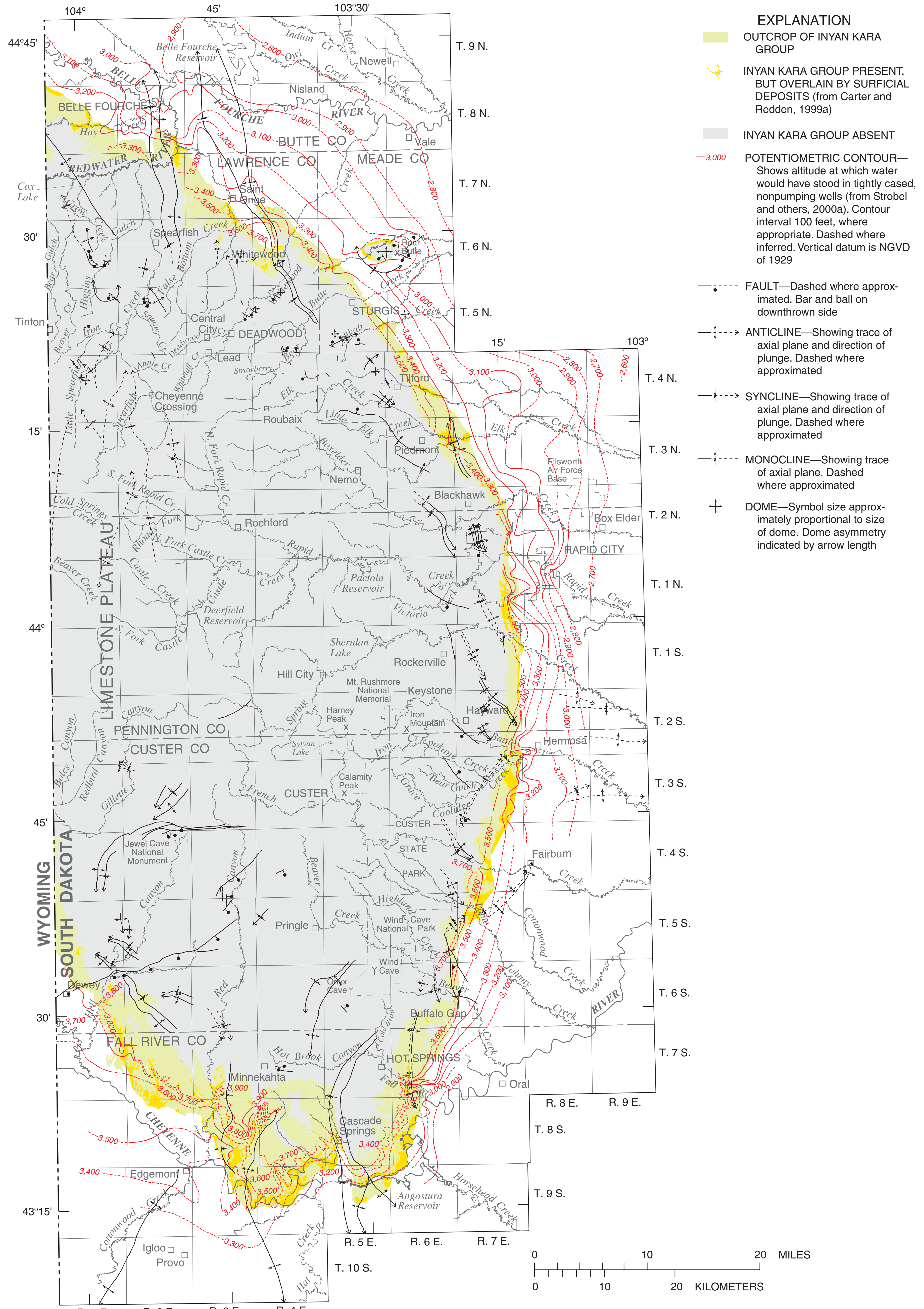

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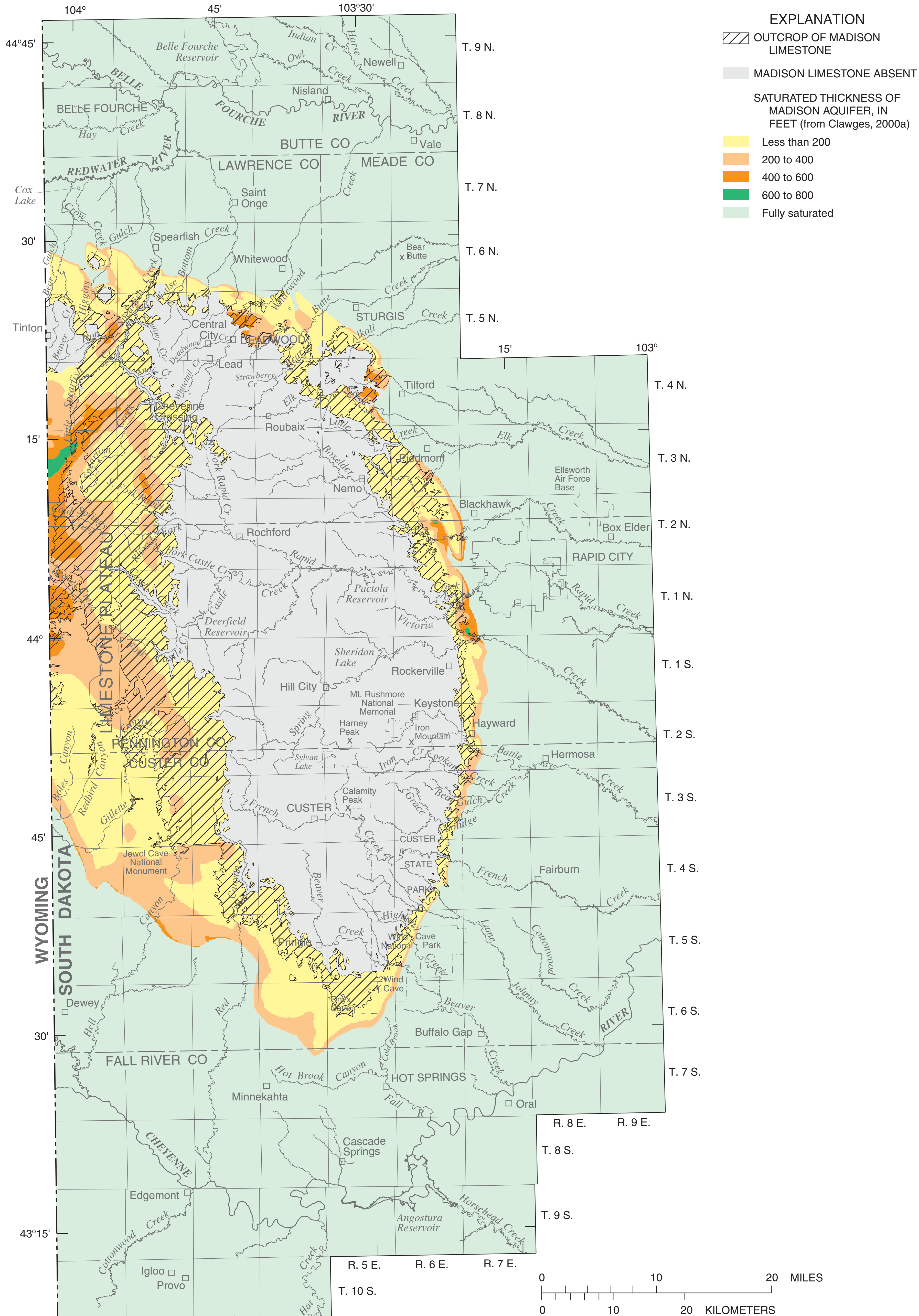
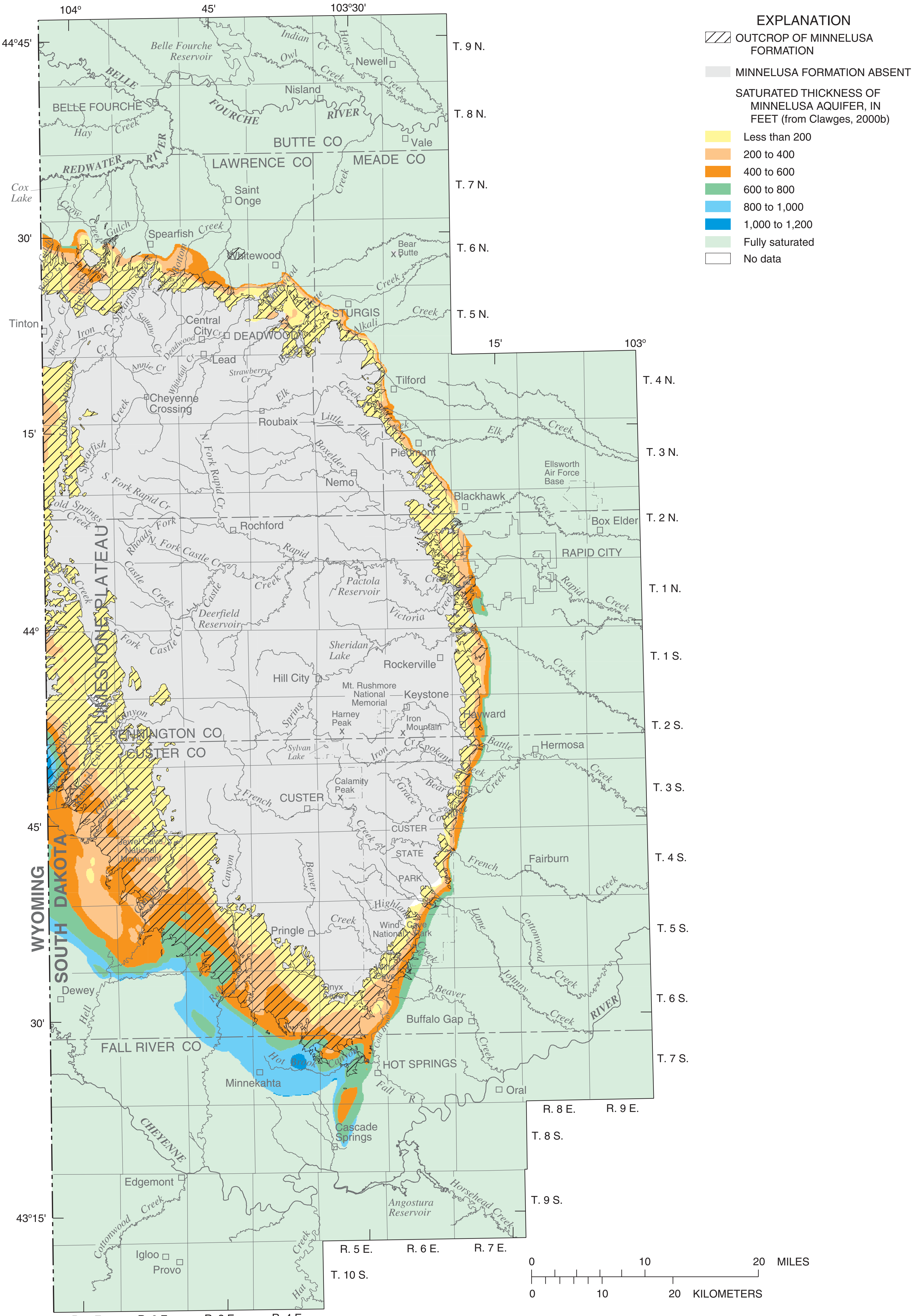
Figure 23. Potentiometric surface of the Inyan Kara aquifer.



