

Water Resources

Photograph by Janet M. Carter

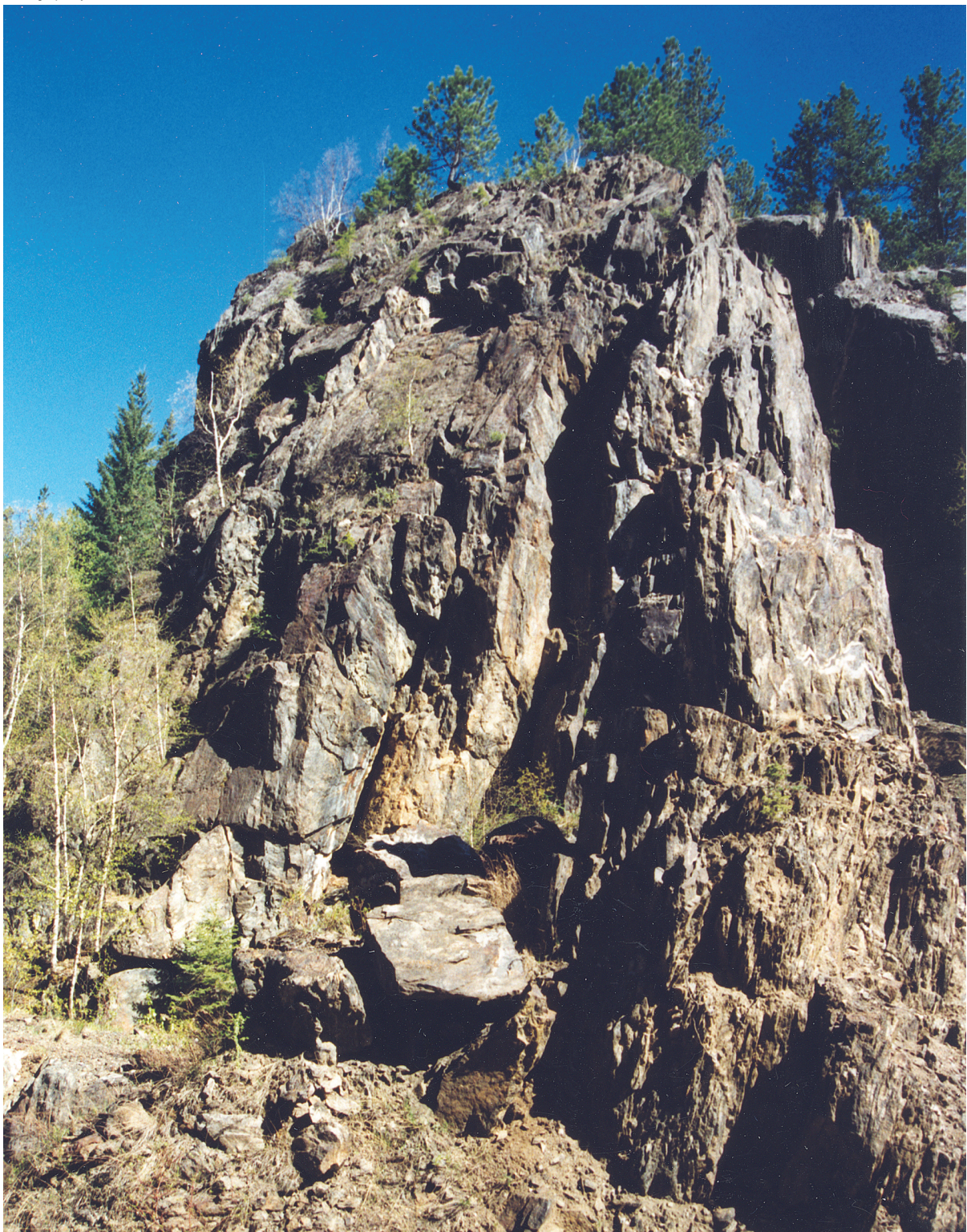


Figure 46. Fracturing and weathering in Precambrian rocks highly influence availability of water in this unit.

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.

The Black Hills strongly influence the hydrology of western South Dakota and northeastern Wyoming. Many streams in western South Dakota originate in the Black Hills, and major bedrock aquifers are recharged along outcrop areas in the Black Hills. Ground and surface water interact extensively in the Black Hills. This section of the report provides a summary of the ground-water and surface-water resources in the study area.

Ground-Water Resources

As previously discussed, several of the major aquifers in the study area are regionally extensive aquifers. Numerous other local and minor aquifers are used throughout the study area. A summary of the ground-water resources, with descriptions of aquifer characteristics, water levels, and water-quality characteristics, is provided in this section of the report.

Characteristics of Major Aquifers

General descriptions of aquifer characteristics, 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.

Aquifer characteristics, including area, thickness, and storage volume are presented in table 5 for the major aquifers in the study area. Aquifer characteristics for the Precambrian aquifer also are presented because numerous wells are in this aquifer in the crystalline core of the Black Hills. The area of the aquifers was determined using a GIS coverage by Williamson and others (2000)

Table 5. Summary of the characteristics of major aquifers in the study area

[Macre-feet, million acre-feet]

Aquifer	Area (square miles)	Maximum formation thickness (feet)	Average saturated thickness (feet)	Effective porosity ¹	Estimated amount of recoverable water in storage ² (Macre-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

¹From Rahn (1985).

²Storage estimated by multiplying area times average saturated thicknesses times effective porosity.

³The area used in storage calculation was the area of the exposed Precambrian rocks, which is 825 square miles.

⁴Average saturated thickness of the confined area of the Madison aquifer. The unconfined area had an average saturated thickness of 300 feet.

⁵Storage values are the summation of storage in the confined and unconfined areas.

⁶Average saturated thickness of the confined area of the Minnelusa aquifer. The unconfined area had an average saturated thickness of 142 feet.

of the hydrogeologic unit map for the study area.

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 is mainly controlled by secondary permeability caused by fracturing and weathering (fig. 46). The aquifer is considered to be contained in the area where the Precambrian 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 thickness (table 5). 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. The area of the sedimentary aquifers is smaller than the area of the Precambrian rocks because erosion has removed the sedimentary rocks in the central core of the Black Hills.

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 5). 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 section of the 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. 1). 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. 47) for 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 rocks than for the major aquifers 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 and median well yields are higher in the Madison aquifer than the other major aquifers. The Minnelusa aquifer also has the potential for high well yields. Low well yields are possible in some locations for all the major aquifers.

A series of maps showing the depth to top of the formations that contain the major aquifers (Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara) is presented in figures 48-52. The depths are to the top of the formation, which is not necessarily the depth to the top of the water-bearing layers. In fact, formations may not contain water-bearing layers at any given location, especially in areas on or near the outcrops.

A series of maps showing the generalized thickness of the formations that contain major aquifers is presented in figures 53-57. Thicknesses shown are not necessarily indicative of the amount of the total thickness that is saturated at any given location that may occur within the formation. In any location, especially in areas on or near outcrops, the formation may have little saturation or may even be dry.

A series of maps showing the potentiometric surface of the major aquifers is presented in figures 58-62. 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 local influence on ground-

water flow directions such that flow may be nearly parallel to potentiometric contours (Long, 2000).

Maps showing the saturated thickness of the unconfined areas of the Madison and Minnelusa aquifers are shown in figures 63 and 64, respectively. Both the Madison and Minnelusa aquifers are unconfined near their outcrops and confined (fully saturated) at a distance away from their outcrops. In general, the saturated thickness is less than 200 feet for most of the outcrop areas. These areas are especially susceptible to drought conditions, and the formations may even be dry in parts of these areas regardless of precipitation conditions. In most areas, the 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.

The Madison and Minnelusa aquifers have the potential for high well yields, although low well yields also are possible.

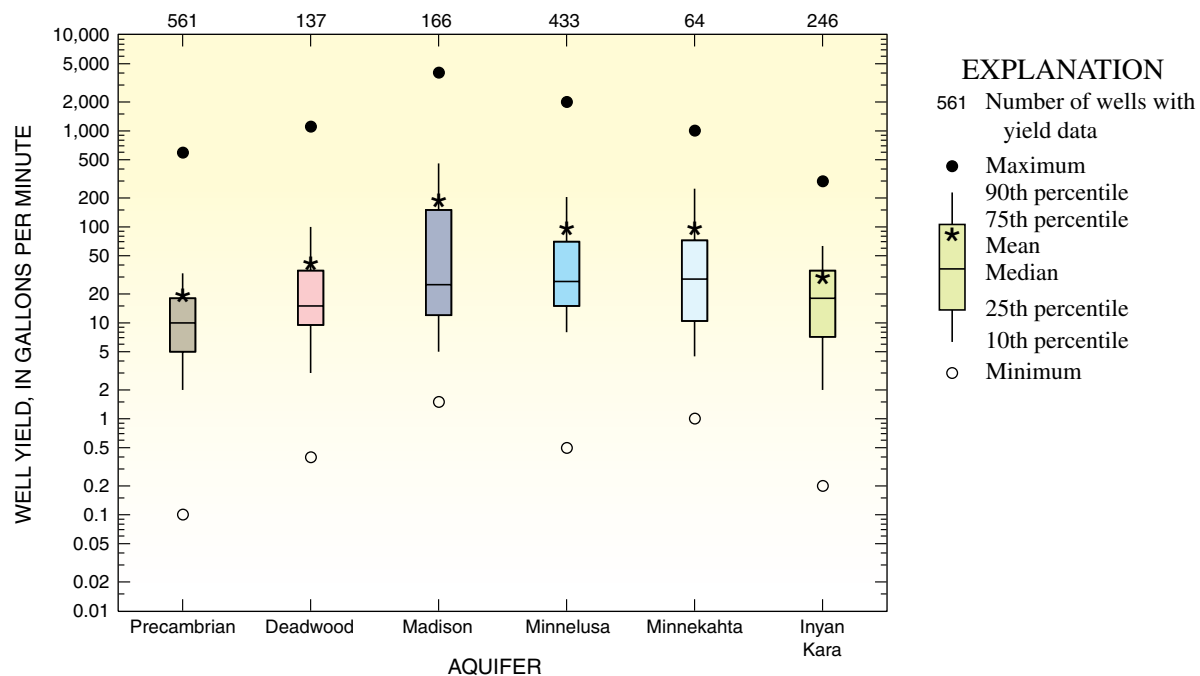


Figure 47. Distribution of well yields from selected aquifers (data obtained from U.S. Geological Survey Ground Water Site Inventory database).

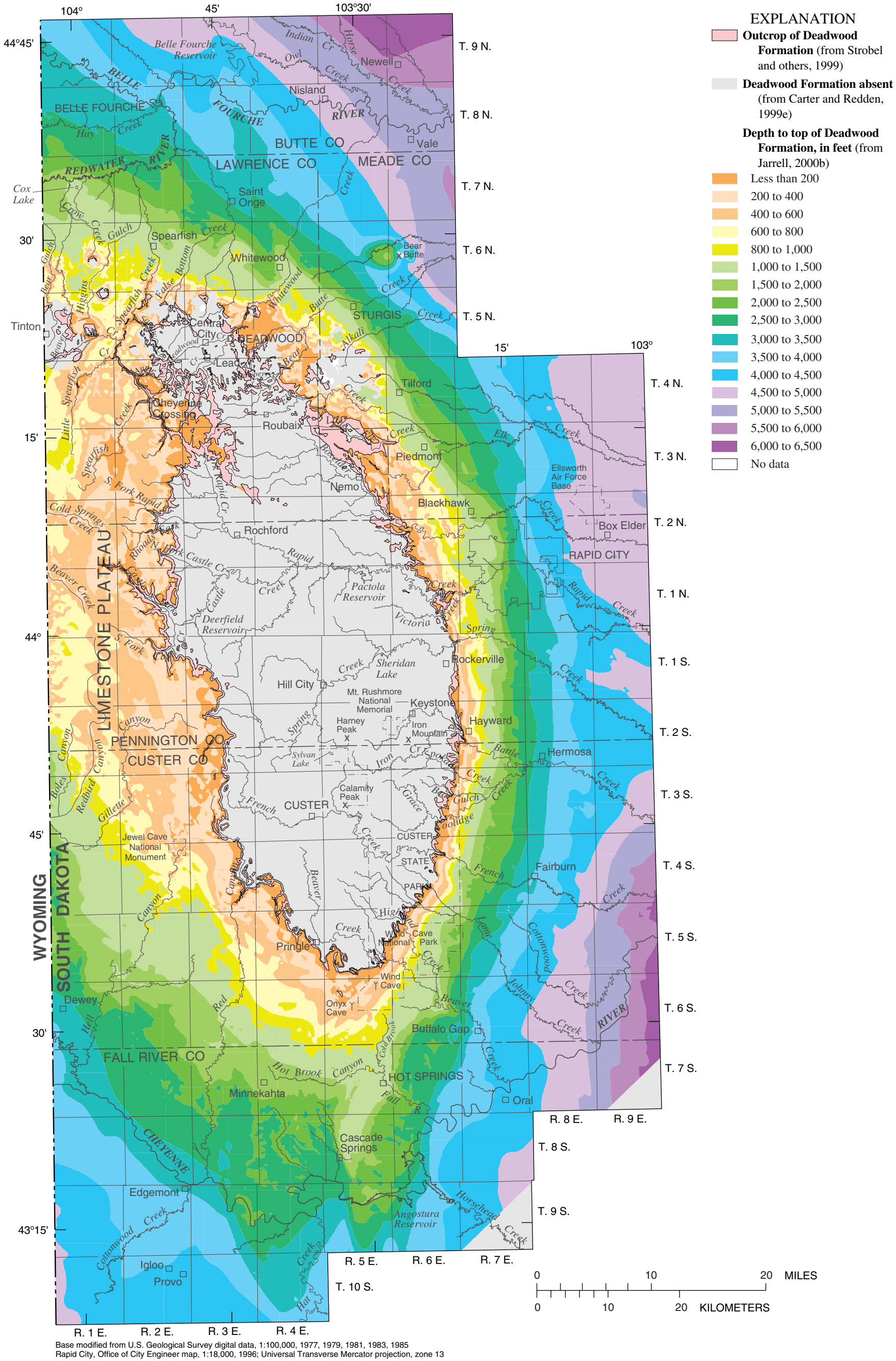


Figure 48. Depth to top of Deadwood Formation.

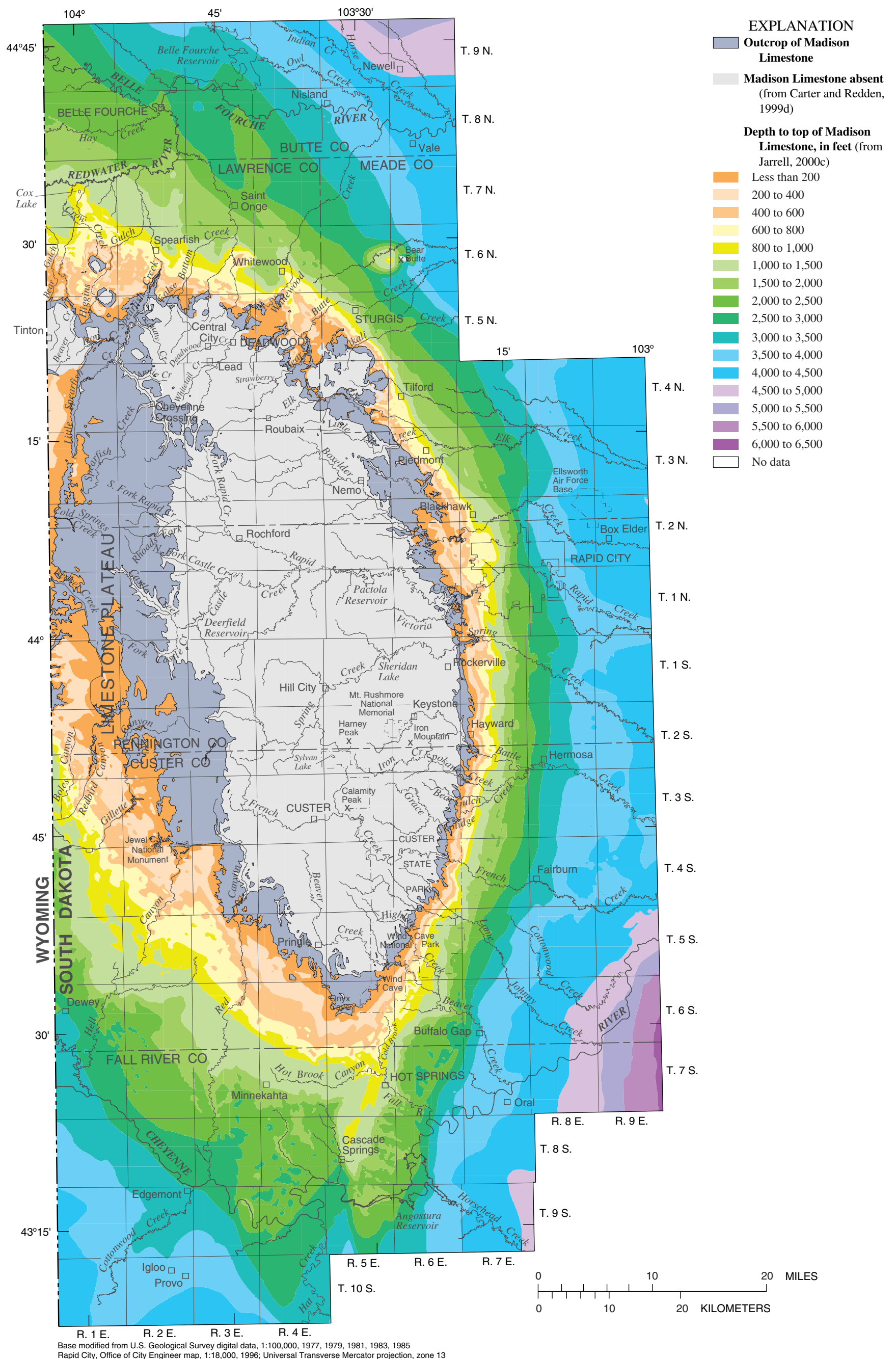


Figure 49. Depth to top of Madison Limestone.