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 24. Saturated thickness of the Madison aquifer.



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 25. Saturated thickness of the Minnelusa aquifer.

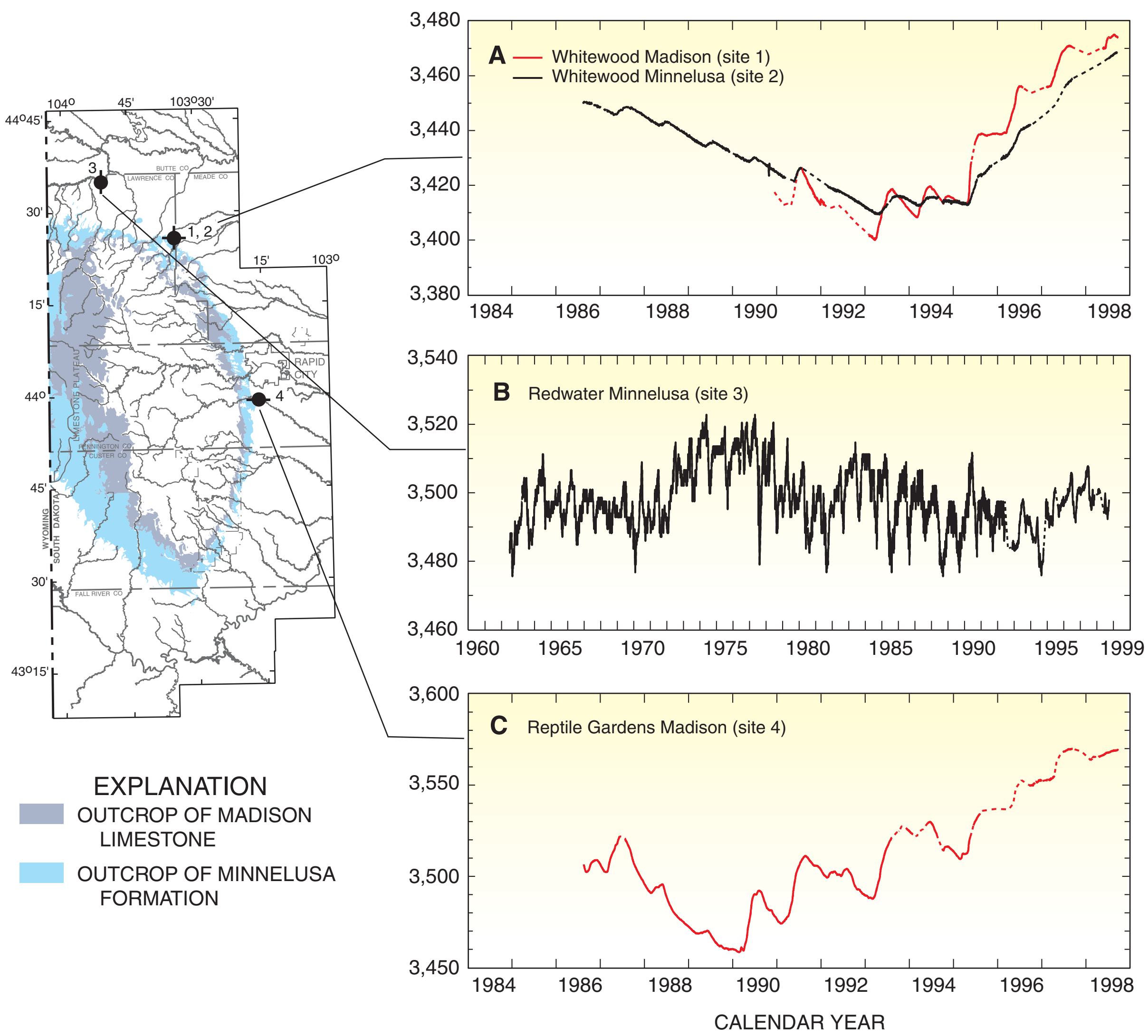


Figure 26. Selected hydrographs illustrating trends in ground-water levels.

WATER QUALITY OF GROUND-WATER RESOURCES

This section of the report includes a summary of water-quality characteristics for both major aquifers and selected minor aquifers in the Black Hills area. A summary of water quality relative to water use also is presented. More detailed descriptions of ground-water quality were presented by Williamson and Carter (2001).

Water quality is a measure of the suitability of water for a particular use based on selected physical, chemical, and biological characteristics. The quality of ground water is an important consideration because aquifers provide water for a variety of purposes including drinking water, livestock watering, irrigation, and industrial use. The quality of water can change as it flows over the land surface in streams and lakes and as it flows underground. Because ground-water and surface-water resources in the Black Hills area can be highly interconnected, the quality of surface water can affect the quality of ground water, and vice versa.

Ground water can contain numerous substances (constituents) from natural and human sources that typically are measured using laboratory analyses. Some constituents potentially can cause serious health effects. As ground water comes in contact with soil and rock materials, some of the chemicals, minerals, and nutrients dissolve and become part of the water chemistry. Two fundamental factors influencing water chemistry are the type of geologic materials that are present and the length of time that water is in contact with those materials (Winter and others, 1998), which typically increases constituent concentrations from natural sources.

Chemical constituents in ground water also can result from human sources, such as industrial, domestic, and agricultural chemicals, that have the potential to contaminate the water. The potential for ground-water contamination in the Black Hills area can be large because many of the outcrops, which are important aquifer recharge areas, could be subject to various forms of land development. Rapid ground-water velocities also are possible in many aquifers because of high secondary permeability. Contamination by septic tanks has been documented for some wells in the Blackhawk, Piedmont, and Sturgis areas (Bartlett and West Engineers, Inc., 1998).

Standards and guidelines have been established to protect water for various designated uses. The U.S. Environmental Protection Agency (USEPA) and the States are responsible for establishing the standards for constituents in water that have been shown to pose a risk to human health. Although drinking-water standards apply only to public water supplies, individuals using water from private wells should be aware of potential health risks associated with drinking water that exceeds these standards. Maximum Contaminant Levels (MCLs) are established for constituents that, if present in drinking water, may cause adverse human health effects; MCLs are enforceable health-based standards (U.S. Environmental Protection Agency, 1994). Secondary Maximum Contaminant Levels (SMCLs) are established for constituents that can adversely affect the taste, odor, or appearance of water and may result in discontinuation of use of the water; SMCLs are nonenforceable, generally non-health-based standards that are related to the aesthetics of water use (U.S. Environmental Protection Agency, 1994).

General Characteristics for Major Aquifers

A brief summary of water-quality characteristics from Williamson and Carter (2001) for the major aquifers in the study area (Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara aquifers) is presented in this section of the report. Characteristics for the Precambrian aquifer also are included in this section of the report because numerous wells are completed in this aquifer in the crystalline core of the Black Hills.

Water temperature affects the usefulness of water for many purposes. For example, hot water needs to be cooled prior to consumption; however, hot water is desirable for geothermal heating purposes. The temperature of water from wells completed in the Madison aquifer is shown in figure 27. Water temperatures generally increase with well depth. Temperatures measured in the Madison aquifer generally are the warmest of the major aquifers in the study area because it generally is the deepest aquifer used at distance from the outcrop. The Madison aquifer is the primary source of water for warm artesian springs in the southern Black Hills; factors other than aquifer depth may affect water temperatures in this area (Whalen, 1994).

The total of all dissolved mineral constituents is measured as the dissolved solids concentration. Specific conductance is a measure of the ability of water to conduct an electrical current. It is highly dependent on the amount of dissolved solids (such as salt) in the water. Pure water, such as distilled water, has a very low specific conductance. Specific conductance is an important water-quality measurement because it can be used to estimate dissolved solids concentrations, which may affect the taste of water and suitability for various uses. When comparing samples, a higher specific conductance indicates a higher dissolved solids concentration. Dissolved constituents tend to increase with residence time as indicated by the increase in specific conductance in the Madison and Minnelusa aquifers with distance from the Madison Limestone and Minnelusa Formation outcrops (figs. 28 and 29).