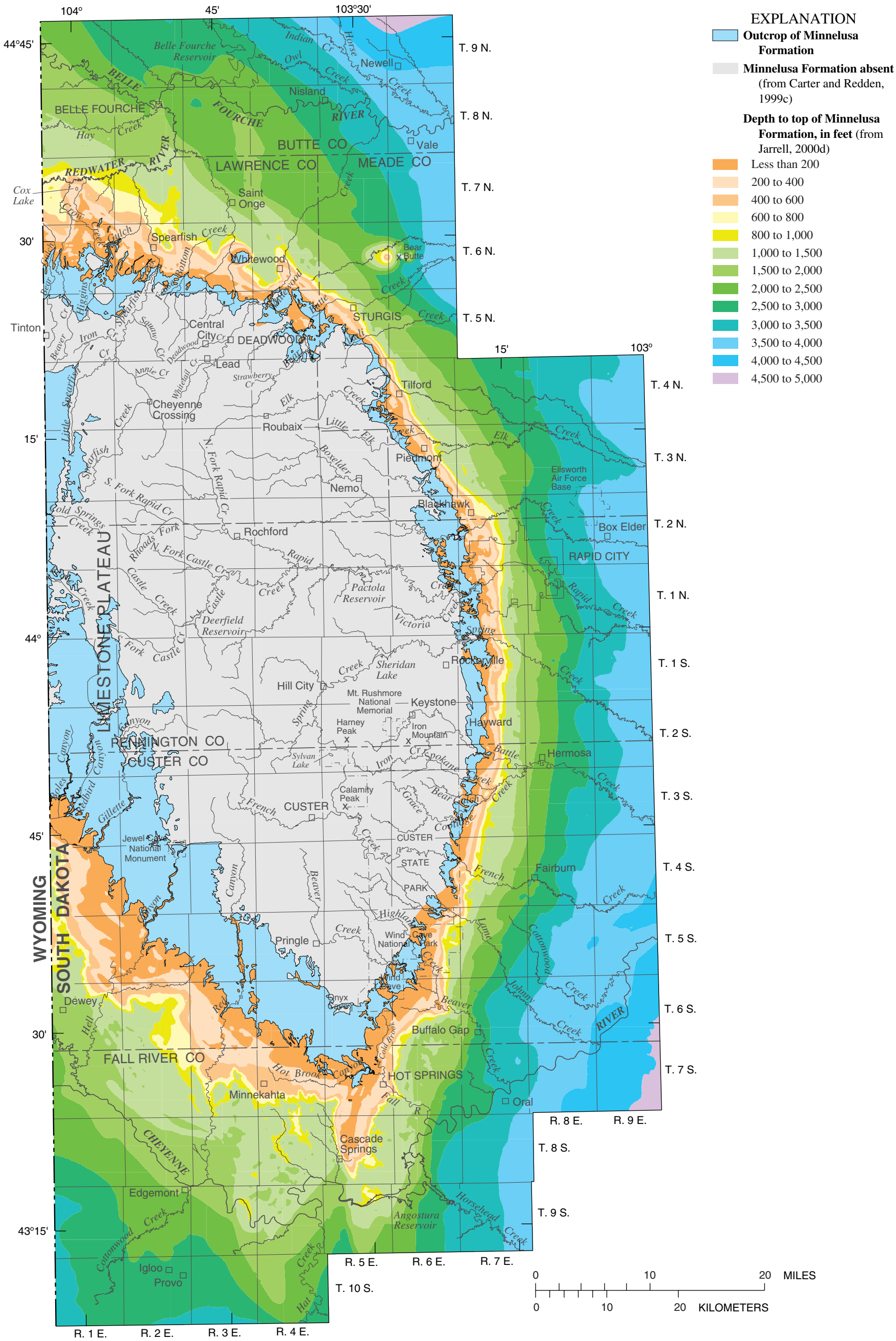


Figure 50. Depth to top of Minnelusa Formation.

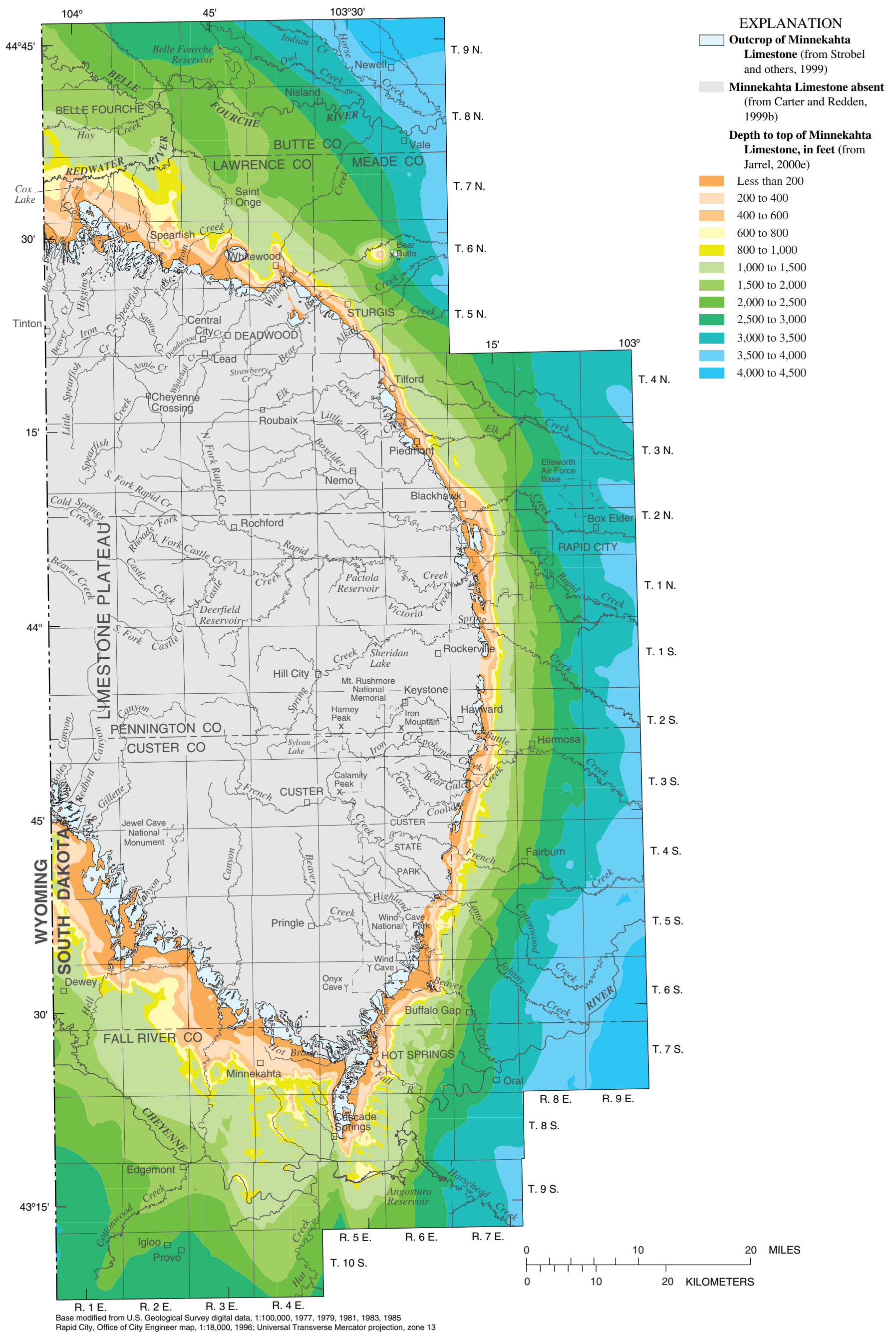


Figure 51. Depth to top of Minnekahta Limestone.

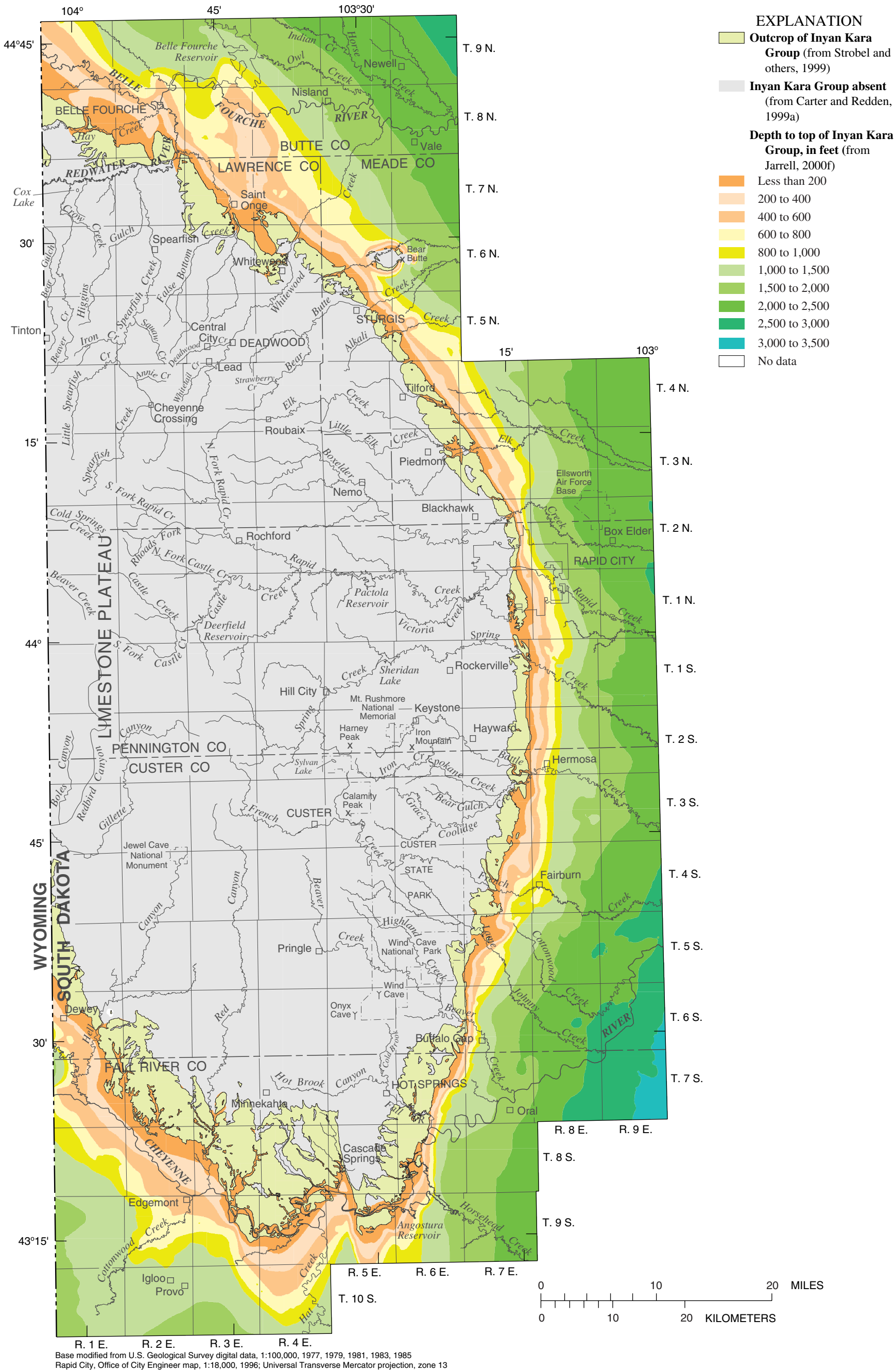


Figure 52. Depth to top of Inyan Kara Group.

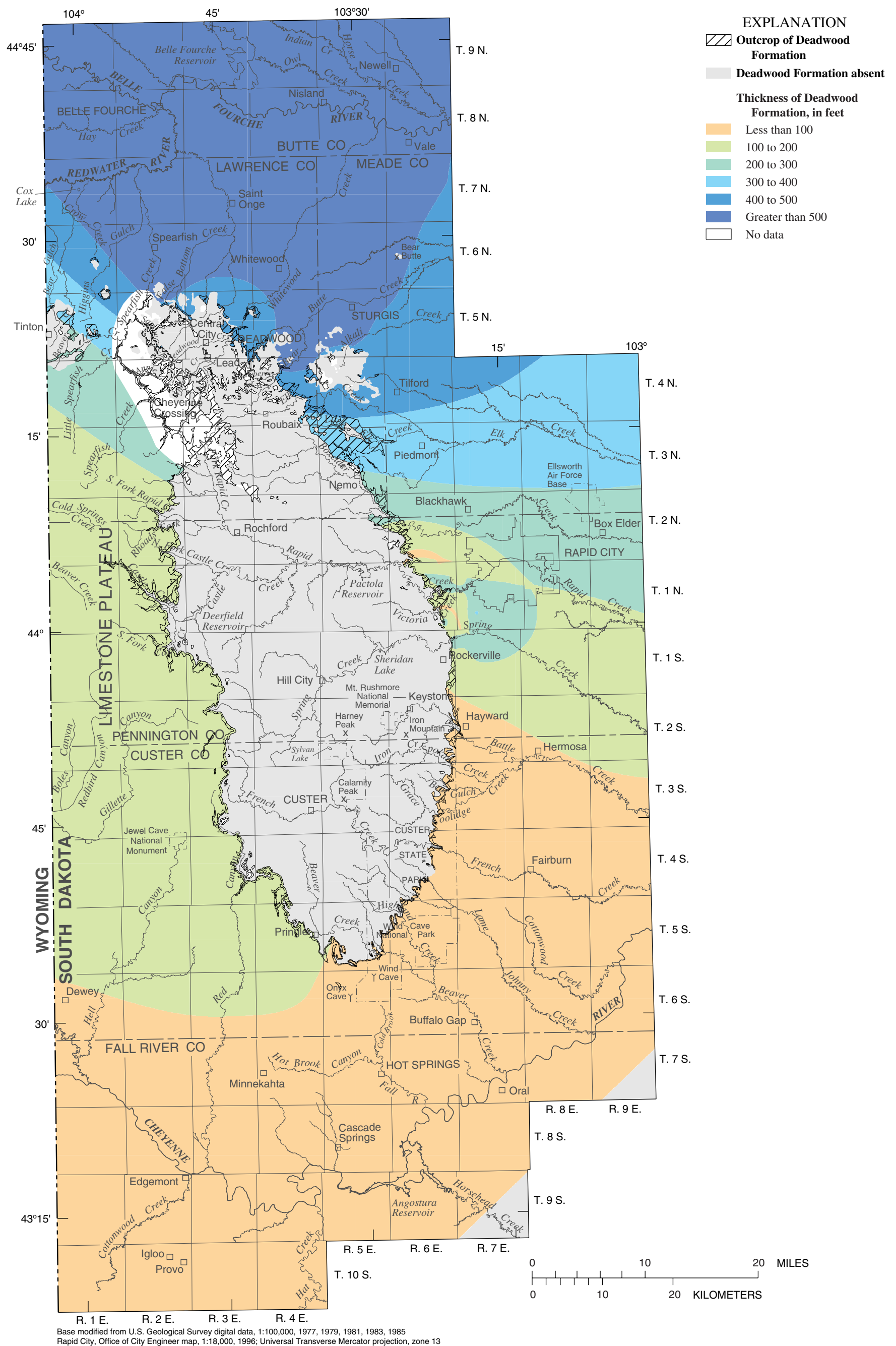


Figure 53. Generalized thickness of the Deadwood Formation.

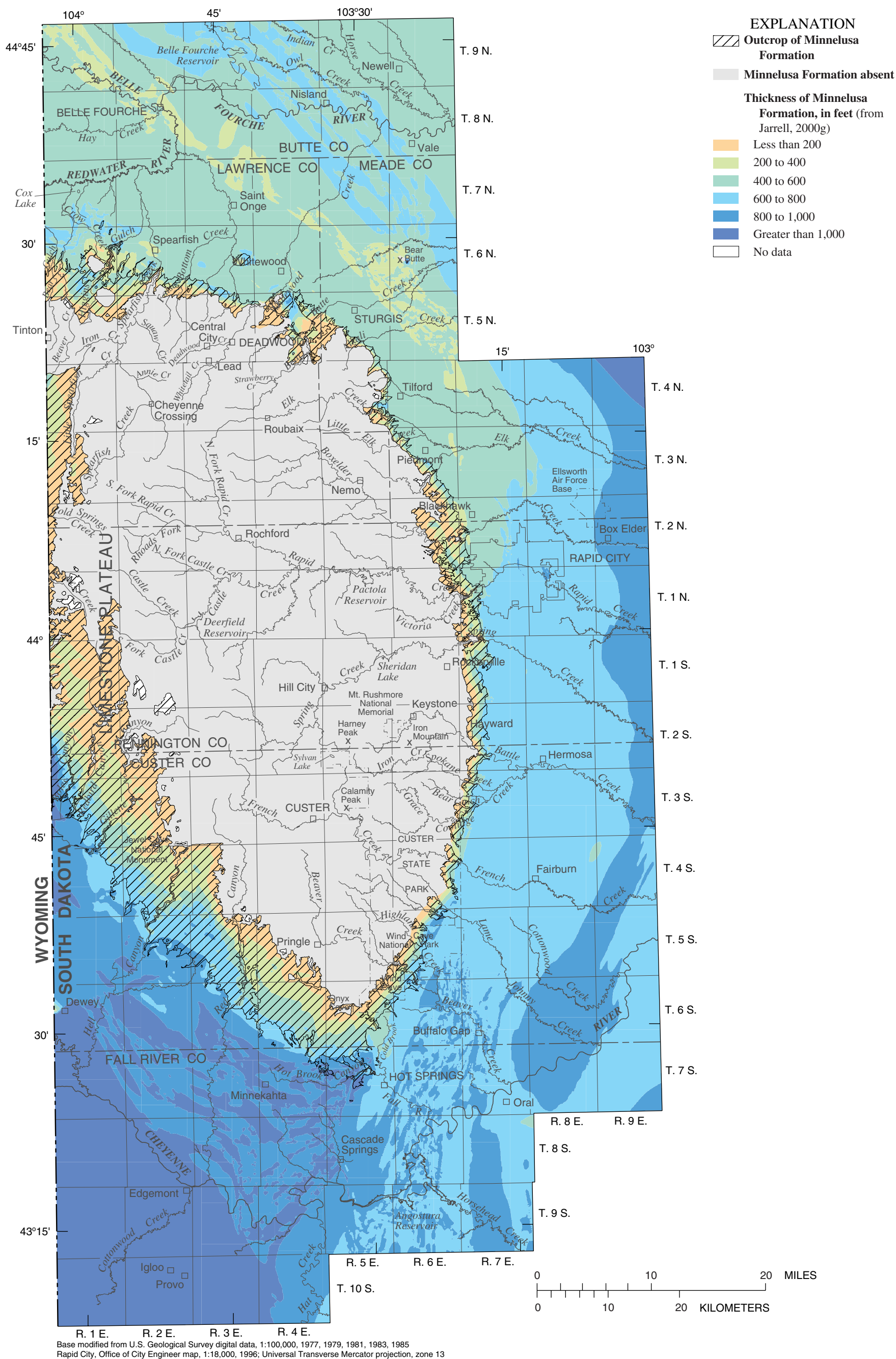


Figure 55. Generalized thickness of the Minnelusa Formation.

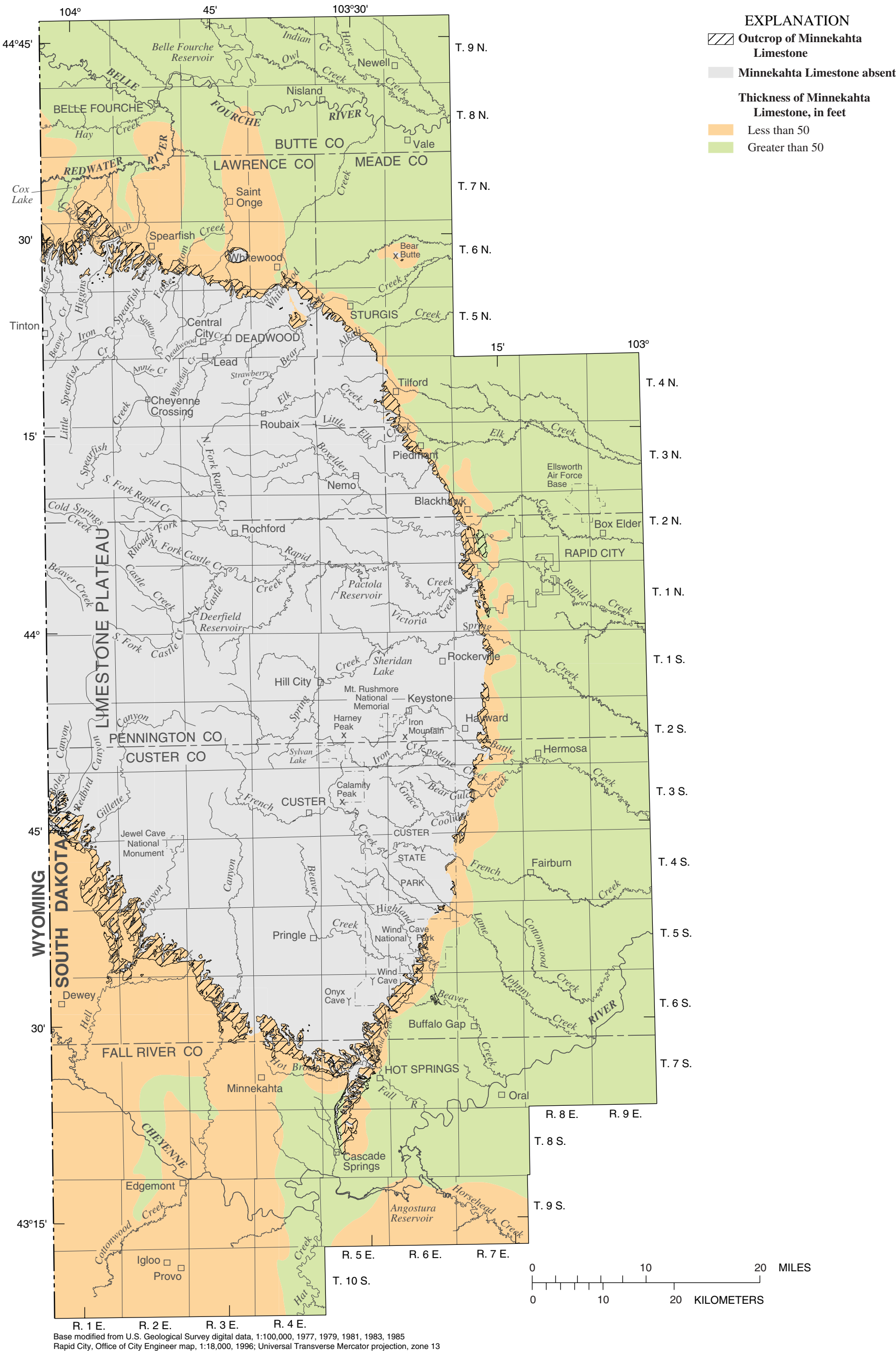


Figure 56. Generalized thickness of the Minnekahta Limestone.

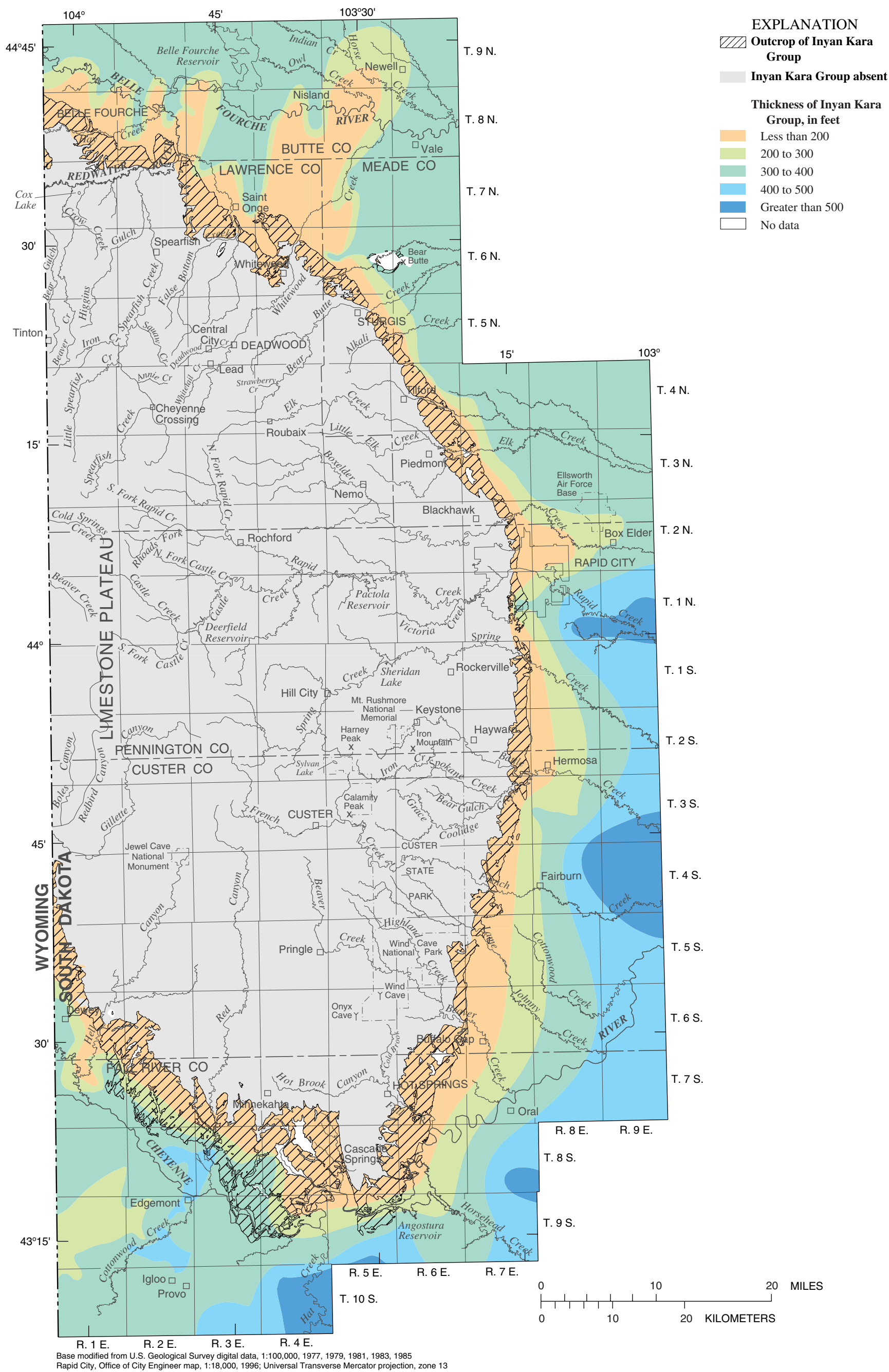


Figure 57. Generalized thickness of the Inyan Kara Group.

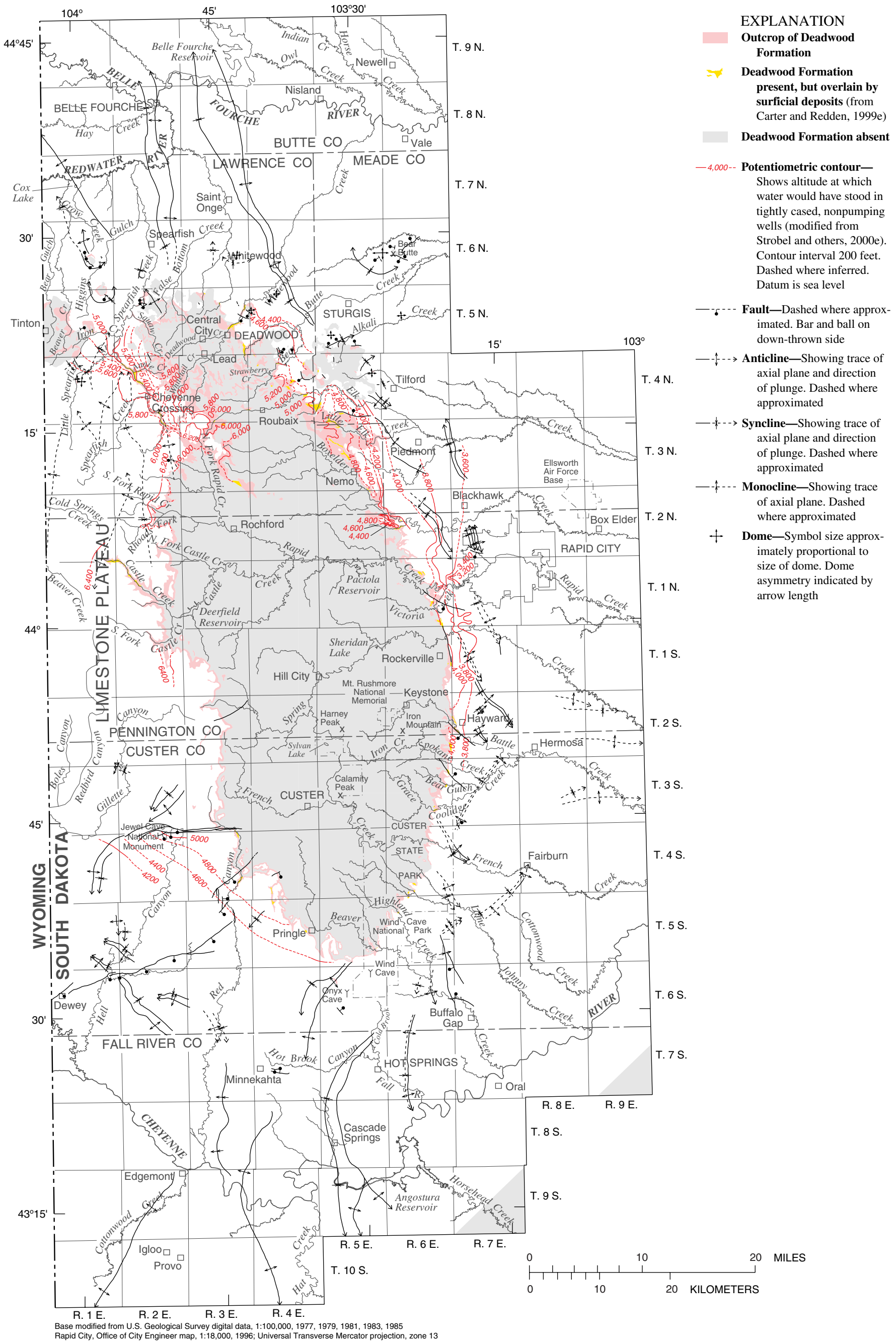
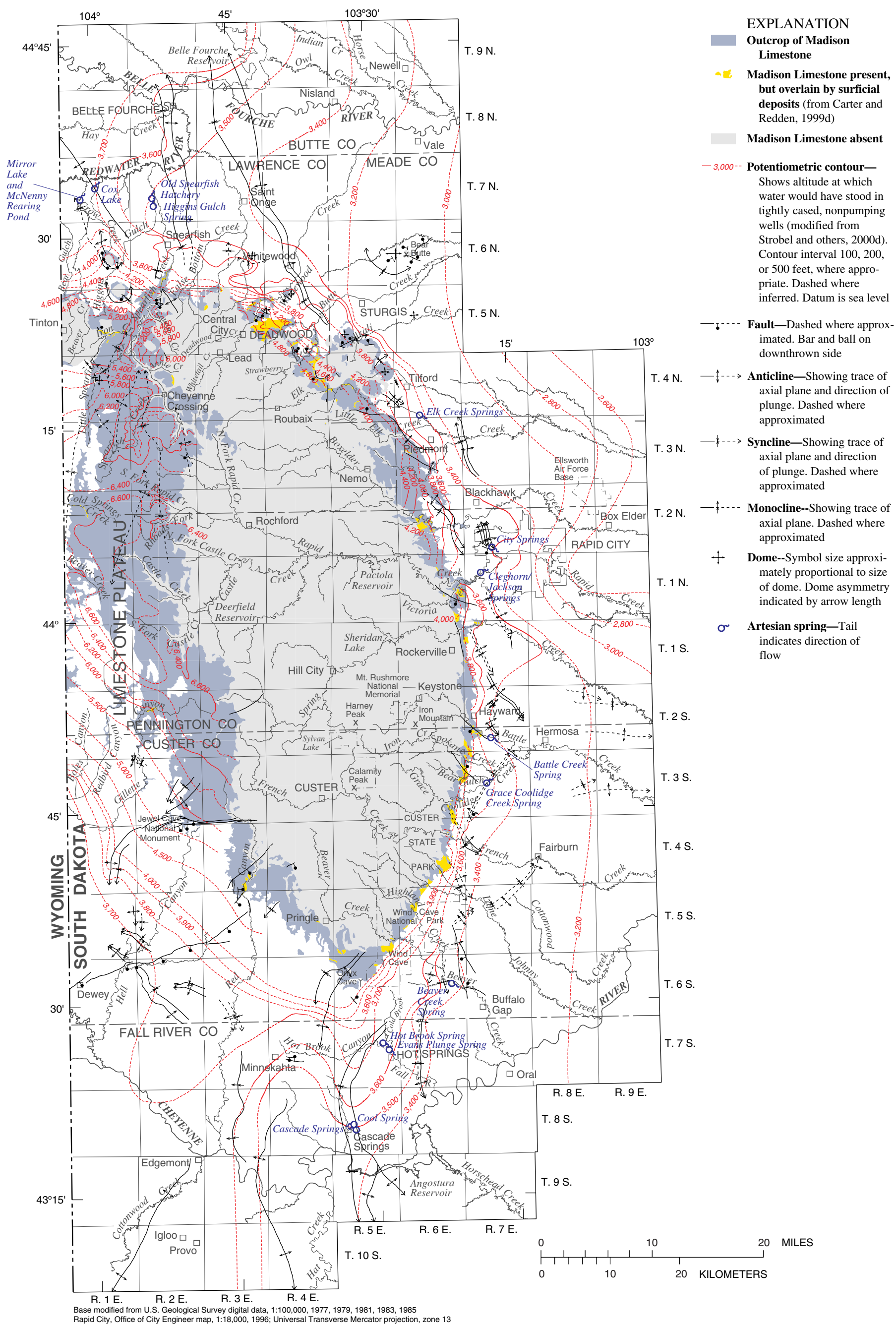


Figure 58. Potentiometric surface of the Deadwood aquifer.



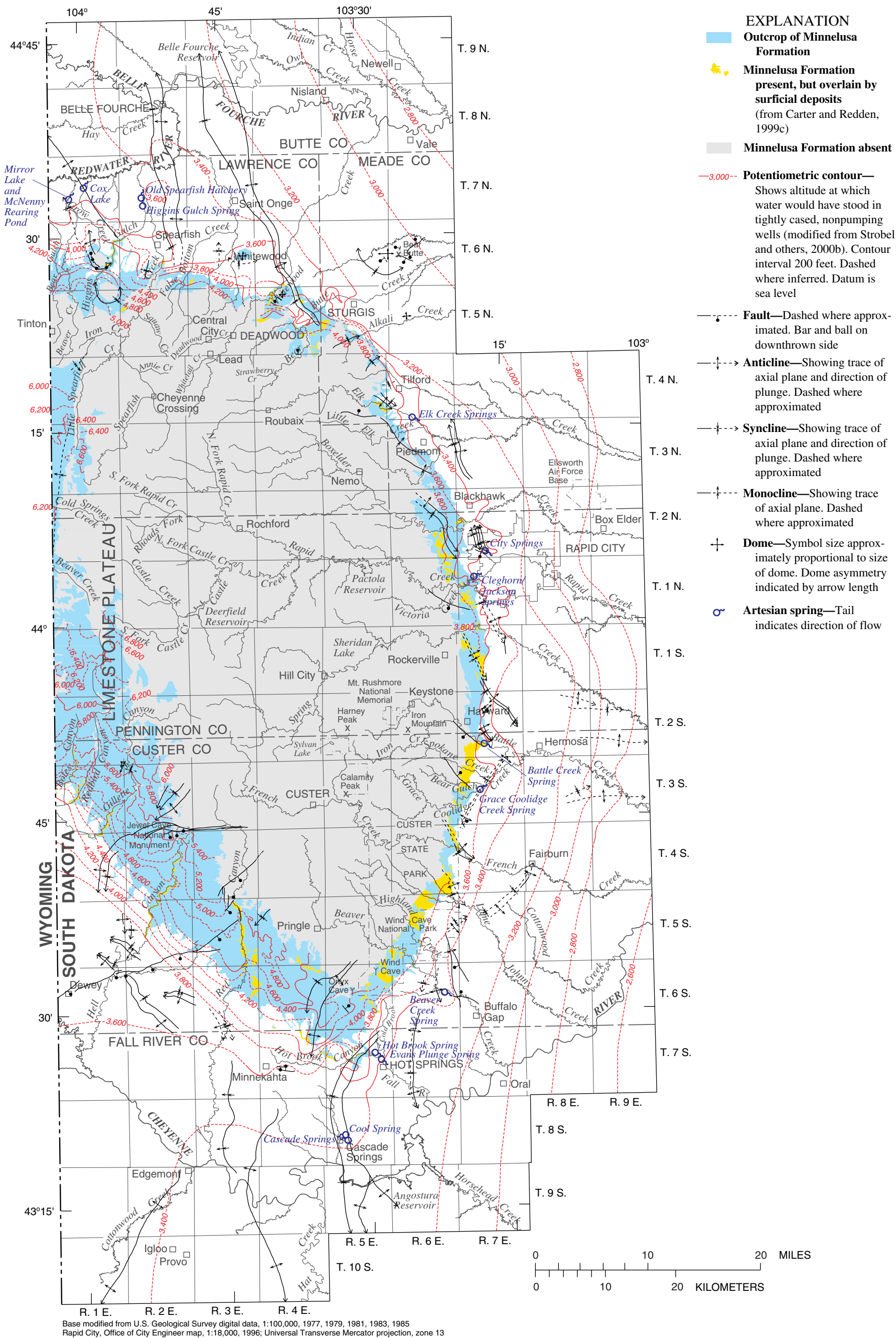


Figure 60. Potentiometric surface of the Minnelusa aquifer and locations of major artesian springs.