Specific conductance generally is lower in water from the Precambrian, Deadwood, and Minnekahta aquifers than in water from the other major aquifers. Generally, water from the Inyan Kara aquifer is high in specific conductance even in some outcrop areas of the Inyan Kara Group (fig. 30) and is higher in specific conductance than the other major aquifers due to greater amounts of shale within the Inyan Kara Group. Water obtained from shales may contain rather high concentrations of dissolved solids (Hem, 1985) and, hence, high specific conductance. Because depths to aquifers increase with distance from outcrop in most locations, concentrations of dissolved solids generally increase with well depth, as shown by the example relation in figure 31.

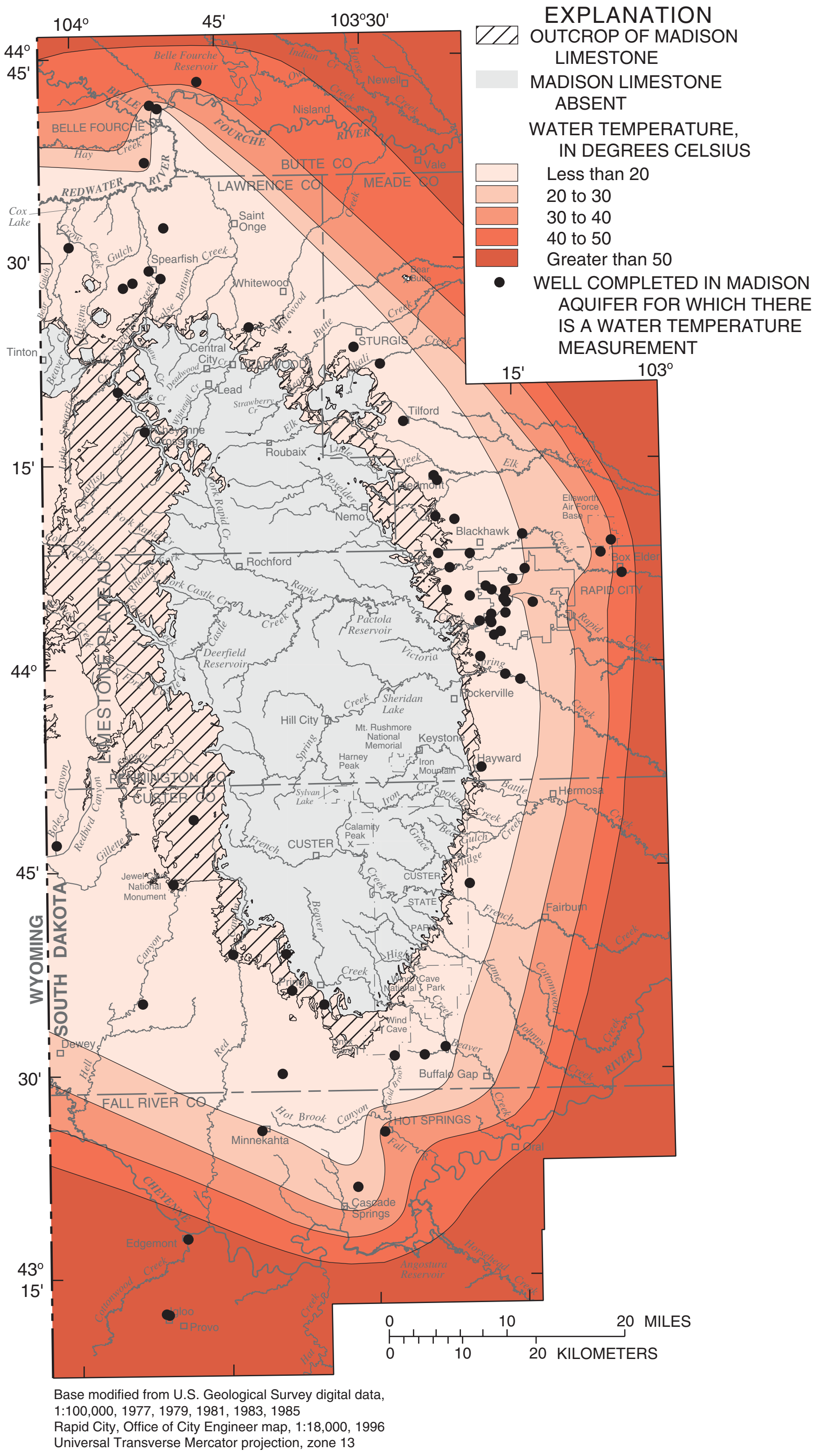


Figure 27. Water temperature in the Madison aquifer (modified from Williamson and Carter, 2001).

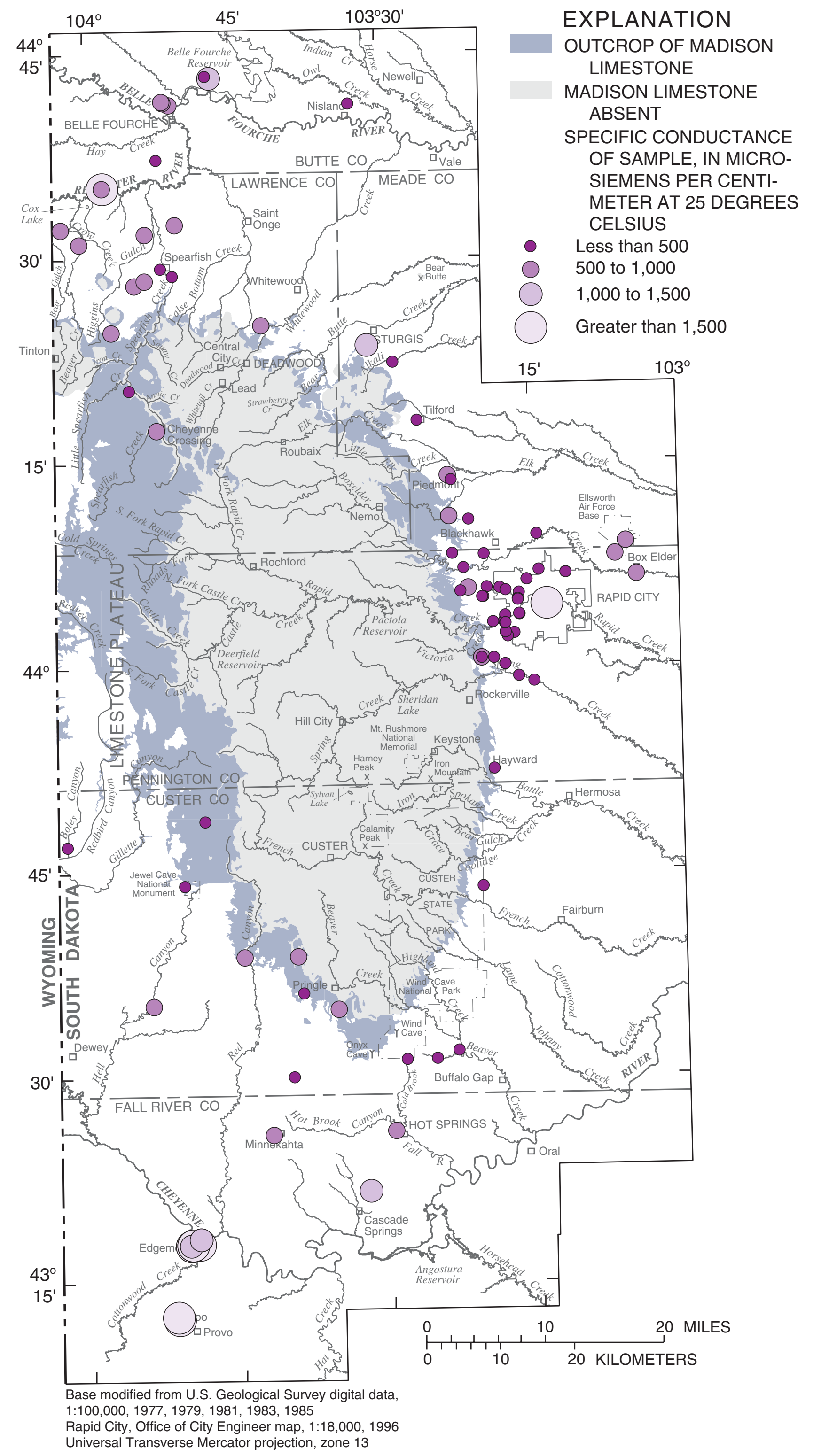


Figure 28. Specific conductance in the Madison aquifer (modified from Williamson and Carter, 2001).

Hardness is related to soap-consuming characteristics of water. Hard water can shorten the life of fabrics and may cause equipment damage. Hardness is determined primarily by the amount of dissolved calcium and magnesium in water. Water that has a hardness less than 61 mg/L (milligrams per liter) is considered soft; 61-120 mg/L, moderately hard; 121-180 mg/L, hard; and more than 180 mg/L, very hard (Heath, 1983). Geologic units that contain few carbonate rocks, such as the Precambrian-age rocks, generally contain water with lower hardness than geologic units that contain mostly carbonate rocks, which are composed primarily of calcium- and magnesium-bearing minerals. Water in the Madison, Minnelusa, and Minnekahta aquifers generally is hard to very hard (fig. 32) because the formations consist primarily of carbonate rocks. Water in the Deadwood aquifer also is hard to very hard because this unit consists primarily of sandstone with a calcium carbonate cement. Water in the Inyan Kara aquifer generally is hard to very hard in or near outcrop areas; however, hardness decreases with increasing distance from the outcrop (fig. 33). Similar to the other major bedrock aquifers, concentrations of dissolved solids in the Inyan Kara aquifer increase with increasing distance from the outcrop because calcium and bicarbonate are replaced by sodium and sulfate as water moves downgradient.

In the Black Hills area, water from the major aquifers generally is fresh and low in dissolved solids in and near outcrop areas except for parts of the Inyan Kara aquifer. The Madison, Minnelusa, and Inyan Kara aquifers may yield slightly saline water (dissolved solids concentrations between 1,000 and 3,000 mg/L) at distance from the outcrops, especially in the southern Black Hills. The water in these aquifers is highly mineralized outside of the study area. In general, concentrations of sodium, chloride, and sulfate in the major aquifers increase with distance from the outcrop.

Sulfate affects the taste of water and has an SMCL of 250 mg/L. Sulfate concentrations in the Minnelusa aquifer are dependent on the amount of anhydrite present in the Minnelusa Formation. Near the outcrop, sulfate concentrations generally are low (less than 250 mg/L) because anhydrite has been removed by dissolution. An abrupt increase in sulfate concentrations occurs downgradient, where a transition zone occurs around the core of the Black Hills. This transition zone is an area within which the sulfate concentrations range from 250 to 1,000 mg/L (fig. 34) and marks an area of active removal of anhydrite by dissolution. Downgradient from the transition zone, sulfate concentrations are greater than 1,000 mg/L, which delineates a zone in which thick anhydrite beds remain in the formation. The transition zone probably is moving downgradient over geologic time as the anhydrite in the formation is dissolved (Kyllonen and Peter, 1987).

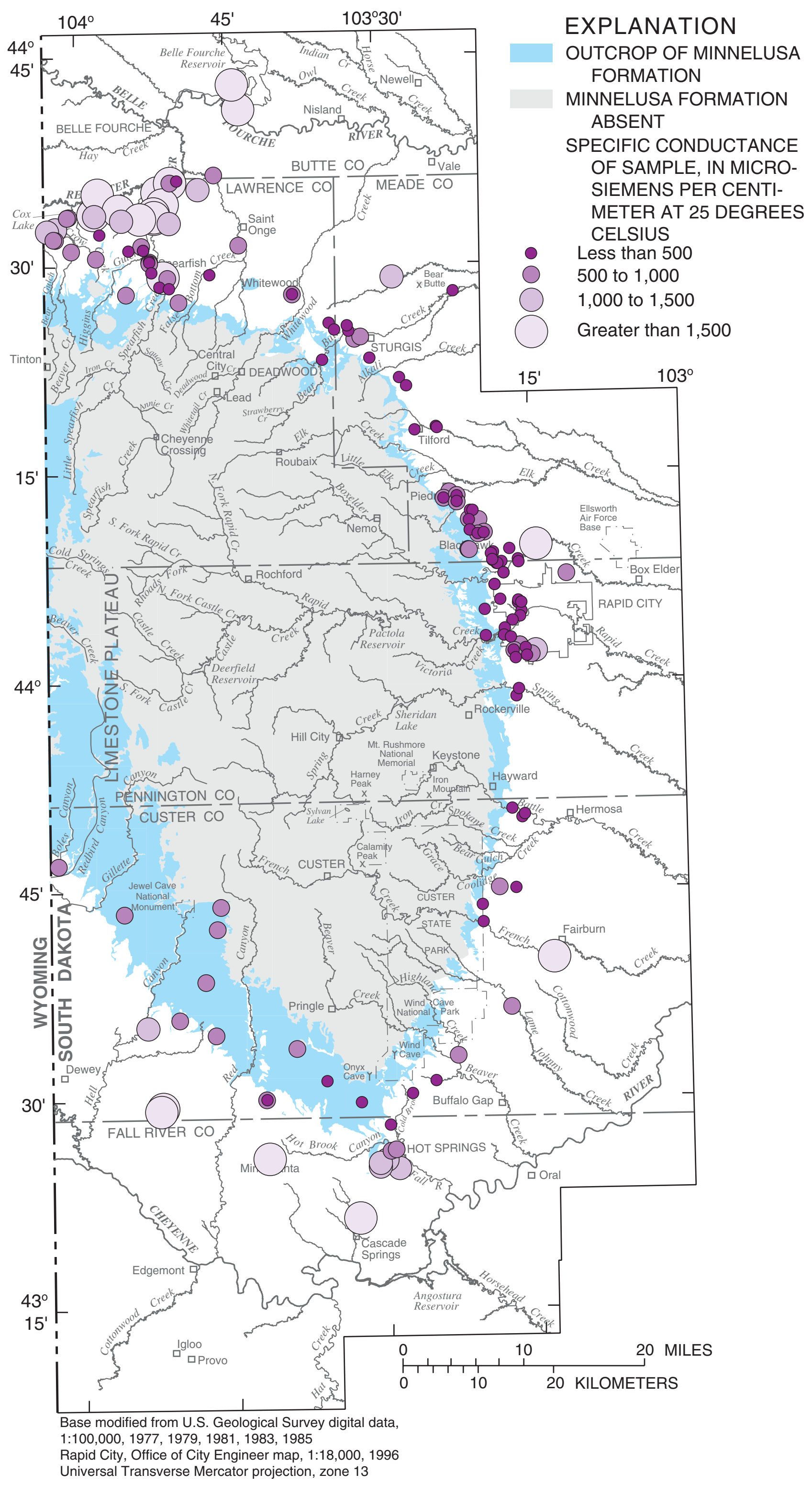


Figure 29. Specific conductance in the Minnelusa aquifer (modified from Williamson and Carter, 2001).

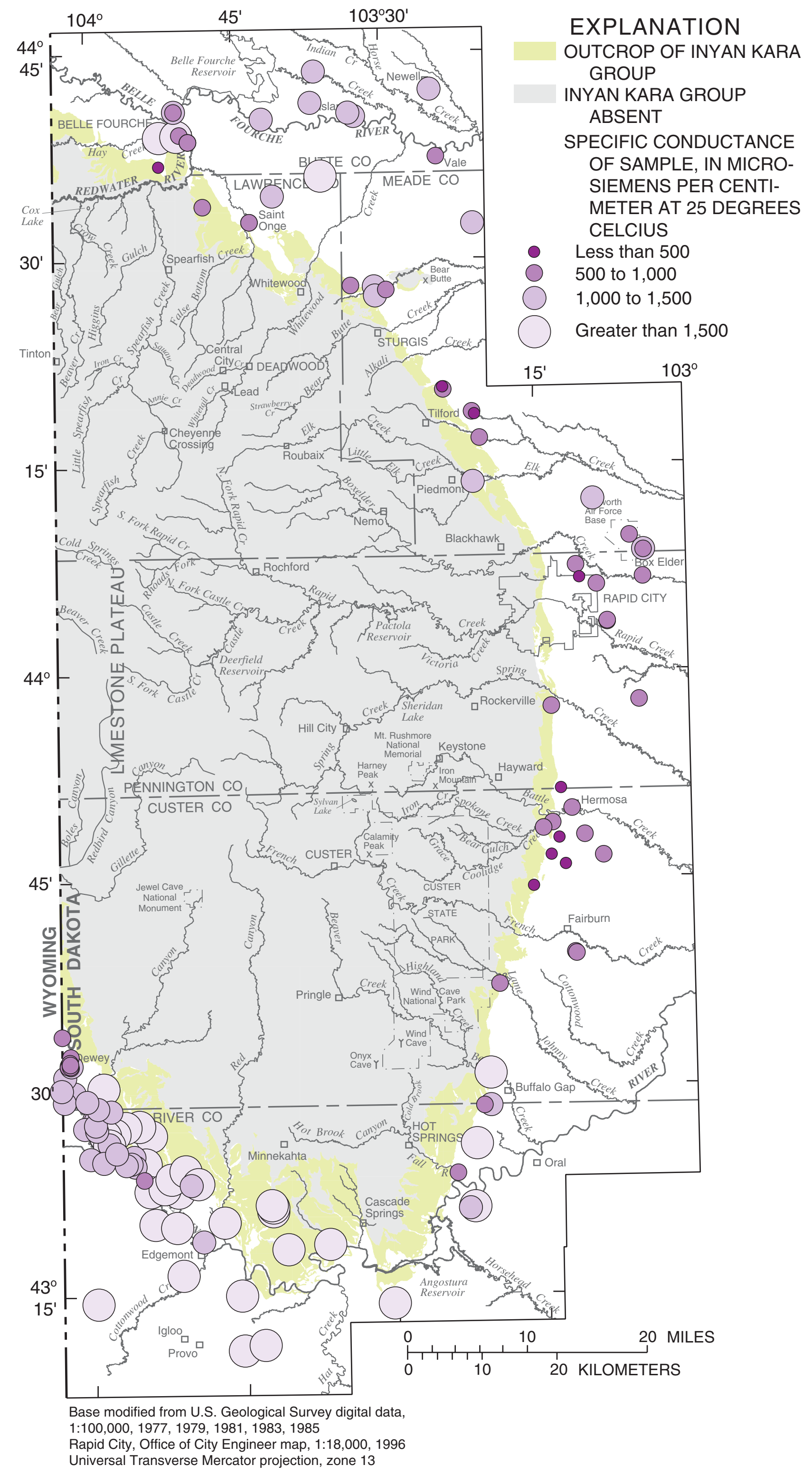


Figure 30. Specific conductance in the Inyan Kara aquifer (modified from Williamson and Carter, 2001).