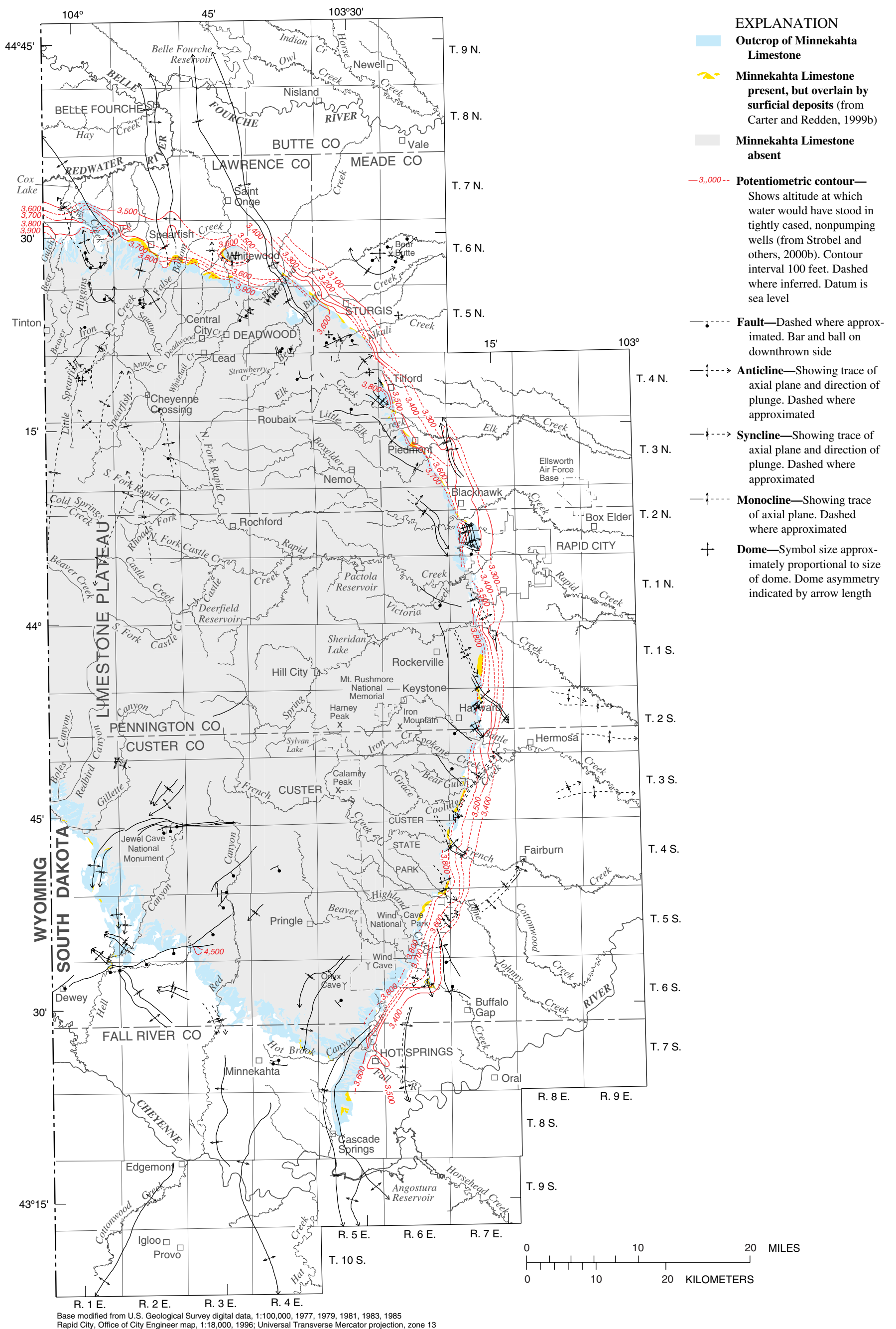


Figure 61. Potentiometric surface of the Minnekahta aquifer.

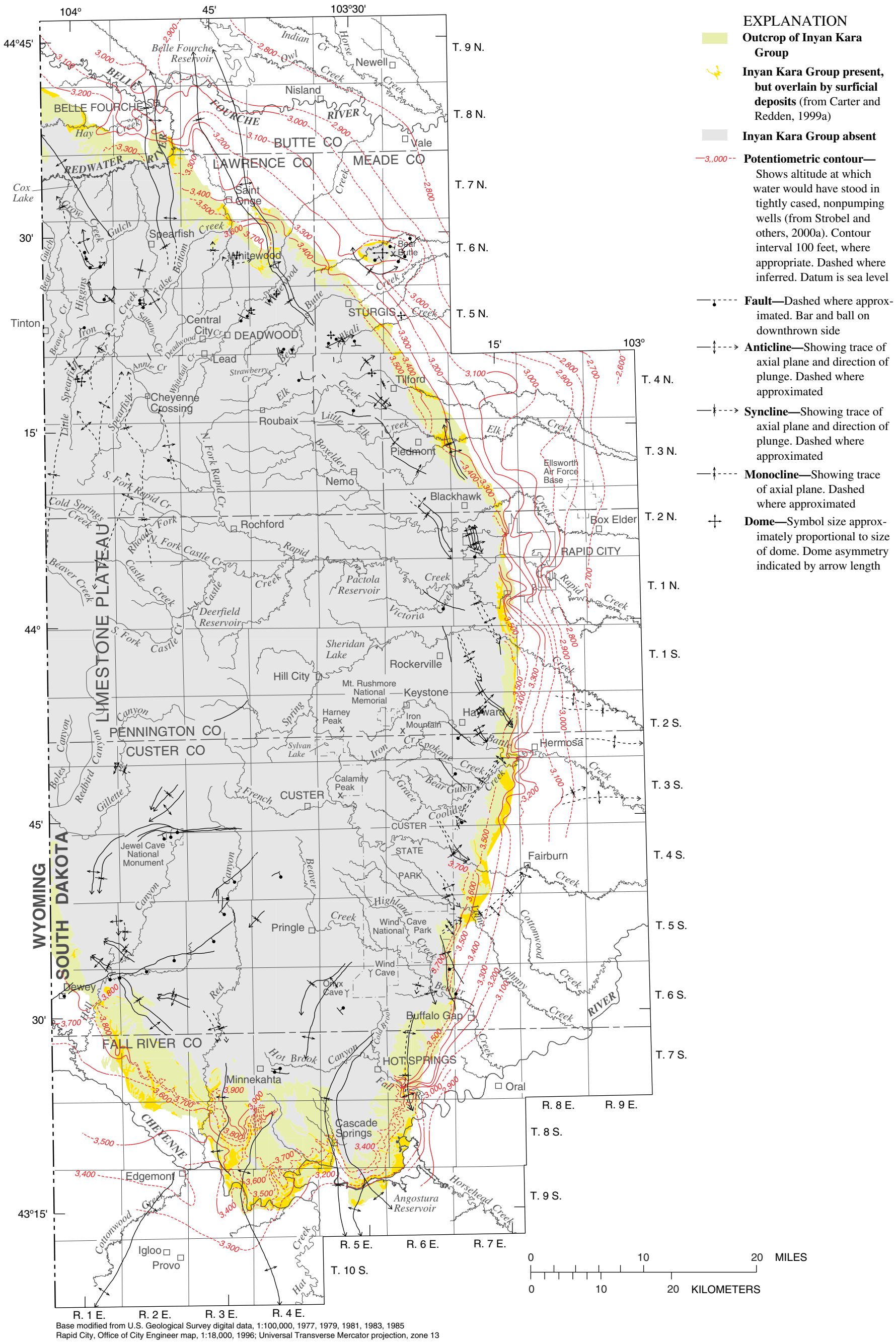


Figure 62. Potentiometric surface of the Inyan Kara aquifer.

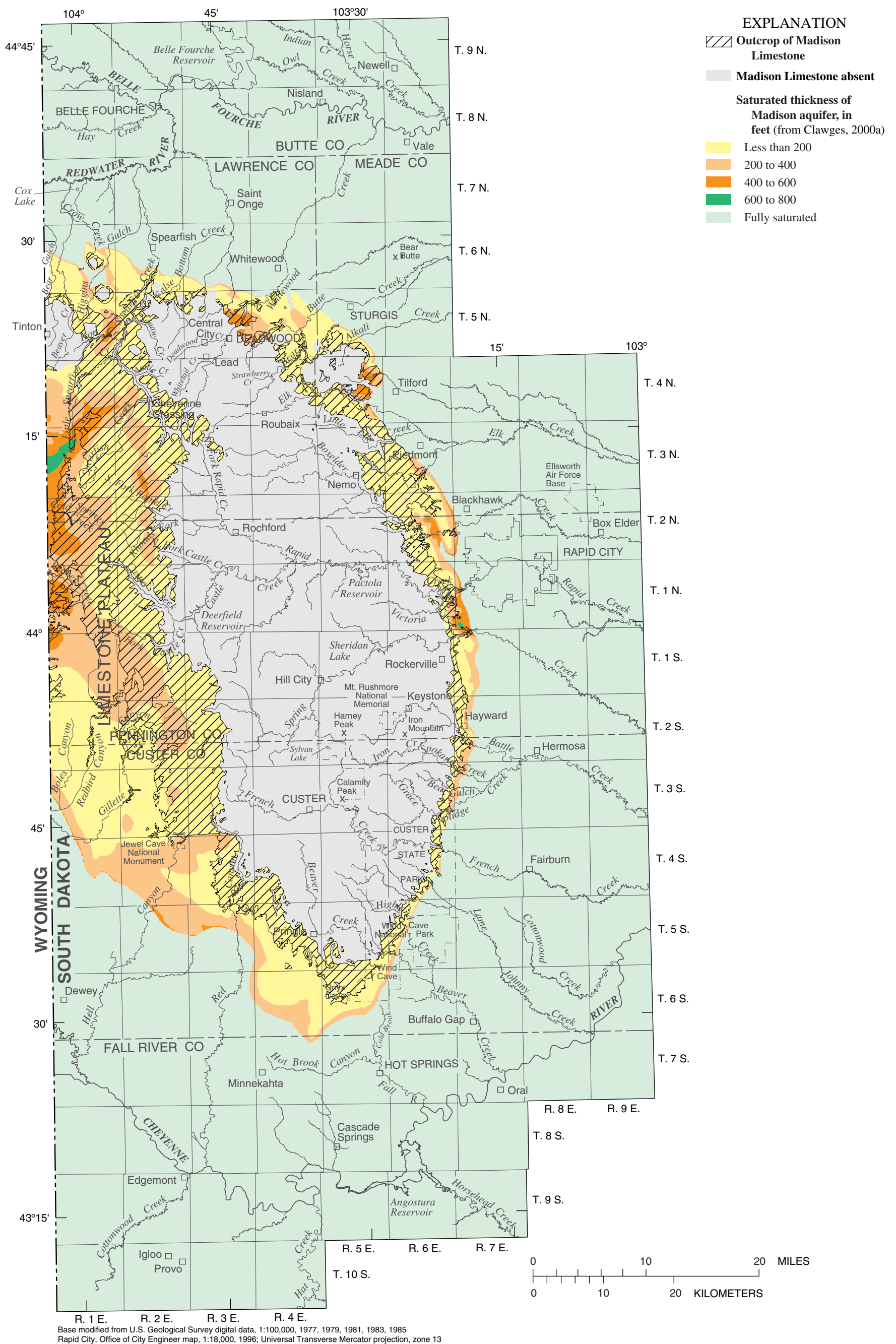


Figure 63. Saturated thickness of the Madison aquifer.

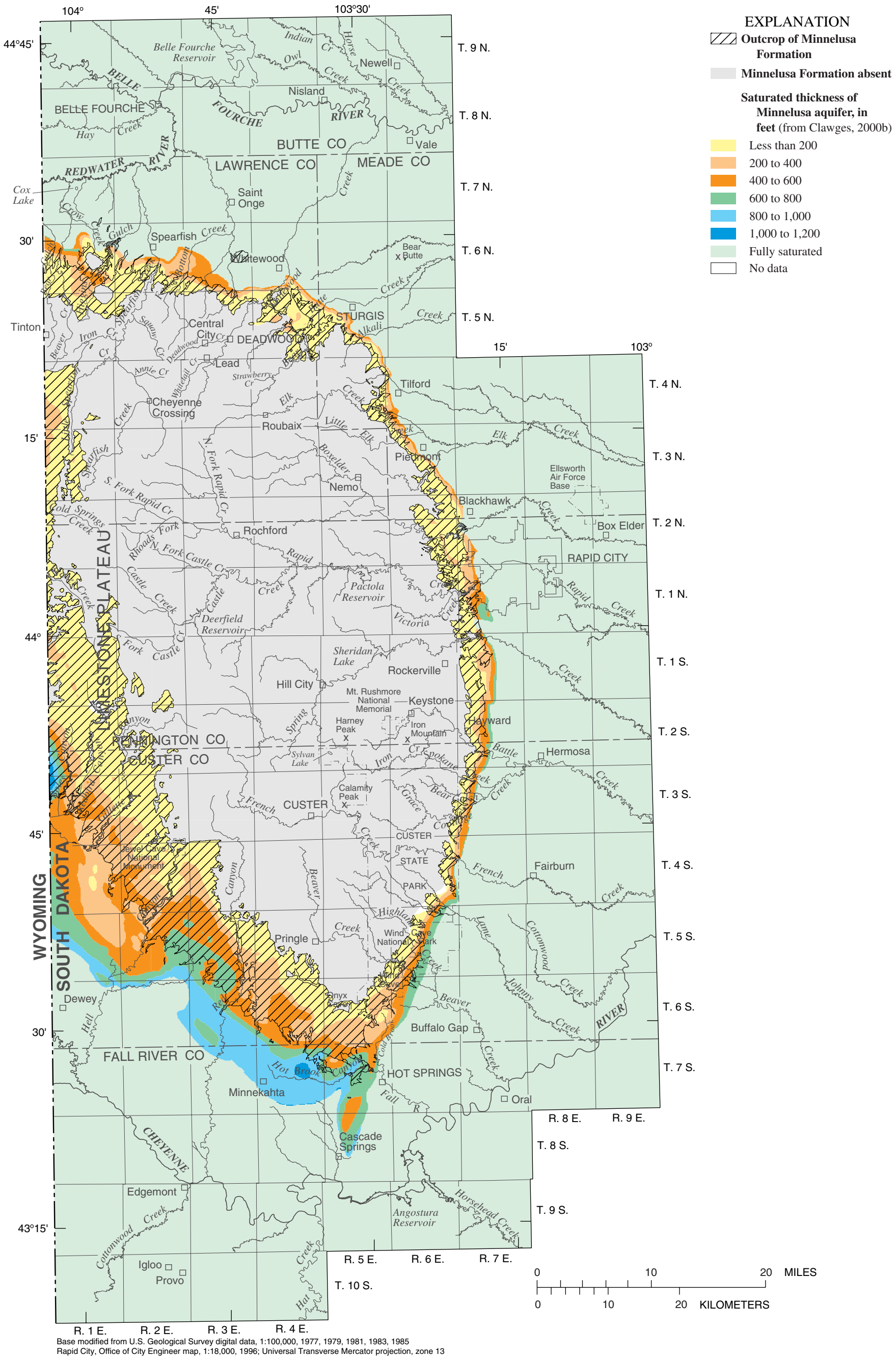


Figure 64. Saturated thickness of the Minnelusa aquifer.

Overview of Other 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 19 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, may contain a local aquifer, but seldom is used because of more reliable sources in the adjacent Madison or Deadwood aquifers. Local aquifers may exist in the Spearfish confining unit where gypsum and anhydrite have been dissolved increasing 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 and is considered a minor aquifer where saturated. Unconsolidated deposits of Tertiary or Quaternary age, including alluvium, colluvium, and wind-blown deposits, all have the potential to be local aquifers where they are saturated.

Ground-Water Levels

Well **hydrographs** provide information regarding temporal trends (over time) in ground-water levels, comparisons between aquifers, and water-level response to climatic conditions. Daily water-level data were collected for 71 observation wells for the study. Hydrographs for these wells through water year 1998 were presented in Driscoll, Bradford, and Moran (2000). Hydrographs for selected wells (fig. 65) are presented in this section of the report. For the hydrographs, 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.

Many of the semiconfining and confining units may contain local aquifers.