Radionuclides are unstable isotopes that exist throughout the environment and have a certain probability of decay. Because several radionuclides are known to cause various types of cancer, drinking-water standards exist for these radionuclides. Most naturally occurring radionuclides in water are the result of radioactive decay of uranium and thorium. Radioactivity is the release of energy and energetic particles by changes occurring within atomic or nuclear structures (Hem, 1985). Alpha, beta, and gamma radiation are types of radiation that commonly are measured in ground water. Radionuclide analyses can be expressed in terms of disintegrations per unit time (typically in units of picocuries per liter) or in mass units (typically in units of micrograms per liter). Some of the radionuclide names include numbers, such as radium-226 and radium-228; these numbers represent chemical variations of the element.

Radium locates primarily in bone in humans; however, inhalation or ingestion of radium may result in lung cancer. Inhaled radon is known to cause lung cancer, and ingested radon is believed to cause cancer. In the Deadwood aquifer, more than 30 percent of the samples analyzed for radium-226 or radium-226 and radium-228 exceeded the MCL of 5 pCi/L (picocuries per liter) for the combined radium-226 and radium-228 standard. Almost 90 percent of the samples from the Deadwood aquifer exceed the proposed MCL of 300 pCi/L for radon in States without an active indoor air program (U.S. Environmental Protection Agency, 1999); three of these samples also exceed the proposed MCL of 4,000 pCi/L for radon in States with an active indoor air program (U.S. Environmental Protection Agency, 1999) (fig. 35).

Uranium is a chemical and radiological hazard and carcinogen. Uranium deposits have been discovered and mined in the Inyan Kara Group in the southern Black Hills. Uranium may be introduced into the Inyan Kara Group by the artesian recharge of water from the Minnelusa aquifer (Gott, 1974). Some water in the Inyan Kara aquifer, especially in the southern Black Hills, contains relatively high concentrations of radionuclides. Almost 20 percent of the samples collected from the Inyan Kara aquifer exceed the MCL for the combined radium-226 and radium-228 standard; all but one of the samples exceeding this standard were from wells in the southern Black Hills. About 4 percent of the samples from the Inyan Kara aquifer exceed the MCL of 30 µg/L (micrograms per liter) for uranium; all the samples exceeding the uranium MCL were from wells located in the southern Black Hills. In general, gross alpha-particle activity, gross-beta activity, and radium-226 are higher in the Deadwood and Inyan Kara aquifers than in the Madison, Minnelusa, and Minnekahta aquifers.

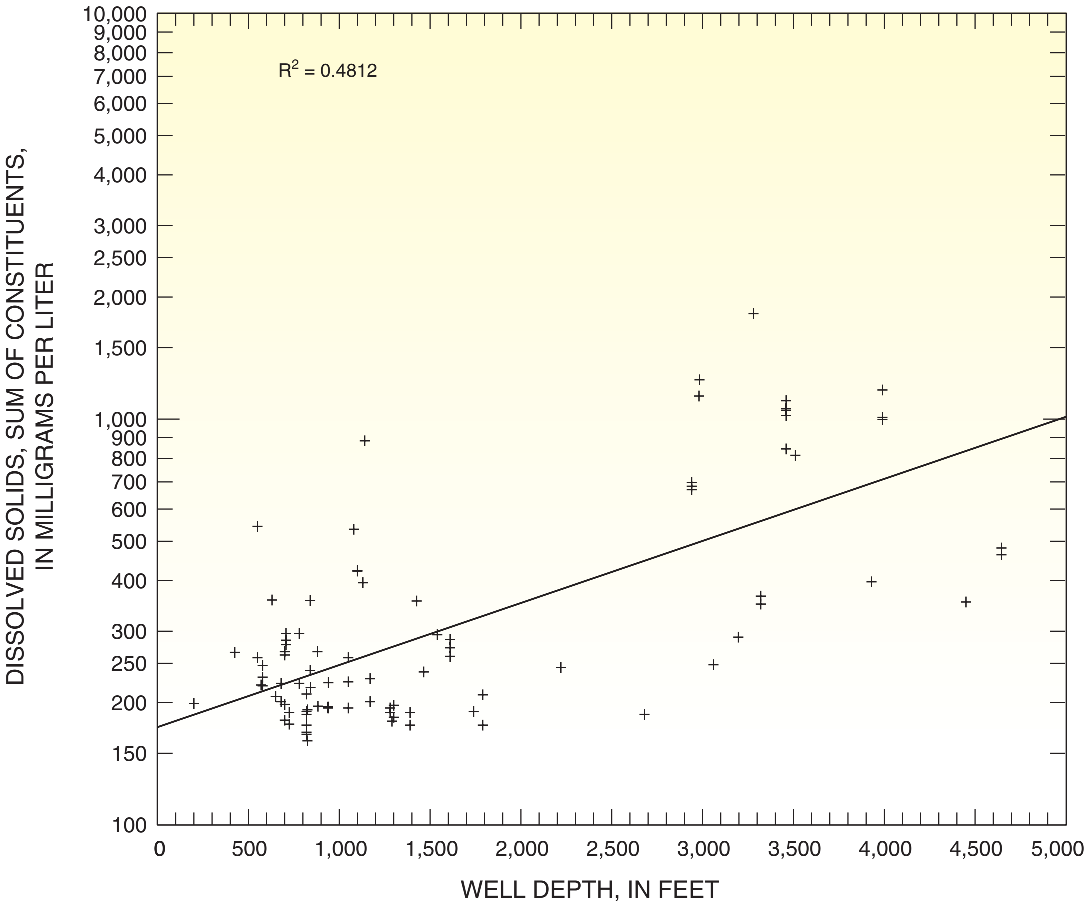


Figure 31. Relation between dissolved solids and well depth for Madison aquifer.

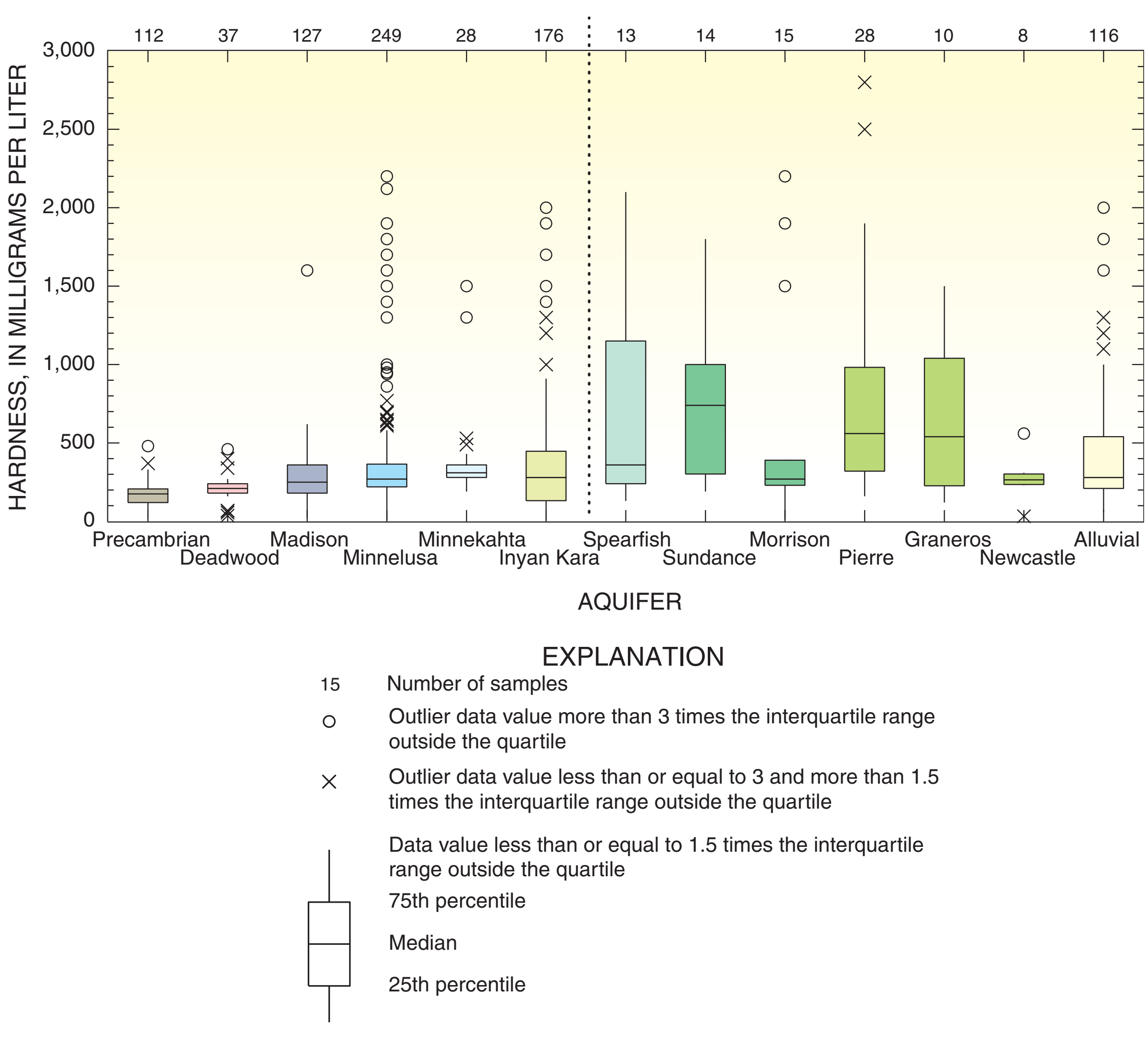


Figure 32. Boxplots showing hardness for selected aquifers (from Williamson and Carter, 2001).