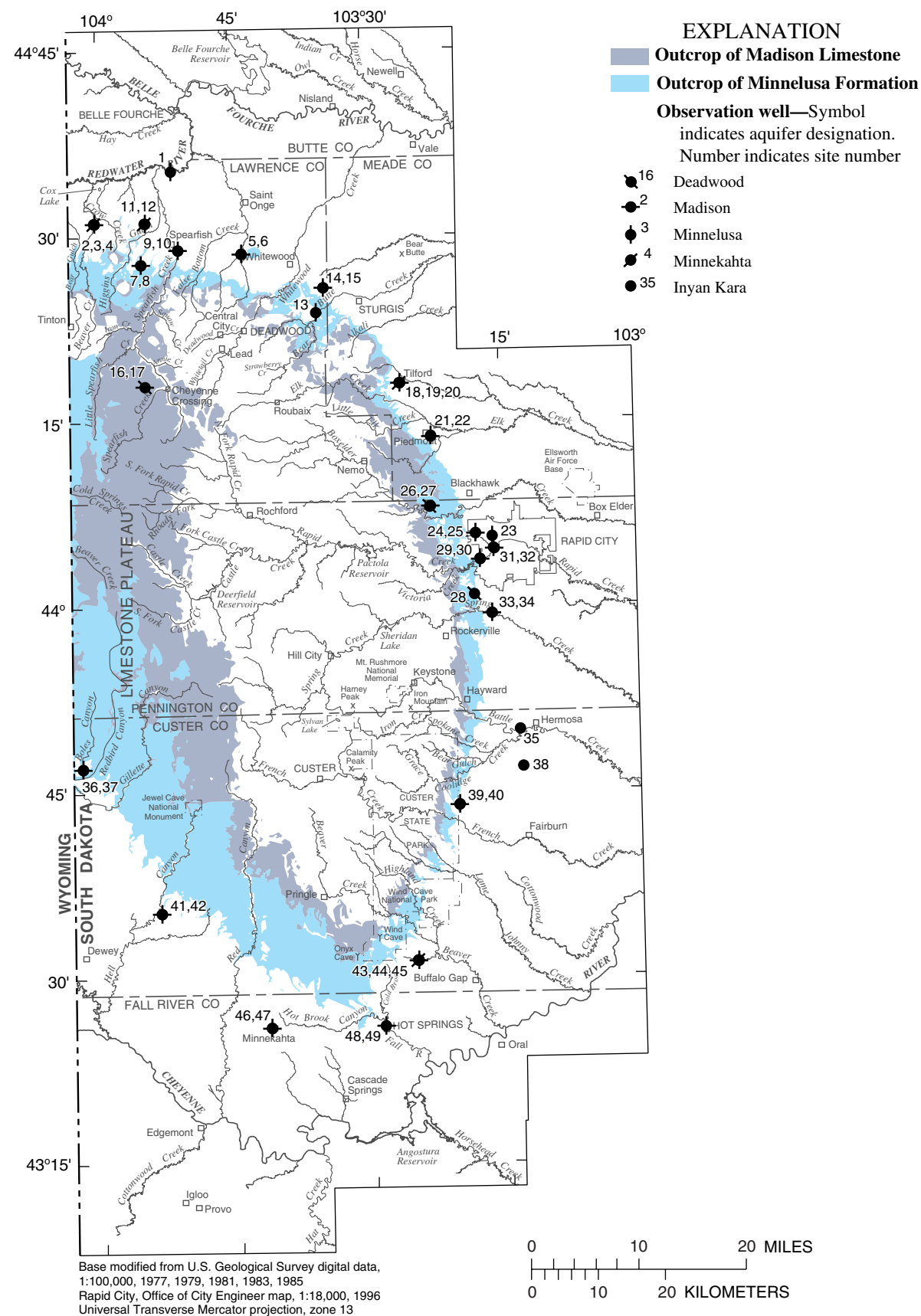


Figure 65. Location of observation wells for which hydrographs are presented.

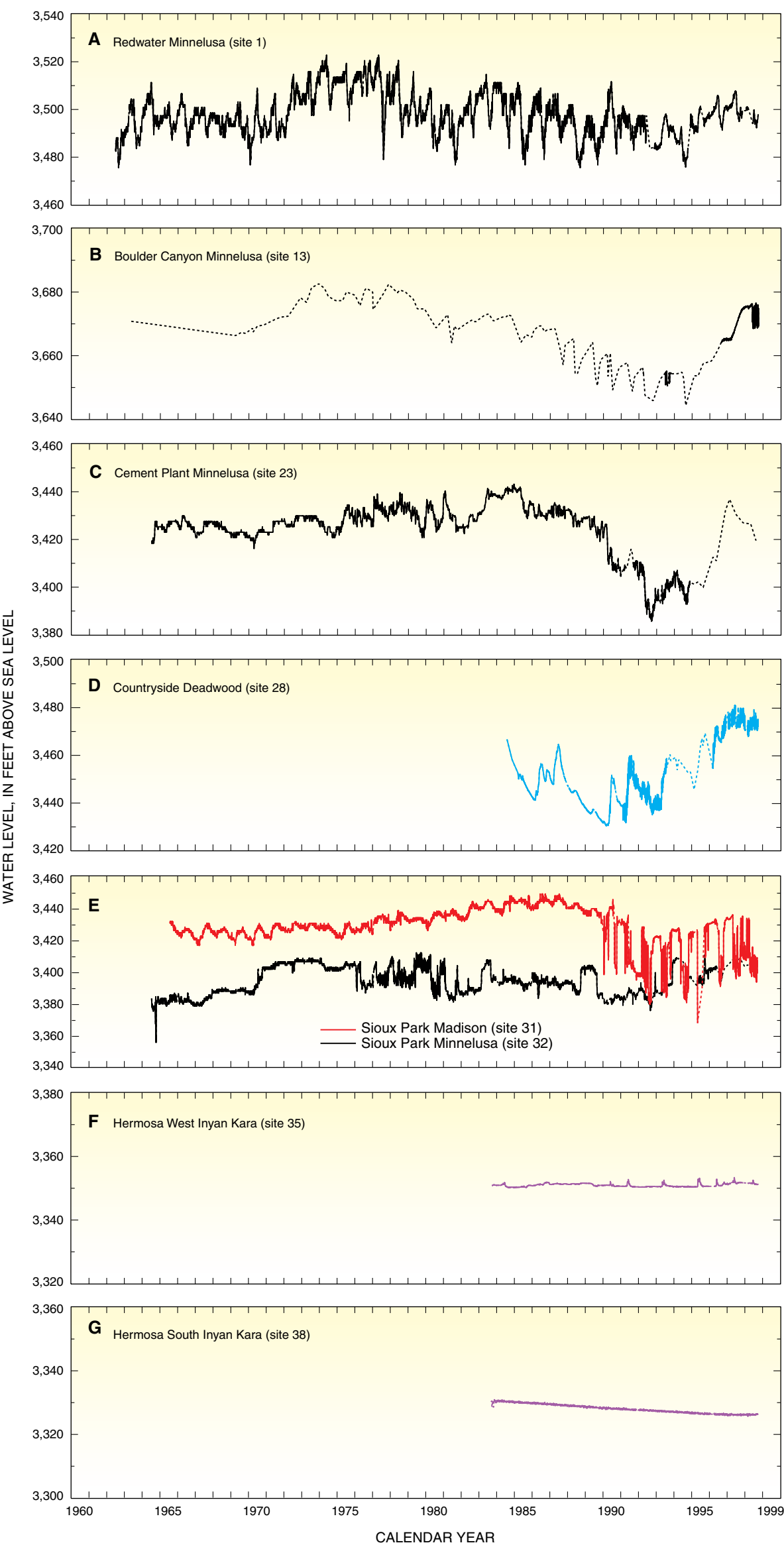


Figure 66. Hydrographs illustrating temporal trends in ground-water levels.

Temporal Trends

In some parts of the United States, such as Texas and Florida, large ground-water withdrawals have caused declining water levels. In some areas, associated land subsidence has occurred and the storage capacity of aquifers has been reduced.

Temporal trends are examined for eight wells with relatively long-term records in the Black Hills area (fig. 66). Most of these wells are in locations that may be affected by withdrawals from production wells. The Hermosa South Inyan Kara well (fig. 66G) is the only observation well in the Black Hills area that shows a steadily declining water-level trend over time. The decline is about 4 feet from 1983 to 1998. The Hermosa West Inyan Kara well (fig. 66F), which is located several miles farther north (fig. 65), does not show a similar decline.

The water level at the Redwater Minnelusa well (fig. 66A) shows a seasonal response to withdrawals for irrigation, but generally recovers each year. The water level at the Boulder Canyon Minnelusa well (fig. 66B) declined steadily during the 1980's and early 1990's, but recovered during subsequent years.

The Sioux Park Madison well (fig. 66E) shows response to increased production by the city of Rapid City from the Madison aquifer beginning in the late 1980's. Recovery occurs during winter when production is reduced. An adjacent Minnelusa well shows no influence from production from the Madison aquifer; however, a decline during the 1990's in the Cement Plant Minnelusa well (fig. 66C) may be related to the increased production from the Madison aquifer.

The Countryside Deadwood well (fig. 66D) is located southwest of Rapid City (fig. 65) in an area where substantial production from the Deadwood aquifer occurs. Increasing demand in this area occasionally has caused water-supply shortages during recent periods of peak demand; however, long-term water-level declines are not apparent.

In the Black Hills area, there is little apparent influence of ground-water withdrawals on long-term water-level trends.

Comparisons between Madison and Minnelusa Aquifers

In many locations, two or more observation wells are colocated (at the same location). The most common colocated wells are paired Madison and Minnelusa wells. Comparisons of well hydrographs for colocated wells provide useful insights regarding hydraulic head differences and potential interactions between aquifers. The Madison and Minnelusa aquifers are known to be hydraulically connected in the vicinity of many artesian springs and may be connected in other locations. Aquifer testing has indicated variable hydraulic connection in the Rapid City area, where water levels in some wells completed in the Minnelusa aquifer responded to pumping in the Madison aquifer, while water levels in other Minnelusa wells did not (Greene, 1993).

Hydrographs illustrating general similarities in water levels for some colocated Madison and Minnelusa wells are presented in figure 67. All of the wells are located where confined conditions exist in both aquifers.

Hydraulic connection between the aquifers has been confirmed through aquifer testing (Greene, 1993) for the City Quarry wells (fig. 67D), which have hydrographs that are nearly identical. These wells are located near City Springs, where dye testing has confirmed a Madison aquifer source for this spring (Greene, 1997), which discharges through the Minnelusa Formation.

Similarities in hydrographs do not necessarily indicate hydraulic connection between the aquifers. Hydrographs for the Spearfish Golf Course wells (fig. 67A) are very similar during 1995-98, but have little similarity prior to that period. Aquifer testing (Greene and others, 1999) provided no indication of hydraulic connection in the vicinity of these wells, however. Hydrographs for the Custer State Park (CSP) wells are nearly identical, and other pairs shown have general similarities. At most pairs of wells, hydraulic connection cannot be confirmed or refuted because aquifer testing has not been performed.

Distinct hydraulic separation between the Madison and Minnelusa aquifers is apparent for two well pairs (fig. 68) where water levels are separated by about 500 to 600 feet in locations where unconfined (water-table) conditions occur. In both locations, the water table in the Minnelusa aquifer is much higher than that in the Madison aquifer, which also is not fully saturated. Both well pairs are located within or near the Minnelusa Formation outcrops (fig. 65), and measured water-level altitudes in Minnelusa aquifer are higher than for most other observation wells in unconfined areas.

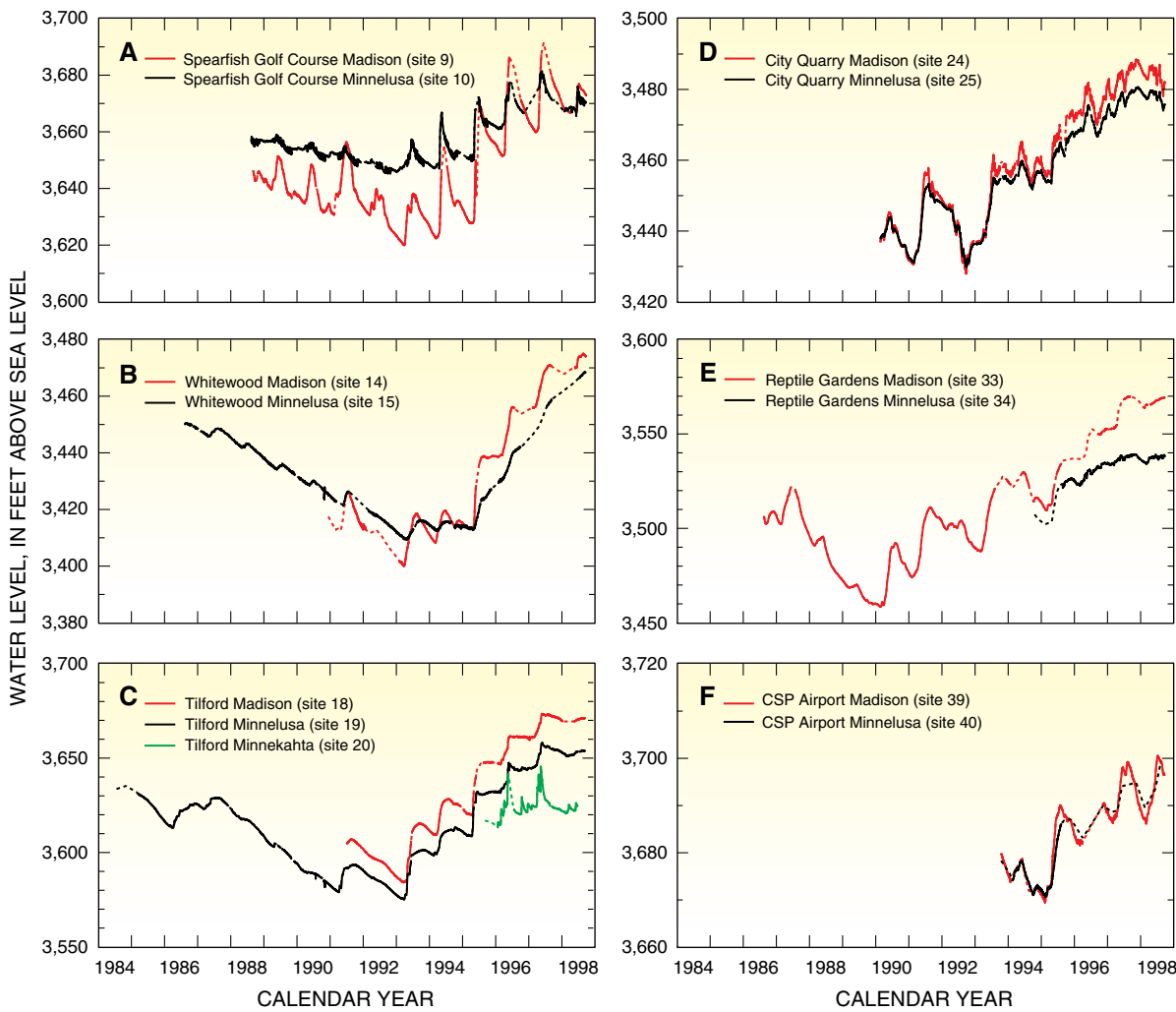


Figure 67. Hydrographs illustrating general similarities in water levels for some colocated Madison/Minnelusa wells with confined conditions.

Hydraulic connection between the Madison and Minnelusa aquifer has been documented at various artesian springs and several wells. Paired hydrographs indicate possible hydraulic connection at several other locations.

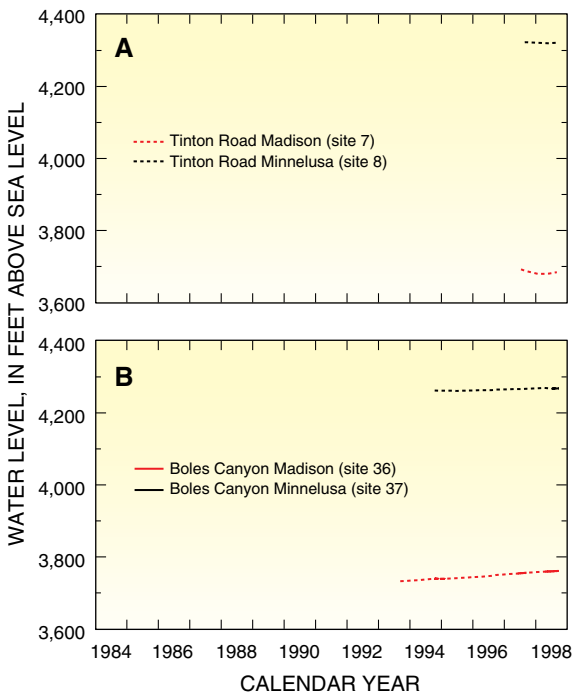


Figure 68. Hydrographs illustrating large hydraulic separation for colocated Madison/Minnelusa wells with unconfined conditions.

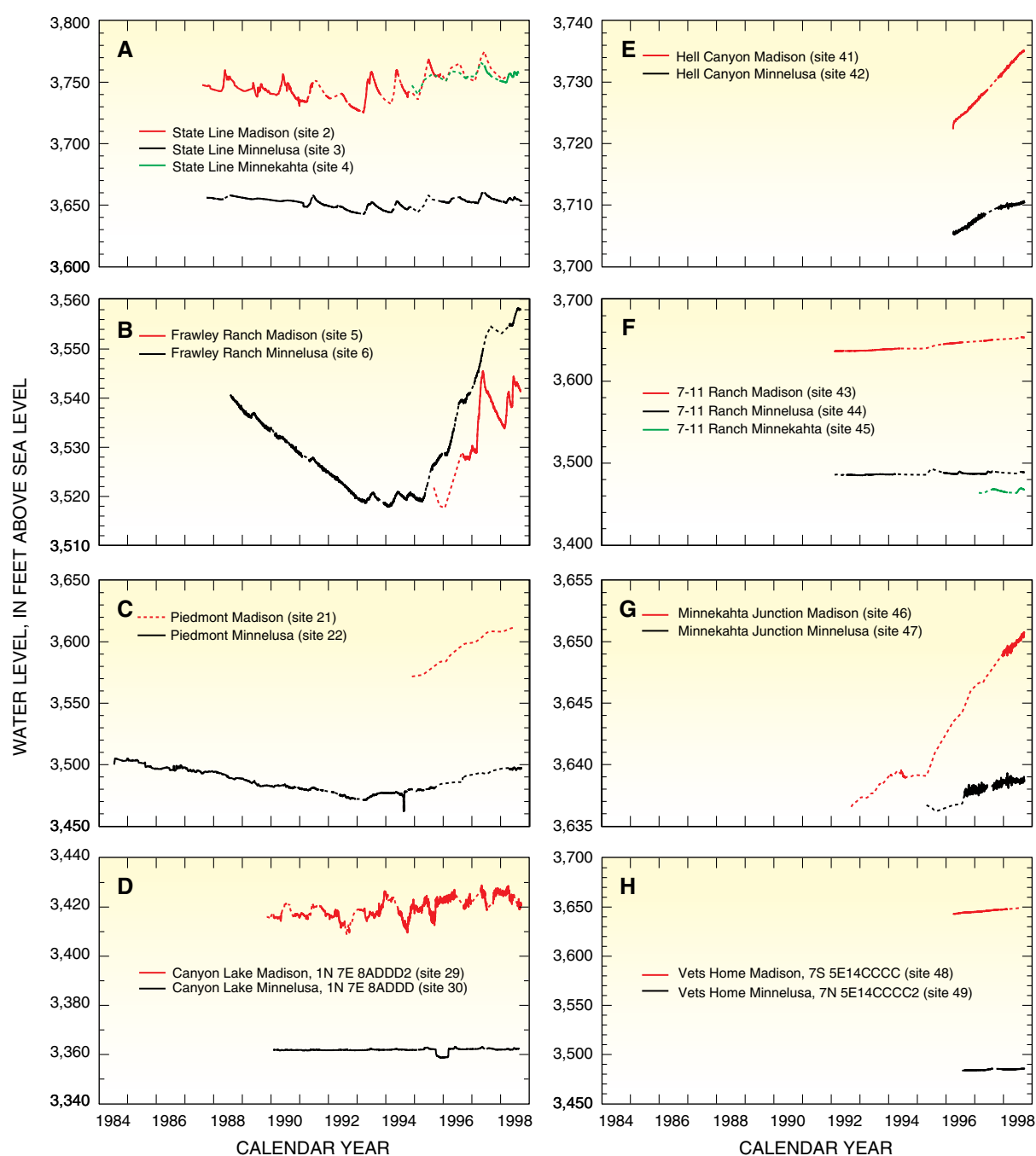


Figure 69. Hydrographs illustrating generally separated water levels for some collocated Madison/Minnelusa wells.

Hydrographs for most wells show declining water levels during dry conditions and rapid recovery during wet conditions.

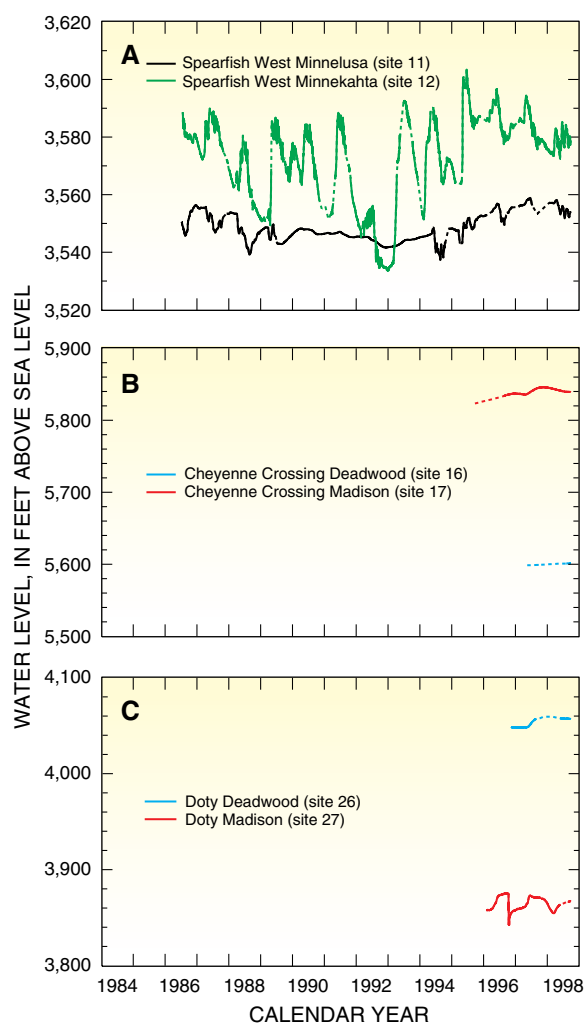


Figure 70. Hydrographs for collocated Minnelusa/Minnekahta and Deadwood/Madison wells.

Figure 69 shows hydrographs for other collocated Madison and Minnelusa wells, most of which are in locations with confined conditions (figs. 63 and 64). Most of these well pairs show distinct hydraulic separation between the aquifers, with hydraulic heads separated by as much as 100 to 150 feet. Hydraulic separation is consistently less than about 30 feet for three well pairs, however, including the Frawley Ranch, Hell Canyon, and Minnekahta Junction wells (figs. 69B, 69E, and 69G, respectively). Periods of record for these wells may be insufficient to indicate similarity or dissimilarity of hydrograph shapes.

Another observation that can be made from comparisons of hydrographs for collocated wells is that the hydraulic head in the Madison aquifer equals or exceeds the hydraulic head in the Minnelusa aquifer in most locations where confined conditions occur. The Madison aquifer has the potential for higher hydraulic head than the Minnelusa aquifer because of generally higher altitude of recharge area for the Madison aquifer. An exception to this generality occurs along the northeastern flank of the Black Hills. The hydraulic head in the Minnelusa aquifer generally equals or exceeds that in the Madison aquifer for the Spearfish Golf Course wells (fig. 67A), the Whitewood wells (fig. 67B), and the Frawley Ranch wells (fig. 69B).

Comparisons for Other Aquifers

Hydrograph comparisons for collocated wells completed in other aquifers are presented in figure 70. Hydrographs for the Spearfish West Minnelusa and Minnekahta wells are shown in figure 70A. Hydrographs for the Minnekahta aquifer also are available for the Tilford wells (fig. 67C), State Line wells (fig. 69A), and 7-11 Ranch wells (fig. 69F). Many artesian springs emerge through the Minnekahta Limestone; thus, hydraulic connections with the underlying Madison and Minnelusa aquifers are possible. Hydrographs for the Minnekahta and Madison wells are very similar for the State Line wells, and the hydraulic head in the Minnekahta aquifer is sometimes higher than in the Madison aquifer. Water levels are notably different in the Minnelusa aquifer at this location.

Hydrographs for collocated Deadwood and Madison wells (fig. 70) are available for two locations. For the Cheyenne Crossing wells (fig. 70B), the water table in the Madison aquifer is perched about 250 feet above the water table in the Deadwood aquifer. For the Doty wells (fig. 70C), the Deadwood aquifer is confined, and hydraulic head is about 200 feet higher than in the Madison aquifer.

Responses to Climatic Conditions

Ground-water levels are directly affected by recharge rates that are influenced by annual precipitation amounts; however, numerous other factors can affect ground-water response. The timing and intensity of precipitation, along with evaporative factors such as temperature, humidity, wind speed, and solar radiation can have a large effect on annual recharge. Streamflow losses (especially to the Madison and Minnelusa aquifers) also contribute to recharge. Ground-water levels also can be affected by well withdrawals, spring discharges, and various hydraulic properties of aquifers. A distinct response to annual precipitation patterns (fig. 14) is indicated by hydrographs for many wells in figures 66-70, which indicates that other influences are relatively minor for many wells. Many of these wells with sufficient periods of record show short-term declines during the late 1980's, with generally increasing water levels during the wetter conditions of the middle to late 1990's.

Hydrographs for the two Inyan Kara wells (figs. 66F and G) show minimal response to climatic conditions. Hydrographs for other Inyan Kara wells that are not shown also show minimal response to climatic conditions (Driscoll, Bradford, and Moran, 2000).

All of the other aquifers show a wide range of responses to climatic conditions, ranging from minimal response to several tens of feet. Driscoll and Carter (2001) noted that for the Madison and Minnelusa aquifers, water-level fluctuations in the extreme southern Black Hills generally are smaller than in the northern Black Hills, which results, in part, from smaller recharge rates in the southern Black Hills.

Hydraulic head in the Madison aquifer equals or exceeds the hydraulic head in the Minnelusa aquifer in most locations where confined conditions occur. The Madison aquifer has the potential for higher hydraulic head than the Minnelusa aquifer because of generally higher altitude of recharge area for the Madison aquifer.

Ground water can contain numerous substances, some of which potentially can cause serious health effects such as cancer.

Ground-Water Quality

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. More detailed descriptions of ground-water quality are presented in Williamson and Carter (2001). A brief discussion of the susceptibility of aquifers to contamination also is presented, as well as a summary of water quality relative to water use.

Ground- and surface-water resources in the Black Hills area are highly interconnected. The quality of surface water can affect the quality of ground water, and vice versa.

Background

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 the ground-water and surface-water resources in the Black Hills area are highly interconnected, changes in the quality of surface water can affect the quality of ground water, and vice versa.

Ground water can contain numerous substances (**constituents**) that typically are measured using laboratory analyses. Some constituents potentially can cause serious health effects such as cancer. 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. Chemical constituents in ground water also can result from manmade sources, such as industrial, domestic, and agricultural chemicals, that have the potential to contaminate the water.

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 the potential health risks associated with drinking water that exceeds these standards. A list of selected USEPA drinking-water standards is provided in table 6. **Maximum Contaminant Levels** (MCL's) are established for contaminants that, if present in drinking water, may cause adverse human health effects; MCL's are enforceable health-based standards (U.S. Environmental Protection Agency, 1994a). **Secondary Maximum Contaminant Levels** (SMCL's) are established for contaminants that can adversely affect the taste, odor, or appearance of water and may result in discontinuation of use of the water; SMCL's are nonenforceable, generally nonhealth-based standards that are related to the aesthetics of water use (U.S. Environmental Protection Agency, 1994a). **Action levels** are concentrations of copper or lead, which if exceeded, trigger treatment or other requirements (U.S. Environmental Protection Agency, 1997). Pertinent MCL's and SMCL's are shown on applicable figures throughout this section of the report.

Standards and guidelines have been established to protect water for designated uses. Maximum Contaminant Levels (MCL's) are established for contaminants that may cause adverse health effects. Secondary Maximum Contaminant Levels (SMCL's) are related to the taste, odor, and appearance of the water.

Table 6. Water-quality criteria, standards, or recommended limits for selected properties and constituents

[All standards are from U.S. Environmental Protection Agency (1994a) unless noted. MCL, Maximum Contaminant Level; SMCL, Secondary Maximum Contaminant Level; USEPA, U.S. Environmental Protection Agency; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; pCi/L, picocuries per liter; --, no limit established]

Constituent or property	Limit	Significance
Physical Properties		
Specific conductance	--	A measure of the ability of water to conduct an electrical current; varies with temperature. Magnitude depends on concentration, kind, and degree of ionization of dissolved constituents; can be used to determine the approximate concentration of dissolved solids. Values are reported in microsiemens per centimeter at 25°Celsius.
pH	6.5-8.5 units SMCL	A measure of the hydrogen ion concentration; pH of 7.0 indicates a neutral solution, pH values smaller than 7.0 indicate acidity, pH values larger than 7.0 indicate alkalinity. Water generally becomes more corrosive with decreasing pH; however, excessively alkaline water also may be corrosive.
Temperature	--	Affects the usefulness of water for many purposes. Generally, users prefer water of uniformly low temperature. Temperature of ground water tends to increase with increasing depth to the aquifer.
Dissolved oxygen	--	Required by higher forms of aquatic life for survival. Measurements of dissolved oxygen are used widely in evaluations of the biochemistry of streams and lakes. Oxygen is supplied to ground water through recharge and by movement of air through unsaturated material above the water table (Hem, 1985).
Carbon dioxide	--	Important in reactions that control the pH of natural waters.
Hardness and noncarbonate hardness (as mg/L CaCO ₃)	--	Related to the soap-consuming characteristics of water; results in formation of scum when soap is added. May cause deposition of scale in boilers, water heaters, and pipes. Hardness contributed by calcium and magnesium, bicarbonate and carbonate mineral species in water is called carbonate hardness; hardness in excess of this concentration is called noncarbonate hardness. Water that has a hardness less than 61 mg/L is considered soft; 61-120 mg/L, moderately hard; 121-180 mg/L, hard; and more than 180 mg/L, very hard (Heath, 1983).
Alkalinity	--	A measure of the capacity of unfiltered water to neutralize acid. In almost all natural waters alkalinity is produced by the dissolved carbon dioxide species, bicarbonate and carbonate. Typically expressed as mg/L CaCO ₃ .
Dissolved solids	500 mg/L SMCL	The total of all dissolved mineral constituents, usually expressed in milligrams per liter. The concentration of dissolved solids may affect the taste of water. Water that contains more than 1,000 mg/L is unsuitable for many industrial uses. Some dissolved mineral matter is desirable, otherwise the water would have no taste. 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 (Heath, 1983).
Common Ions		
Calcium plus magnesium	--	Cause most of the hardness and scale-forming properties of water (see hardness).
Sodium plus potassium	--	Large concentrations may limit use of water for irrigation and industrial use and, in combination with chloride, give water a salty taste. Abnormally large concentrations may indicate natural brines, industrial brines, or sewage.
Bicarbonate	--	In combination with calcium and magnesium forms carbonate hardness.
Sulfate	250 mg/L SMCL	Sulfates of calcium and magnesium form hard scale. Large concentrations of sulfate have a laxative effect on some people and, in combination with other ions, give water a bitter taste.
Chloride	250 mg/L SMCL	Large concentrations increase the corrosiveness of water and, in combination with sodium, give water a salty taste.
Fluoride	4.0 mg/L MCL 2.0 mg/L SMCL	Reduces incidence of tooth decay when optimum fluoride concentrations are present in water consumed by children during the period of tooth calcification. Potential health effects of long-term exposure to elevated fluoride concentrations include dental and skeletal fluorosis (U.S. Environmental Protection Agency, 1994b).
Nutrients		
Nitrite (mg/L as N)	1.0 mg/L MCL	Commonly formed as an intermediate product in bacterially mediated nitrification and denitrification of ammonia and other organic nitrogen compounds. An acute health concern at certain levels of exposure. Nitrite typically occurs in water from fertilizers and is found in sewage and wastes from humans and farm animals. Concentrations greater than 1.0 mg/L, as nitrogen, may be injurious to pregnant women, children, and the elderly.
Nitrite plus nitrate (mg/L as N)	10 mg/L MCL	Concentrations greater than local background levels may indicate pollution by feedlot runoff, sewage, or fertilizers. Concentrations greater than 10 mg/L, as nitrogen, may be injurious to pregnant women, children, and the elderly.
Ammonia	--	Plant nutrient that can cause unwanted algal blooms and excessive plant growth when present at elevated levels in water bodies. Sources include decomposition of animal and plant proteins, agricultural and urban runoff, and effluent from wastewater treatment plants.
Phosphorus, orthophosphate	--	Dense algal blooms or rapid plant growth can occur in waters rich in phosphorus. A limiting nutrient for eutrophication because it is typically in shortest supply. Sources are human and animal wastes and fertilizers.
Trace Elements		
Arsenic	¹ 10 µg/L MCL	No known necessary role in human or animal diet, but is toxic. A cumulative poison that is slowly excreted. Can cause nasal ulcers; damage to the kidneys, liver, and intestinal walls; and death. Recently suspected to be a carcinogen (Garold Carlson, U.S. Environmental Protection Agency, written commun., 1998).
Barium	2,000 µg/L MCL	Toxic; used in rat poison. In moderate to large concentrations can cause death; smaller concentrations can cause damage to the heart, blood vessels, and nerves.
Boron	--	Essential to plant growth, but may be toxic to crops when present in excessive concentrations in irrigation water. Sensitive plants show damage when irrigation water contains more than 670 µg/L and even tolerant plants may be damaged when boron exceeds 2,000 µg/L. The recommended limit is 750 µg/L for long-term irrigation on sensitive crops (U.S. Environmental Protection Agency, 1986).
Cadmium	5 µg/L MCL	A cumulative poison; very toxic. Not known to be either biologically essential or beneficial. Believed to promote renal arterial hypertension. Elevated concentrations may cause liver and kidney damage, or even anemia, retarded growth, and death.