General Characteristics for Minor Aquifers

A brief summary of water-quality characteristics from Williamson and Carter (2001) for minor aquifers in the study area is presented in this section of the report. The minor aquifers in the study area include the Newcastle aquifer, alluvial aquifers, and local aquifers that exist in various semiconfining and confining units. These local aquifers include the Spearfish, Sundance, Morrison, Graneros, and Pierre aquifers.

Water in many of the minor aquifers can be very hard (fig. 32) and high in dissolved solids concentrations. Most samples from the Sundance aquifer indicate slightly saline water. Sulfate concentrations also can be high in the minor aquifers, such as the Spearfish aquifer where high sulfate concentrations can result from dissolution of gypsum. Both dissolved solids and sulfate concentrations are low in the Newcastle aquifer. In general, the dominance of sodium and sulfate increases with increasing amounts of shale present in the geologic units. The dominance of calcium, magnesium, and bicarbonate increases with increasing amounts of sandstone and carbonate rocks present in the geologic units.

Concentrations of dissolved solids in alluvial aquifers generally increase with increasing distance from the core of the Black Hills, which is largely due to contact with underlying geologic units and alluvial materials derived from underlying units. Wells completed in alluvial deposits that do not overlie Cretaceous-age shales generally yield fresh water. Wells that are completed in alluvial deposits that overlie the Cretaceous-age shales generally yield slightly saline water in which sodium and/or sulfate is dominant. Samples from alluvial aquifers may be high in uranium concentrations, especially in the southern Black Hills.

Ground-Water Quality Relative to Water Use

Concentrations exceeding SMCLs and MCLs affect the use of water in some areas for many aquifers within the study area. Most concentrations exceeding standards are for various SMCLs and generally affect the water only aesthetically. Radionuclide concentrations can be high in some of the major aquifers, especially in the Deadwood and Inyan Kara aquifers, and may preclude the use of water in some areas. Hard water may require special treatment for certain uses. Other factors, such as high concentrations of sodium and dissolved solids, may affect irrigation use. Water from all aquifers, with the exceptions of the Pierre and Sundance aquifers, generally is suitable for irrigation in most locations.

High concentrations of iron and manganese, which can stain, occasionally can hamper the use of water from the Precambrian aquifer. None of the reported samples from the Precambrian aquifer exceeded drinking-water standards for radionuclides.

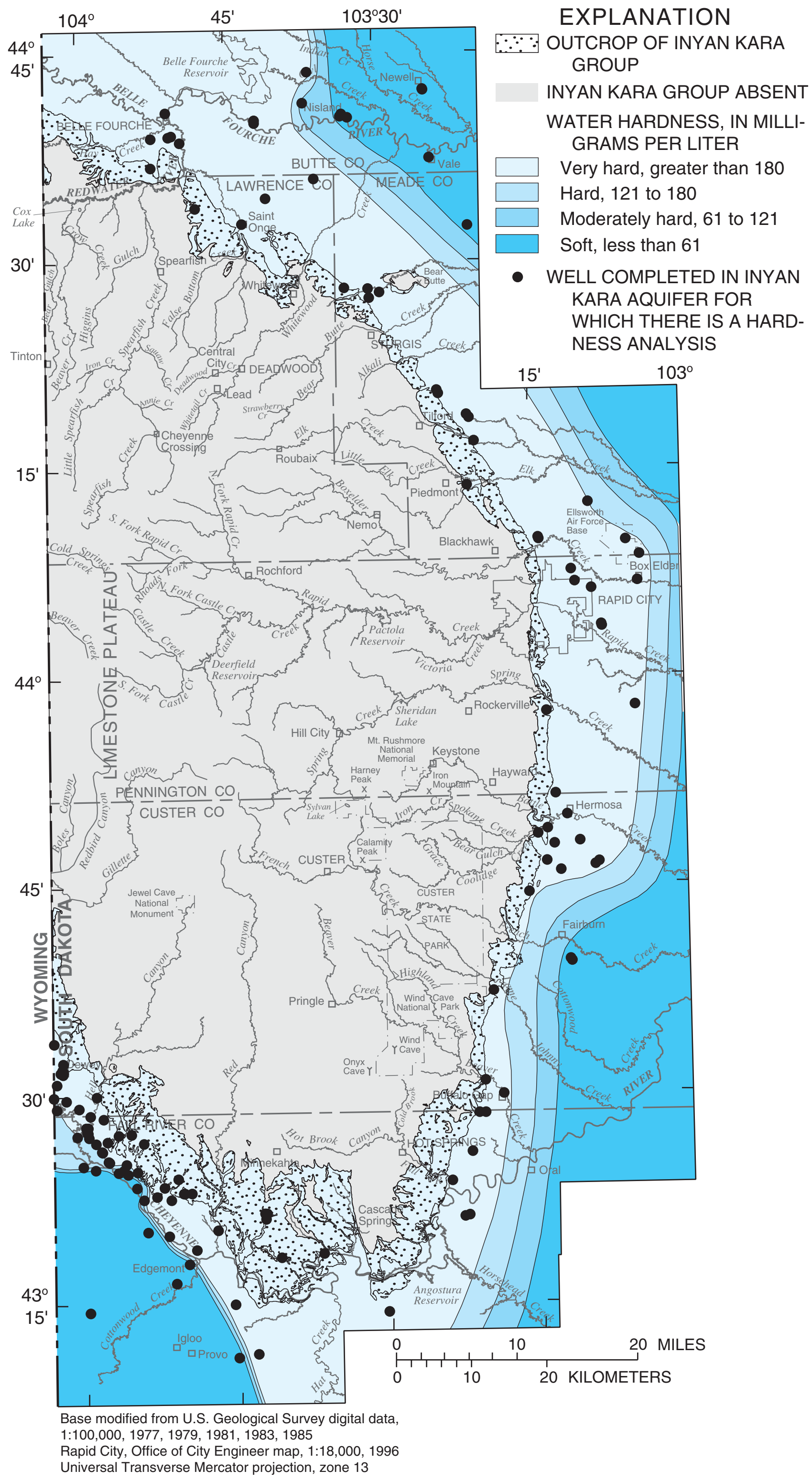


Figure 33. Hardness in the Inyan Kara aquifer (modified from Williamson and Carter, 2001).

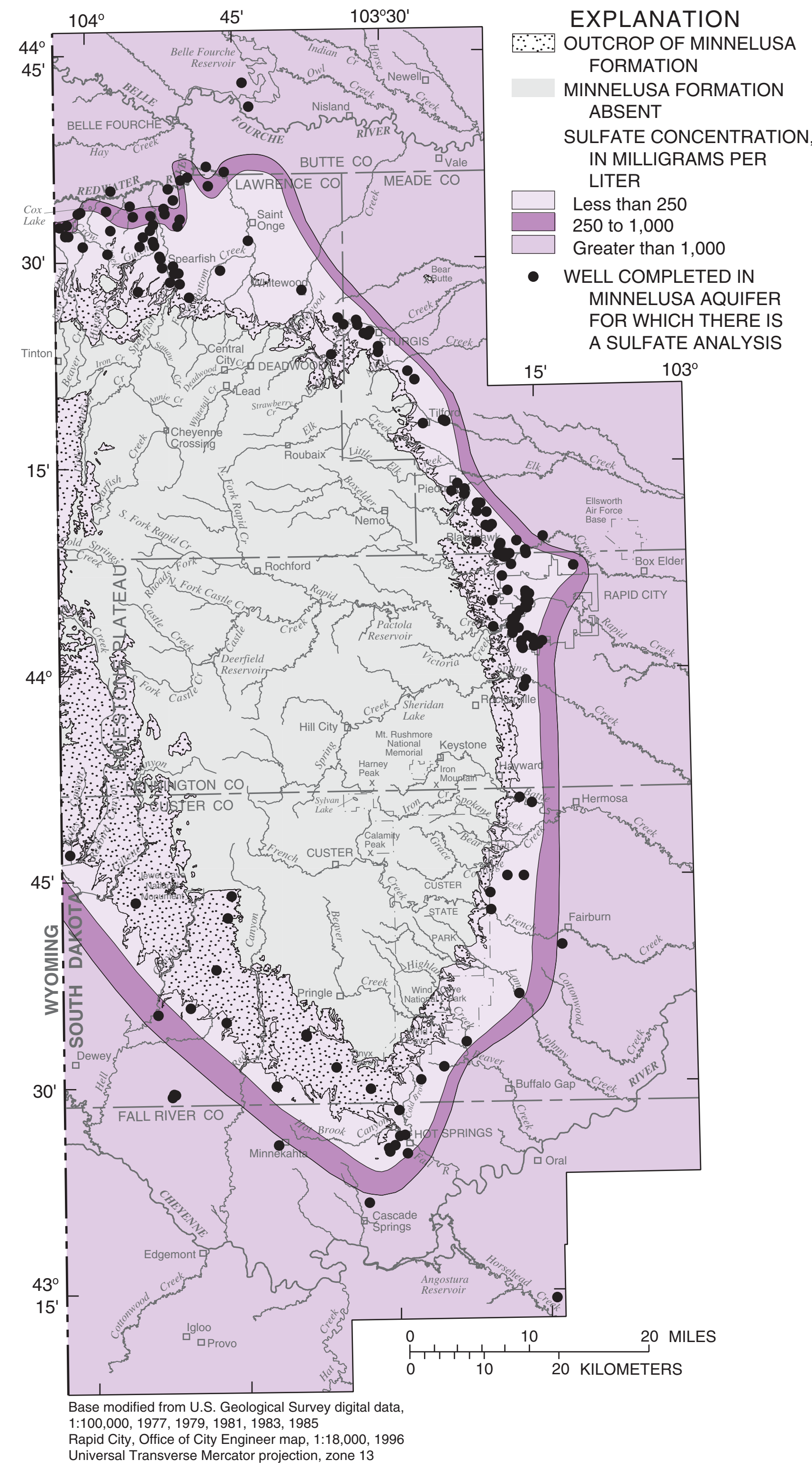


Figure 34. Sulfate concentrations in the Minnelusa aquifer (modified from Naus and others, 2001).