Table 6. Water-quality criteria, standards, or recommended limits for selected properties and constituents—Continued

[All standards are from U.S. Environmental Protection Agency (1994a) unless noted. MCL, Maximum Contaminant Level; SMCL, Secondary Maximum Contaminant Level; USEPA, U.S. Environmental Protection Agency; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; pCi/L, picocuries per liter; --, no limit established]

Constituent or property	Limit	Significance
Trace Elements—Continued		
Copper	1,300 µg/L (action level)	Essential to metabolism; copper deficiency in infants and young animals results in nutritional anemia. Large concentrations of copper are toxic and may cause liver damage. Moderate levels of copper (near the action level) can cause gastro-intestinal distress. If more than 10 percent of samples at the tap of a public water system exceed 1,300 µg/L, the USEPA requires treatment to control corrosion of plumbing materials in the system.
Iron	300 µg/L SMCL	Forms rust-colored sediment; stains laundry, utensils, and fixtures reddish brown. Objectionable for food and beverage processing. Can promote growth of certain kinds of bacteria that clog pipes and well openings.
Lead	15 µg/L (action level)	A cumulative poison; toxic in small concentrations. Can cause lethargy, loss of appetite, constipation, anemia, abdominal pain, gradual paralysis in the muscles, and death. If 1 in 10 samples of a public supply exceed 15 µg/L, the USEPA recommends treatment to remove lead and monitoring of the water supply for lead content (U.S. Environmental Protection Agency, 1991).
Lithium	--	Reported as probably beneficial in small concentrations (250-1,250 µg/L). Reportedly may help strengthen the cell wall and improve resistance to genetic damage and to disease. Lithium salts are used to treat certain types of psychosis.
Manganese	50 µg/L SMCL	Causes gray or black stains on porcelain, enamel, and fabrics. Can promote growth of certain kinds of bacteria that clog pipes and well openings.
Mercury (inorganic)	2 µg/L MCL	No known essential or beneficial role in human or animal nutrition. Liquid metallic mercury and elemental mercury dissolved in water are comparatively nontoxic, but some mercury compounds, such as mercuric chloride and alkyl mercury, are very toxic. Elemental mercury is readily alkylated, particularly to methyl mercury, and concentrated by biological activity. Potential health effects of exposure to some mercury compounds in water include severe kidney and nervous system disorders (U.S. Environmental Protection Agency, 1994b).
Nickel	--	Very toxic to some plants and animals. Toxicity for humans is believed to be very minimal.
Selenium	50 µg/L MCL	Essential to human and animal nutrition in minute concentrations, but even a moderate excess may be harmful or potentially toxic if ingested for a long time (Callahan and others, 1979). Potential human health effects of exposure to elevated selenium concentrations include liver damage (U.S. Environmental Protection Agency, 1994b).
Silver	100 µg/L SMCL	Causes permanent bluish darkening of the eyes and skin (argyria). Where found in water is almost always from pollution or by intentional addition. Silver salts are used in some countries to sterilize water supplies. Toxic in large concentrations.
Strontium	--	Importance in human and animal nutrition is not known, but believed to be essential. Toxicity believed very minimal—no more than that of calcium.
Zinc	5,000 µg/L SMCL	Essential and beneficial in metabolism; its deficiency in young children or animals will retard growth and may decrease general body resistance to disease. Seems to have no ill effects even in fairly large concentrations (20,000-40,000 mg/L), but can impart a metallic taste or milky appearance to water. Zinc in drinking water commonly is derived from galvanized coatings of piping.
Radionuclides		
Gross alpha-particle activity	15 pCi/L MCL	The measure of alpha-particle radiation present in a sample. A limit is placed on gross alpha-particle activity because it is impractical at the present time to identify all alpha-particle-emitting radionuclides due to analytical costs. Gross alpha-particle activity is a radiological hazard. The 15 pCi/L standard also includes radium-226, a known carcinogen, but excludes any uranium or radon that may be present in the sample. Thorium-230 radiation contributes to gross alpha-particle activity.
Beta-particle and photon activity (formerly manmade radionuclides)	4 millirem/yr MCL (under review)	The measure of beta-particle radiation present in a sample. Gross beta-particle activity is a radiological hazard. See strontium-90 and tritium.
Radium-226 & 228 combined	5 pCi/L MCL	Radium locates primarily in bone; however, inhalation or ingestion may result in lung cancer. Radium-226 is a highly radioactive alkaline-earth metal that emits alpha-particle radiation. It is the longest lived of the four naturally occurring isotopes of radium and is a disintegration product of uranium-238. Concentrations of radium in most natural waters are usually less than 1.0 pCi/L (Hem, 1985).
Radon ²	300 or 4,000 pCi/L proposed MCL	Inhaled radon is known to cause lung cancer (MCL for radon in indoor air is 4 pCi/L). Ingested radon also is believed to cause cancer. A radon concentration of 1,000 pCi/L in water is approximately equal to 1 pCi/L in air. The ultimate source of radon is the radioactive decay of uranium. Radon-222 has a half-life of 3.8 days and is the only radon isotope of importance in the environment (Hem, 1985).
Strontium-90 (contributes to beta-particle and photon activity)	Gross beta-particle activity (4 millirem/yr) MCL	Strontium-90 is one of 12 unstable isotopes of strontium known to exist. It is a product of nuclear fallout and is known to cause adverse human health affects. Strontium-90 is a bone seeker and a relatively long-lived beta emitter with a half-life of 28 years. The USEPA has calculated that an average annual concentration of 8 pCi/L will produce a total body or organ dose of 4 millirem/yr (U.S. Environmental Protection Agency, 1997).
Thorium-230 (contributes to gross alpha-particle activity)	15 pCi/L MCL	Thorium-230 is a product of natural radioactive decay when uranium-234 emits alpha-particle radiation. Thorium-230 also is a radiological hazard because it is part of the uranium-238 decay series and emits alpha-particle radiation through its own natural decay to become radium-226. The half-life of thorium-230 is about 80,000 years.
Tritium (³ H) (contributes to beta-particle and photon activity)	Gross beta-particle activity (4 millirem/yr) MCL	Tritium occurs naturally in small amounts in the atmosphere, but largely is the product of nuclear weapons testing. Tritium can be incorporated into water molecules that reach the Earth’s surface as precipitation. Tritium emits low energy beta particles and is relatively short-lived with a half-life of about 12.4 years. The USEPA has calculated that a concentration of 20,000 pCi/L will produce a total body or organ dose of 4 millirem/yr (U.S. Environmental Protection Agency, 1997).
Uranium	30 µg/L MCL (under review)	Uranium is a chemical and radiological hazard and carcinogen. It emits alpha-particle radiation through natural decay. It is a hard, heavy, malleable metal that can be present in several oxidation states. Generally, the more oxidized states are more soluble. Uranium-238 and uranium-235, which occur naturally, account for most of the radioactivity in water. Uranium concentrations range between 0.1 and 10 µg/L in most natural waters.

¹USEPA currently is implementing a revised MCL for arsenic from 50 µg/L to 10 µg/L; public-water systems must meet the revised MCL by January 2006 (U.S. Environmental Protection Agency, 2001).
²USEPA currently is working to set an MCL for radon in water. The proposed standards are 4,000 pCi/L for States that have an active indoor air program and 300 pCi/L for States that do not have an active indoor air program (Garold Carlson, U.S. Environmental Protection Agency, oral commun., 1999). At this time, it is not known whether South Dakota will participate in an active indoor air program (Darron Busch, South Dakota Department of Environment and Natural Resources, oral commun., 1999).

The most common dissolved substances in water are minerals or salts that, as a group, are referred to as dissolved solids. Dissolved solids include mainly three water-quality categories: common ions, nutrients, and trace elements.

Table 6 also provides a description of the general significance of the usability of water for various categories of water-quality properties and constituents, many of which do not have established standards. The physical properties include specific conductance, pH, water temperature, dissolved oxygen, carbon dioxide, hardness, alkalinity, and dissolved solids. Most of the physical properties are determined at the sampling site.

The most common dissolved substances in water are minerals or salts that, as a group, are referred to as dissolved solids. Dissolved solids include mainly three water-quality categories: **common ions**, **nutrients**, and **trace elements**. The common ions, which include calcium, magnesium, sodium, bicarbonate, sulfate, and chloride, make up greater than 95 percent of the dissolved solids for most natural (uncontaminated) waters. Nitrogen and phosphorus are nutrients, which are essential for plant growth. Nitrate is the major form of nitrogen in ground water, although it also can occur in other forms including ammonia and nitrite. Trace elements are constituents found in only minor amounts in water, such as arsenic, copper, iron, lead, manganese, mercury, selenium, and zinc.

Another water-quality category includes **radionuclides**, which are unstable **isotopes** and have a certain probability of decay (Clark and Fritz, 1997). Radionuclides exist throughout the environment, including water. Most radionuclides occur naturally like uranium, thorium, radium, and radon, while others are mostly or entirely manufactured like technetium, plutonium, neptunium, and americium (Langmuir, 1997). To date, more than 1,700 radionuclides have been identified (Clark and Fritz, 1997).

Radioactive decay series consist of a succession of radionuclides each with different decay rates. In each decay series, the original elements and each successive “daughter” product disintegrate, forming radionuclides until a stable lead isotope is formed. The decay rate usually is expressed as a half-life, which is the length of time required for one-half of the quantity present to disintegrate. Uranium and thorium are the original elements in the natural decay series (Wanty and Nordstrom, 1993) and give rise to most of the naturally occurring radioactivity in water (Hem, 1985).

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.

Although no samples collected for the study were analyzed for bacteria or other micro-organisms, these micro-organisms should be mentioned. Many types of harmless bacteria, including coliform bacteria, occur in human and animal intestinal tracts and have historically been used as an indicator of contamination by human sewage (Yates and Yates, 1993). Pathogenic (disease-causing) bacteria, such as *Salmonella*, are present in the feces of infected individuals and, thus, can contaminate water from leaking septic tanks, wastewater discharge, and animal wastes. Protozoan parasites, such as *Cryptosporidium parvum*, are another group of micro-organisms that are present in the feces of infected individuals that can contaminate a water supply. Although filtration and disinfection, usually using chlorine, have been effective means of controlling harmful micro-organisms, the protozoan parasite *Giardia lamblia* can be transported in a form that is resistant to chlorine (Hem, 1985) and is thought to cause the most common waterborne disease (giardiasis) in the United States (Lin, 1985). Another group of micro-organisms includes viruses, such as viral gastroenteritis and hepatitis A. The presence of harmful micro-organisms, especially viruses and parasites, is considerably more difficult to determine than most other properties of water (Hem, 1985) because it requires the collection of very large samples, typically hundreds to thousands of liters of water (Yates and Yates, 1993).

The presence of disease-causing bacteria, parasites, and viruses is very difficult to detect in water and can contaminate water.

General Characteristics for Major Aquifers

A 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.

The pH is a measure of how acidic (pH less than 7.0) or basic (pH greater than 7.0) a water sample is. Water generally becomes more corrosive with decreasing pH. Most pH values for the major aquifers are within the range specified by the SMCL (6.5 to 8.5 standard units). About 13 percent of the samples from wells completed in Precambrian rocks had pH values less than the lower limit specified by the SMCL, which indicates acidity. In general, pH values are lower in wells completed in Precambrian rocks than in the other major aquifers, which is indicative of a unit containing few carbonate rocks.

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 71. Water temperatures generally increase with well depth. Temperatures in the Madison aquifer generally are the warmest of the major aquifers because it is the deepest aquifer generally used at distance from the outcrop. The Madison aquifer is the primary source of water for warm artesian springs in the southern Black Hills, which may be influenced by factors other than aquifer depth (Whalen, 1994).

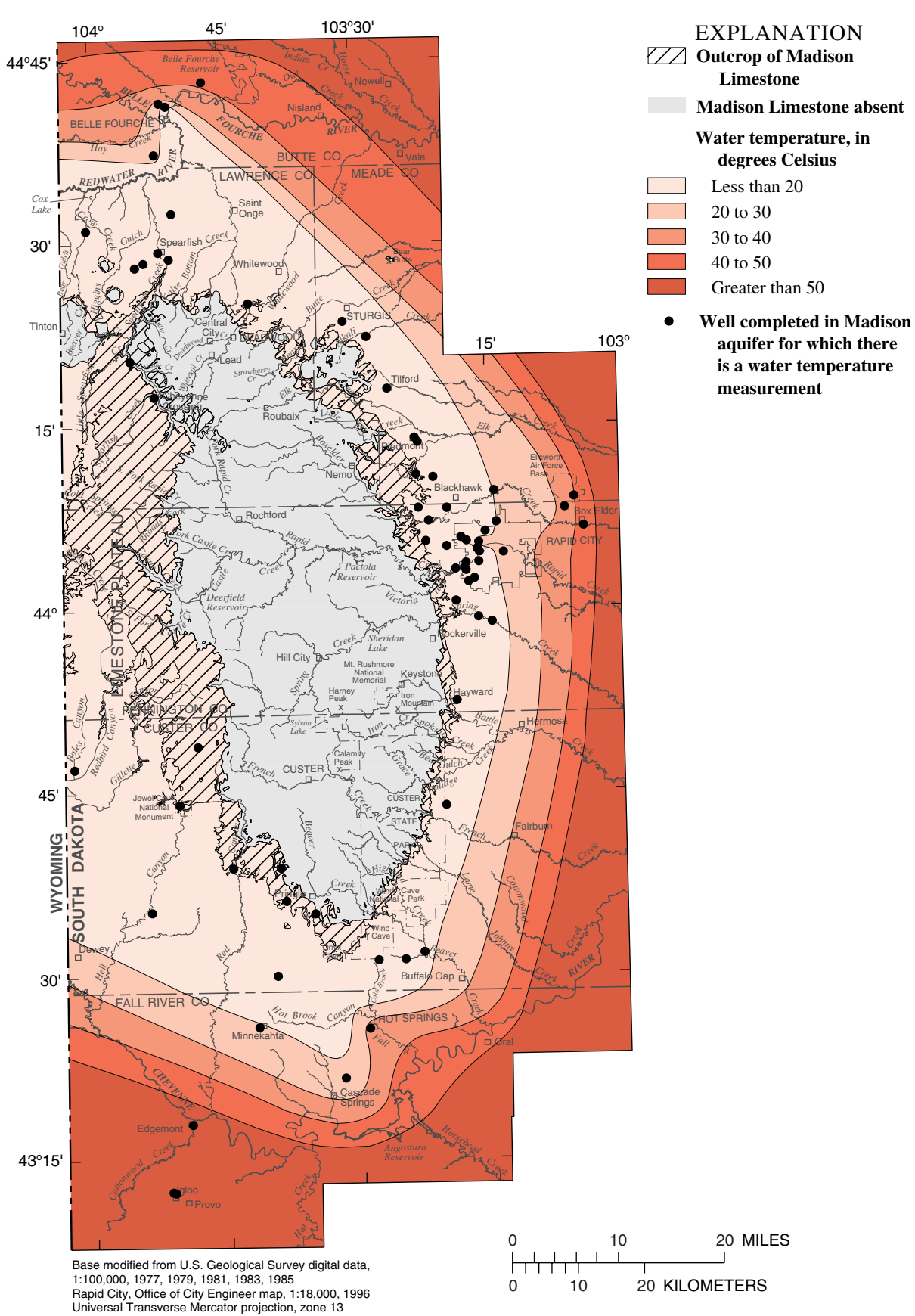


Figure 71. Water temperature in the Madison aquifer (modified from Williamson and Carter, 2001).

The Madison aquifer is the primary source of water for warm artesian springs in the southern Black Hills.

Specific conductance can be used to estimate dissolved solids concentrations, which may affect the taste of water and suitability for various uses.

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. Sea water has a very high 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. Specific conductance generally is low in water from the Precambrian, Deadwood, and

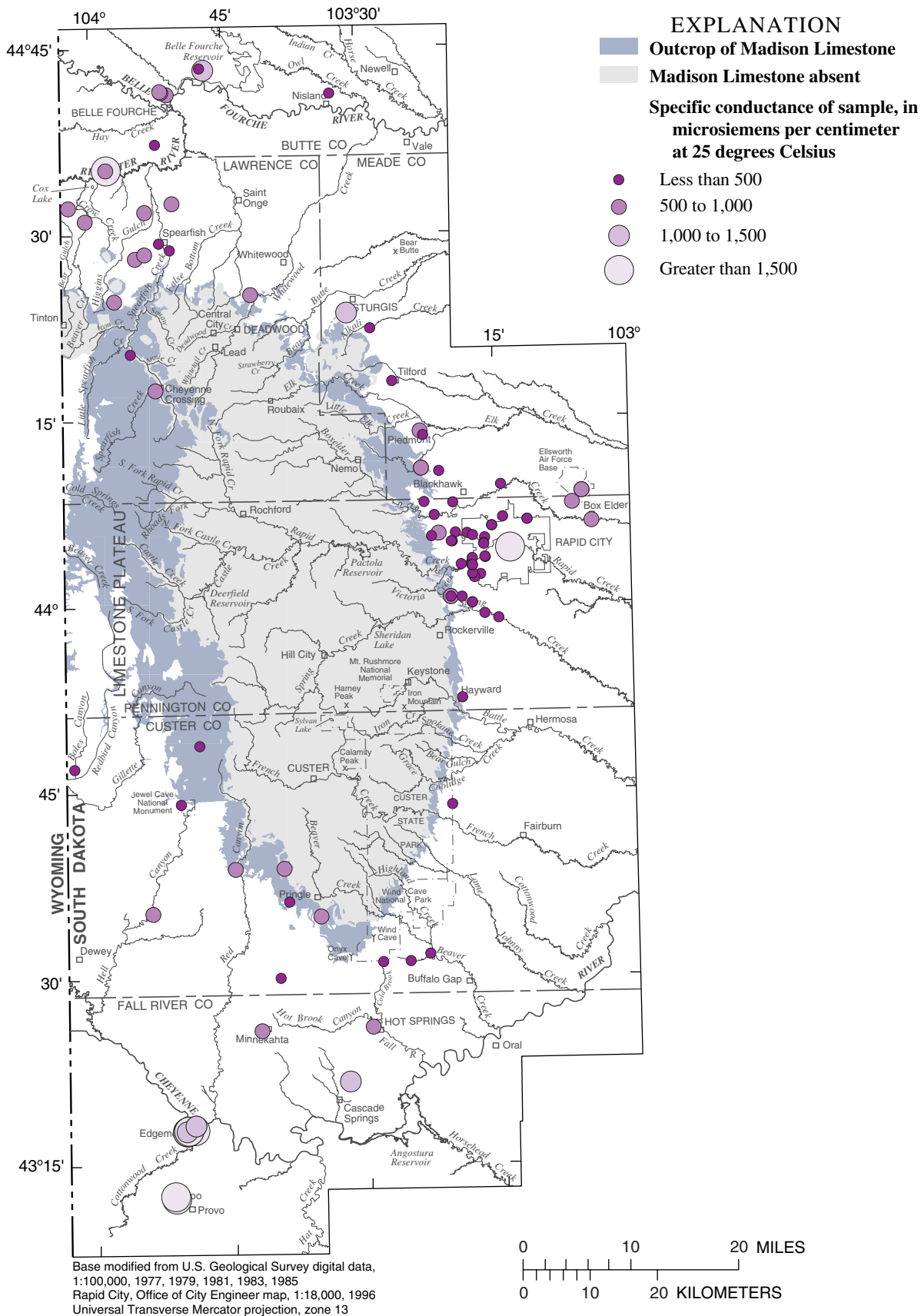
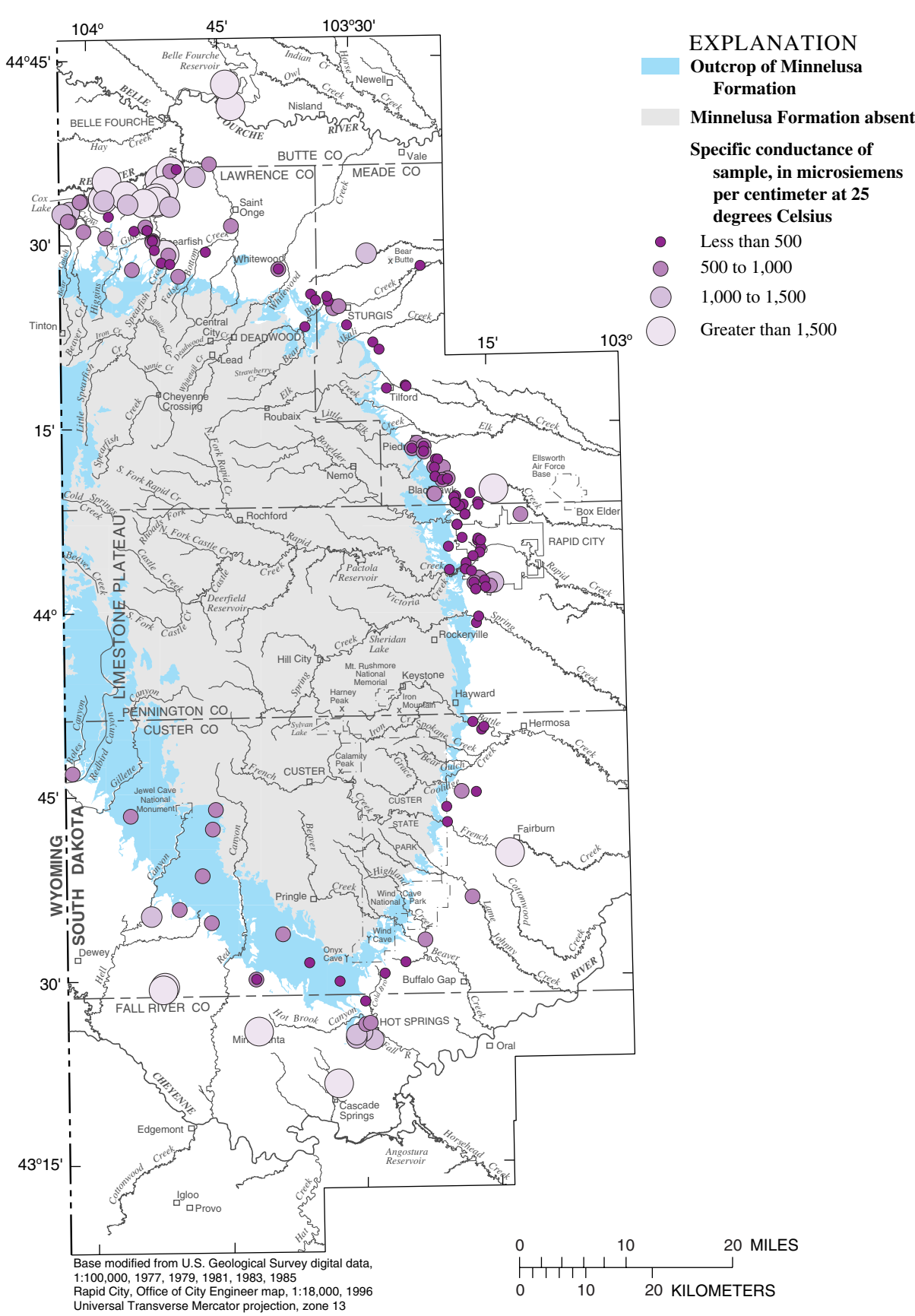


Figure 72. Specific conductance in the Madison aquifer (modified from Williamson and Carter, 2001).