The principal deterrents to use of water from the Deadwood aquifer are high concentrations of radionuclides, including radium-226 and radon. In addition, concentrations of iron and manganese can be high.

Water from the Madison aquifer can contain high concentrations of iron and manganese that may hamper its use. Water from the Madison aquifer is hard to very hard and may require special treatment for certain uses. In downgradient wells (generally deeper than 2,000 feet), concentrations of dissolved solids and sulfate also may deter use from this aquifer. Hot water, from deep wells and in the Hot Springs area, may not be desirable for some uses. Radionuclide concentrations in the Madison aquifer generally are acceptable.

In water from the Minnelusa aquifer, hardness and high concentrations of iron and manganese may hamper use. Generally, downgradient wells (generally deeper than 1,000 feet) also have high concentrations of dissolved solids and sulfate. Hot water from deep wells may not be desirable for some uses. Arsenic concentrations in the Minnelusa aquifer exceed the MCL of 10 μg/L in some locations. Only a few samples exceed the MCLs for various radionuclides.

The use of water from the Inyan Kara aquifer may be hampered by high concentrations of dissolved solids, iron, sulfate, and manganese. In the southern Black Hills, radium-226 and uranium concentrations in water from this aquifer also may preclude its use. Hard water from wells located on or near the outcrop of the Inyan Kara Group may require special treatment. Suitability for irrigation may be affected by high dissolved solids and sodium concentrations.

The use of water from the minor aquifers may be hampered by hardness and concentrations of dissolved solids and sulfate. Concentrations of radionuclides, with the exception of uranium, generally are at acceptable levels in samples from these minor aquifers. Concentrations of selenium, which may be harmful or potentially toxic if ingested in moderate excess for a long time (Callahan and others, 1979), are an additional deterrent to use of water from the Sundance aquifer in some places. Water from the Pierre and Sundance aquifers generally is not suitable for irrigation because dissolved solids concentrations generally are high. Water from the other minor aquifers generally is suitable for irrigation, but may not be in specific locations if concentrations of either dissolved solids or sodium are high.

Water from alluvial aquifers generally is very hard and may require special treatment for certain uses. High concentrations of dissolved solids, sulfate, iron, and manganese may limit the use of water from alluvial aquifers that overlie the Cretaceous-age shales. In the southern Black Hills, uranium concentrations in alluvial aquifers can be high in many locations.

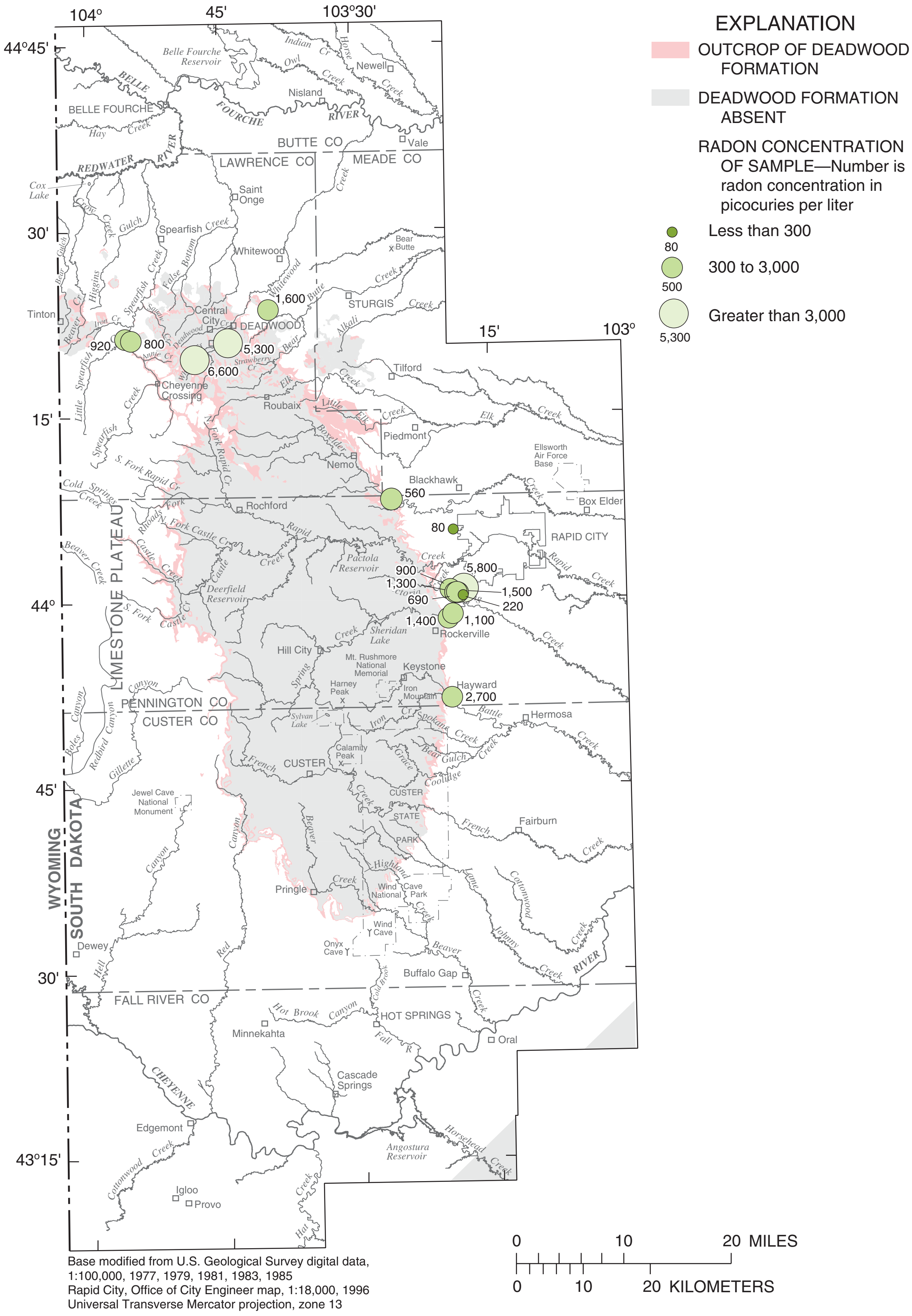


Figure 35. Radon concentrations in the Deadwood aquifer (modified from Williamson and Carter, 2001).

SUMMARY

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 water is 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.

The Precambrian-age basement rocks generally have low permeability and form the lower confining unit for a series of sedimentary aquifers. However, localized aquifers occur in the igneous and metamorphic rocks that make up the central crystalline core of the Black Hills and are referred to collectively as the Precambrian aquifer. Water-table (unconfined) conditions generally occur in the Precambrian aquifer, and topography can strongly control ground-water flow directions. The aquifer is considered to be contained in the area where the Precambrian-age rocks are exposed in the central core of the Black Hills.

Surrounding the central 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. The more permeable of these sedimentary rocks—the Deadwood Formation, Madison Limestone, Minnelusa Formation, Minnekahta Limestone, and Inyan Kara Group—contain major aquifers that are able to store and transmit large quantities of water and are used extensively as water supplies within and beyond the study area. Alluvial deposits along streams also commonly are used as local aquifers.

Various information and maps are presented in this report to help characterize water availability and quality in locations throughout the Black Hills. 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.

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. Although the volume of stored water is very large, water quality may not be suitable for all uses in some parts of the study area.

Water-level records are presented for selected observation wells to illustrate potential fluctuations in water levels that can occur in the bedrock aquifers. 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. However, dry wells or reduced pumping capacity could result during periods of declining water levels.

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. Water from the major bedrock aquifers generally is fresh and low in dissolved solids concentrations in and near outcrop areas but becomes progressively more saline with distance from the outcrops. In the Minnelusa aquifer, concentrations of dissolved sulfate vary markedly over short distances, influenced by a zone of active anhydrite dissolution. Water from most minor aquifers generally has higher concentrations of dissolved sulfate than major aquifers because of larger influence from shale layers.

Water from all aquifers, with the exceptions of the Pierre and Sundance aquifers, generally is suitable for irrigation in most locations. Very few health-related limitations exist for ground water; most of these limitations are for radionuclides, such as radon and uranium, especially in the Deadwood and Inyan Kara aquifers. In addition, high concentrations of arsenic have been detected in a few samples from the Minnelusa aquifer.

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GLOSSARY

Alluvium A general term for unconsolidated sedimentary accumulations deposited by rivers or streams. It includes sediment deposited in river beds and flood plains.

Anhydrite A calcium sulfate mineral ($CaSO_4$) that alters readily to gypsum.

Anticline A fold in which the strata dip away from the axis. After erosion, the oldest rocks are exposed in the central core of the fold.

Aquifer An underground body of porous materials, such as sand, gravel, or fractured rock, filled with water and capable of supplying useful quantities of water to a well or spring.

Artesian aquifer An aquifer that contains water that would rise above the top of the aquifer in a penetrating well; also confined aquifer.

Artesian well A well in which the water will rise above the top of the aquifer. When the water level is above land surface, water will flow from the well.

Axial plane With reference to folds, such as anticlines and synclines, an imaginary plane that intersects the crest or trough of a fold.

Basal Located at the bottom of a geologic unit.

Bedrock aquifer An aquifer composed of consolidated material such as limestone, dolomite, sandstone, siltstone, shale, or fractured crystalline rock.

Carbonate rocks Rocks consisting mainly of carbonate minerals, which contain the carbonate radical (CO_3^{-2}) combined with other elements. Examples are limestone and dolomite.

Cenozoic The most recent of the four eras into which geologic time is divided. It extends from the end of the Mesozoic Era to the present.

Clay An earthy, extremely fine-grained sediment or soft rock composed primarily of clay-sized or colloidal particles, having high plasticity and a considerable content of clay minerals.

Colluvium A general term applied to unconsolidated material deposited by rainwash or slow continuous downslope creep, usually collecting at the base of hillsides.

Concentration The amount of a constituent present in a given volume of sample. Usually expressed as milligrams per liter or micrograms per liter for a water sample.

Confined Said of ground water that is under pressure greater than that of the atmosphere. When an aquifer is completely filled with water (fully saturated) and is overlain by a confining unit, the water can be confined under pressure.

Confined aquifer An aquifer that contains water that would rise above the top of the aquifer in a penetrating well; also artesian aquifer. See figure 1B.

Confining unit A relatively low permeability geologic unit that impedes the vertical movement of water.

Conglomerate A coarse-grained sedimentary rock composed of rounded fragments of pebbles, cobbles, or boulders cemented into a solid mass.

Constituent A chemical substance in water that can be measured by analytical methods.

Cross section A diagram or drawing that shows features transected by a given vertical plane. See figure 6.

Crystalline rock Igneous or metamorphic rock.

Dip The slope of a tilted layer of rock.

Dissolution Process by which minerals and rock materials are dissolved by a fluid.

Dissolved solids The total of all dissolved mineral constituents, usually expressed in milligrams per liter (mg/L). The dissolved solids concentration commonly is called the water's salinity and is classified as follows: fresh, 0-1,000 mg/L; slightly saline, 1,000-3,000 mg/L; moderately saline, 3,000-10,000 mg/L; very saline, 10,000-35,000 mg/L; and briny, more than 35,000 mg/L.

Dolomite A sedimentary rock composed primarily of calcium-magnesium carbonate, $CaMg(CO_3)_2$.

Dome An uplift that is circular or elliptical in map view, with beds dipping away in all directions from a central area.

Effective porosity The porosity consisting of interconnected voids.

Fault A surface along which a rock body has broken and been displaced.

Fold A bend or flexure in a rock.

Formation The fundamental unit in the local classification of rocks into geologic units based on similar characteristics in lithology, which is the description of rocks on the basis of such characteristics as color, mineralogic composition, and grain size. Formations may represent rocks deposited during short or long time intervals, may be composed of materials from several sources, and may include breaks in deposition. Formations typically are named after geographic localities where they were first studied or described.

Fracture A crack in a rock. Also includes joints and faults.

Fresh water Water that has a dissolved solids concentrations of less than 1,000 milligrams per liter.

Geologic time scale An arbitrary chronologic arrangement of geologic events, commonly presented in a chart form with the oldest event and time unit at the bottom and the youngest at the top.

Ground water Water beneath the land surface in the saturated zone.

Ground-water level The level of the water table in an unconfined aquifer or of the potentiometric surface in a confined aquifer.

Group A geologic classification consisting of two or more formations.

Gypsum The mineral form of hydrated calcium sulfate, $CaSO_4 \cdot 2H_2O$.

Hogback A steep, elongate ridge; commonly protected from erosion by a steeply dipping resistant stratum.

Hydraulic connection Exists when changes in hydraulic head in adjacent aquifers or surface-water bodies influence each other.

Hydraulic gradient The rate of change in total head per unit of distance of flow in a given direction. Water will flow from higher hydraulic head to lower hydraulic head.

Hydraulic head In an aquifer, the altitude to which water will rise in a properly constructed well. This is the altitude of the water table in an unconfined aquifer or of the potentiometric surface in a confined aquifer.

Hydrogeology Factors that deal with geologic influences on water.

Hydrograph A graph showing flow rates or water levels with respect to time. A stream hydrograph commonly shows rate of flow; a well hydrograph commonly shows water level.

Igneous rocks Rocks that solidified from molten or partly molten material, such as magma. Granite is an example of an igneous rock.

Infiltration Movement of water from the land surface into the soil or porous rock.

Intrusion The process of emplacement of magma in pre-existing rock.

Isotope One of two or more species of the same chemical element that differ from one another by having a different number of neutrons in the nucleus. The isotopes of an element have slightly different physical and chemical properties due to their mass difference.

Karst A type of topography that is formed over limestone, dolomite, or gypsum by dissolution. It is characterized by sinkholes, caves, and underground drainage.

Laminated Said of a rock containing very thin layers; platy.

Limestone A sedimentary rock consisting mostly of calcium carbonate, $CaCO_3$, primarily in the form of the mineral calcite.

Massive Said of rocks that occur in very thick beds that are uniform in structure and composition throughout.

Maximum Contaminant Level (MCL) Maximum permissible level of a contaminant in water that is delivered to any user of a public water system. MCL's are enforceable standards established by the U.S. Environmental Protection Agency.

Mean The arithmetic average of a series of values.

Median The value of the middle number in a set of data arranged in rank order. The 50th percentile.

Mesozoic The era of geologic time from the end of the Paleozoic Era to the beginning of the Cenozoic Era.

Metamorphic rock Derived from pre-existing rocks in response to changes to temperature, pressure, or stress that result in changes in the mineralogy, chemistry, or structure of the rock. Examples of metamorphic rocks are slate and schist.

Monocline A step-like bend or fold in otherwise horizontal or gently dipping beds.

Nutrients Nitrogen and phosphorus, which are essential to plant growth.

Observation well A well constructed for collection of hydrologic data, such as water levels and water quality.

Outcrop That part of a geologic formation that is exposed at the land surface.

Paleozoic The era of geologic time from the end of the Precambrian Era to the beginning of the Mesozoic Era.

Perched ground water Unconfined ground water separated from an underlying main body of ground water by an unsaturated zone.

Permeability The capacity of a porous rock, sediment, or soil for transmitting a fluid.

Porosity The percentage of the soil or rock volume that is occupied by pore space, void of material; defined by the ratio of voids to the total volume of a specimen.

Potentiometric surface A surface representing the hydraulic head of ground water; represented by the water-table altitude in an unconfined aquifer or by the altitude to which water will rise in a properly constructed well in a confined aquifer.

Precambrian The oldest geologic time period, which occurred before the beginning of the Paleozoic Era. The Precambrian Era constitutes about 90 percent of all geologic time.

Public water supply Water supply provided to the public; defined in South Dakota as having at least 15 service connections or regularly serving at least 25 individuals daily for at least 60 days out of the year.

Radioactive decay Spontaneous emission of particles (alpha or beta) and gamma rays from the nucleus of an unstable nuclide. The resulting product nucleus may be stable or unstable, in which case decay continues until a stable nuclide is formed.

Radioactivity The emission of energetic particles and/or radiation during radioactive decay.

Radionuclide A radioactive nuclide. (A nuclide is a species of atoms characterized by the number of neutrons and protons in its nucleus.)

Recharge The process involved whereby infiltration reaches the saturated zone. Also the amount of water added.

Residence time In ground water, the length of time water remains underground before it is extracted or discharged.

Saline water Salty water. Classified by the dissolved solids concentration in water.

Sandstone A sedimentary rock composed of abundant rounded or angular fragments of sand set in a fine-grained matrix (silt or clay) and more or less firmly united by a cementing material.

Saturated The condition in which the pores of a material are filled with water.

Secondary Maximum Contaminant Level (SMCL) Maximum level established by the U.S. Environmental Protection Agency for contaminants that can adversely affect the odor or appearance of water and may result in discontinuation of use of the water. SMCL's are nonenforceable, generally non-health-based standards that are related to the aesthetics of water use.

Secondary permeability The permeability developed in a rock after its deposition, through such processes as weathering and fracturing.

Secondary porosity The porosity developed in a rock after its deposition, through such processes as dissolution or fracturing.

Sedimentary rock Rocks resulting from the consolidation of loose sediment that has accumulated in layers. Examples of sedimentary rocks are sandstone, siltstone, limestone, and shale.

Semiconfining unit Unit that may transmit some water to and from adjacent aquifers.

Shale A fine-grained sedimentary rock, formed by the consolidation of clay, silt, or mud.

Sill A tabular igneous intrusion that parallels the bedding of the surrounding sedimentary or metamorphic rock.

Solution opening An opening in a rock material resulting from the dissolution of calcium carbonate in limestone or chalk.

Spring Any natural discharge of water from rock or soil onto the land surface or into a surface-water body.

Stratigraphic column The vertical (or chronological) sequence of rock units portrayed in a column from oldest (bottom) to youngest (top). See figure 4.

Structural feature A feature produced by deformation or displacement of the rocks, such as a fold or fault.

Surface water Water on the Earth's surface.

Syncline A fold in which the strata dip toward the axis. After erosion, the youngest beds are exposed in the central core of the fold.

Unconfined Said of ground water that has a water table; the water is not confined under pressure.

Unconfined aquifer An aquifer in which the water table is exposed to the atmosphere through openings in the overlying materials.

Unconsolidated aquifer An aquifer composed of material that is loosely arranged or whose particles are not cemented together, such as sands and gravels.

Unsaturated The condition in which the pores of a material contain at least some air.

Water table The top of the water surface in the saturated zone of an unconfined aquifer.

Water year The 12-month period, October 1 through September 30, that is designated by the calendar year in which it ends.