Minnekahta aquifers. 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 their respective outcrops (figs. 72 and 73). Generally, water from the Inyan Kara aquifer is high in specific conductance even in some outcrop areas (fig. 74) 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.



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 their respective outcrops.

Figure 73. Specific conductance in the Minnelusa aquifer (modified from Williamson and Carter, 2001).

Water from the Inyan Kara aquifer is high in specific conductance even in some outcrop areas and is higher in specific conductance than the other major aquifers due to greater amounts of shale within the Inyan Kara Group.

Hardness is related to the 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. Geologic units that contain few carbonate rocks, such as the Precambrian rocks, generally contain water with lower hardness and alkalinity 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 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. The Inyan Kara aquifer may yield soft water, with hardness decreasing with increasing distance from the outcrop (fig. 75). Although concentrations of dissolved solids in the Inyan Kara aquifer actually increase with increasing distance from the outcrop, hardness decreases as 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. The Madison, Minnelusa, and Inyan Kara aquifers may yield slightly **saline water** (dissolved solids concentrations between

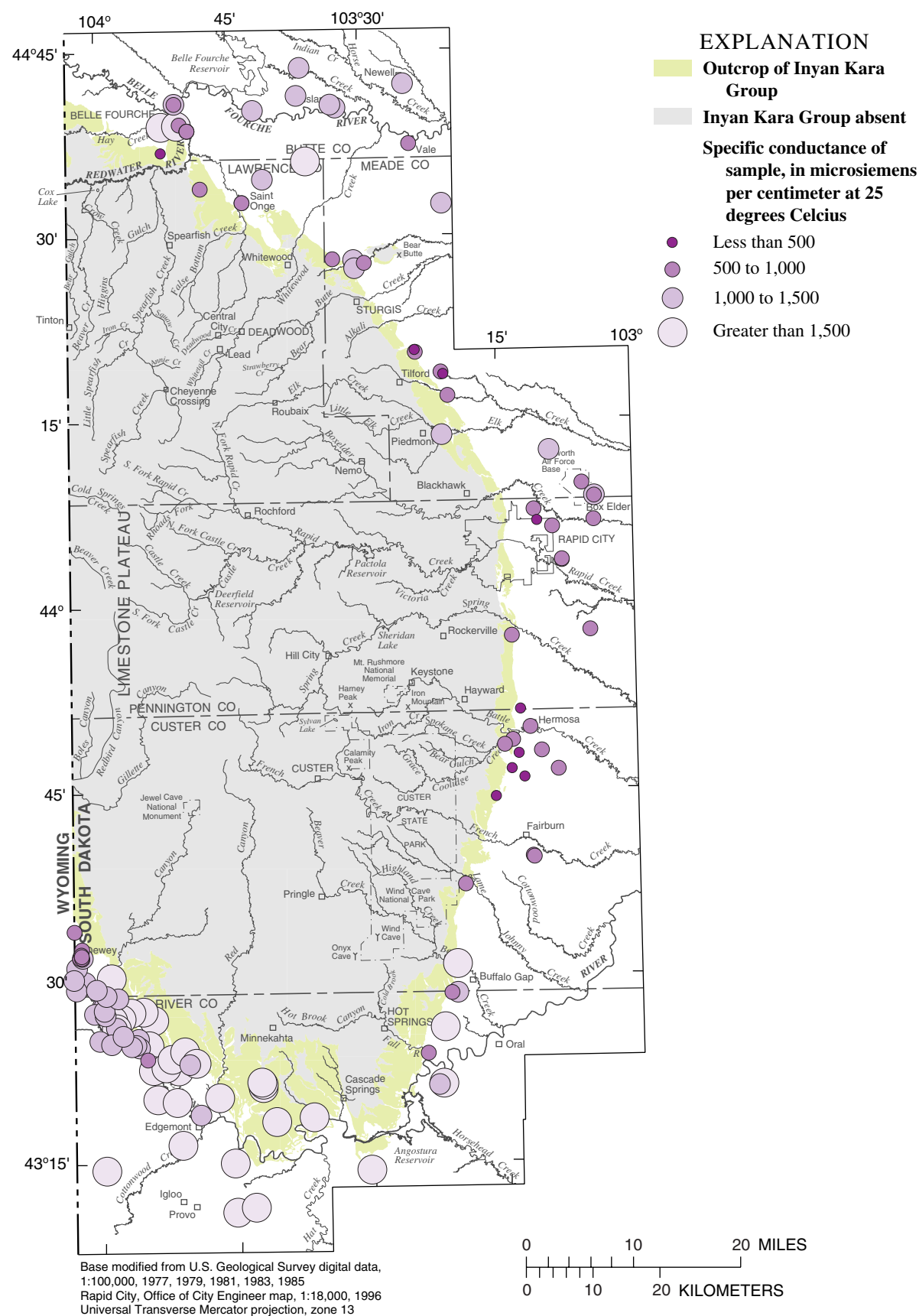


Figure 74. Specific conductance in the Inyan Kara aquifer (modified from Williamson and Carter, 2001).

1,000 and 3,000 mg/L) at distance from the outcrops, especially in the southern Black Hills. The water in these aquifers generally is highly mineralized outside of the study area, as previously described and shown in figure 45 for aquifers in the Paleozoic units.

Many of the major aquifers yield a calcium bicarbonate type water in and near outcrop areas, with increasing concentrations of sodium, chloride, and sulfate with distance from the outcrop. High concentrations of sodium, chloride, and sulfate occur in the Madison aquifer in the southwestern part of the study area relative to the rest of the study area. These high concentrations could be due to long residence times, long flowpaths

associated with regional flow from the west (Wyoming), or greater amounts of evaporite minerals, such as anhydrite and gypsum, available for dissolution (Naus and others, 2001). In the southern part of the study area, water in the Minnelusa aquifer also is characterized by higher concentrations of sodium and chloride. The high chloride concentrations in this area could reflect hydraulic connection between the Madison and Minnelusa aquifers (Naus and others, 2001). The dissolution of **evaporite minerals** composed of salt (such as **halite**), and long residence time also are possible explanations for the occurrence of this water type in the Minnelusa aquifer (Naus and others, 2001).

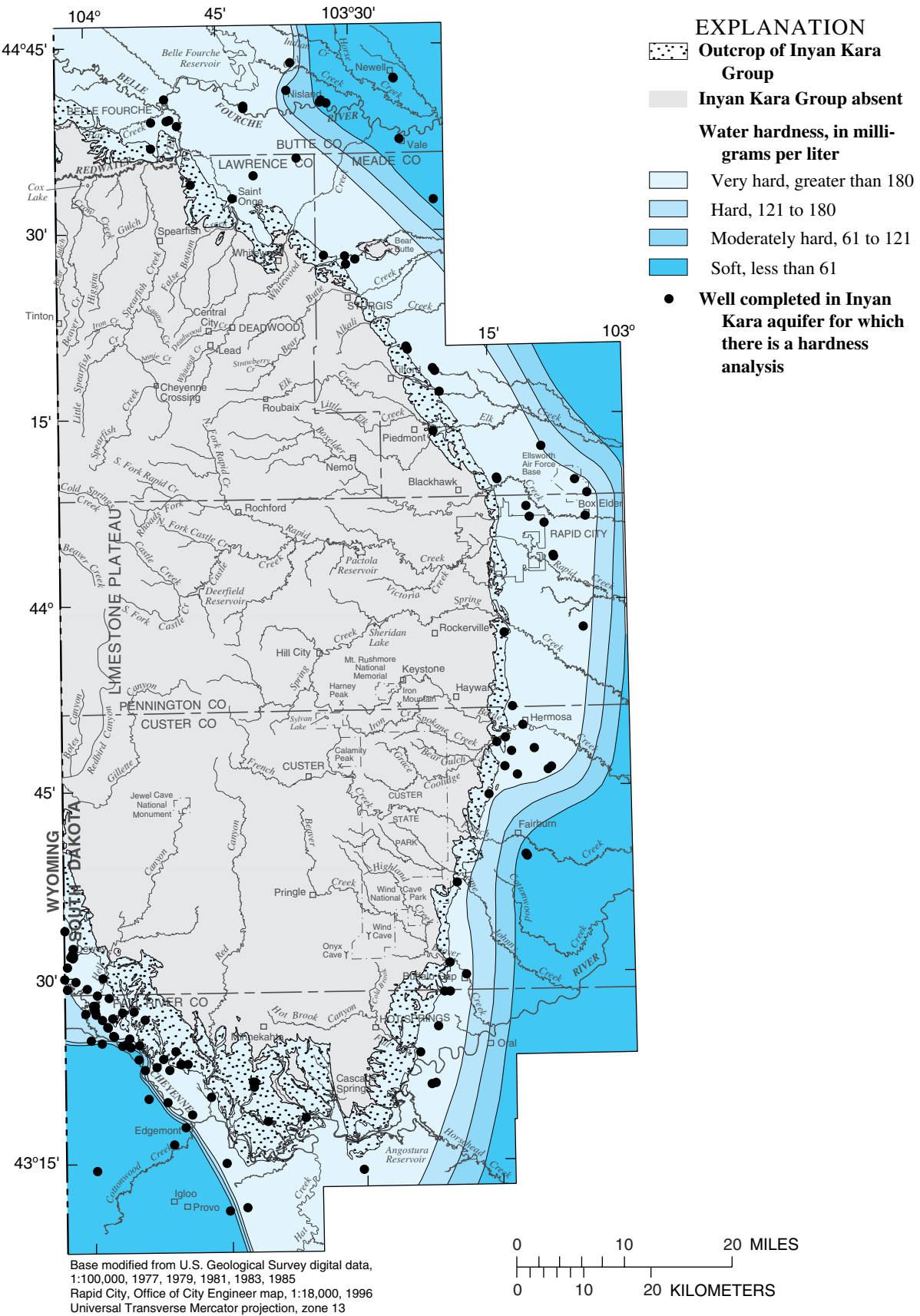


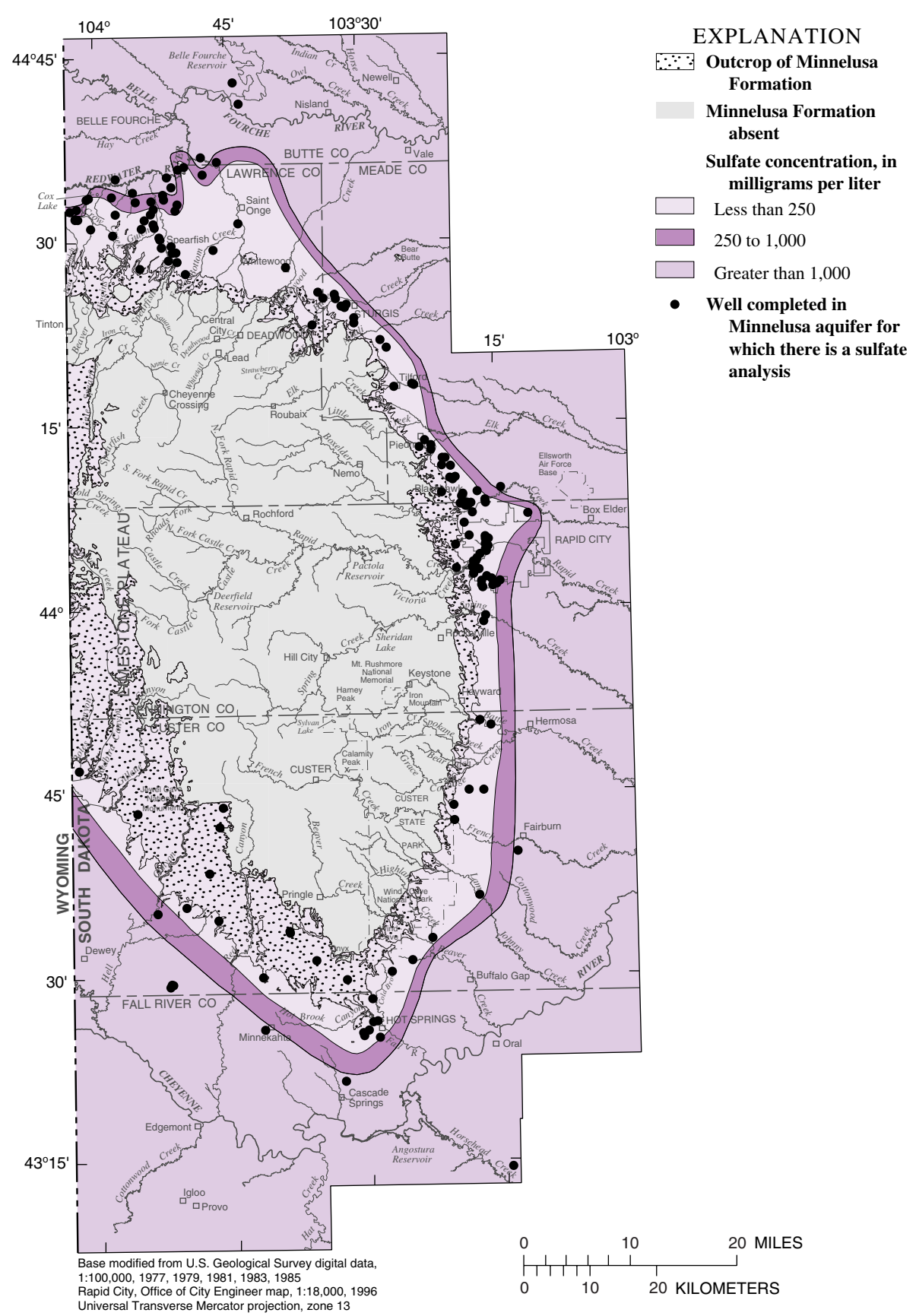
Figure 75. Hardness in the Inyan Kara aquifer (modified from Williamson and Carter, 2001).

The Inyan Kara aquifer may yield soft water, with hardness decreasing with increasing distance from the outcrop.

Sulfate affects the taste of water. 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 surrounds the core of the Black Hills. This transition zone is the area within which the sulfate concentrations range from 250 to 1,000 mg/L (fig. 76) 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).

Concentrations and variability of many trace elements are small in the major aquifers. Strontium generally is higher in concentration than other trace elements, but is not harmful. Similarly, barium, boron, iron, manganese, lithium, and zinc concentrations also may be high in comparison to other trace elements.

Because several radionuclides are known to cause various types of cancer, drinking-water standards (table 6) exist for these radionuclides. Most naturally occurring radionuclides in water are the result of **radioactive decay** of uranium and thorium. 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.



Sulfate concentrations in the Minnelusa aquifer are dependent on the amount of anhydrite present in the Minnelusa Formation. A transition zone marks an area of active removal of anhydrite by dissolution, downgradient of which dissolved sulfate concentrations generally exceed 1,000 milligrams per liter.

Figure 76. Sulfate concentrations in the Minnelusa aquifer (modified from Naus and others, 2001).

Water in many of the minor aquifers can be very hard and high in dissolved solids concentrations. High sulfate concentrations also are common in the minor aquifers.

General Characteristics for Minor Aquifers

Water-quality characteristics were summarized by Williamson and Carter (2001) for various minor aquifers. The minor aquifers in the study area include the Newcastle aquifer (known as the Dakota aquifer in eastern South Dakota) and alluvial aquifers. Local aquifers exist in the various semiconfining and confining units. Water-quality data also were summarized for several of these local aquifers, which included the Spearfish, Sundance, Morrison, Graneros, and Pierre aquifers.

Water in many of the minor aquifers can be very hard 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. A variety of water types can occur within and among the minor aquifers. In general, the dominance of sodium and sulfate increases with increasing amounts of shale present in the geologic units due to the large cation-exchange capabilities of clay

minerals (generally sodium concentrations increase) and due to the reduced circulation of water through the shale (Hem, 1985). The dominance of calcium, magnesium, and bicarbonate increases with increasing amounts of sandstone (where calcium bicarbonate commonly is the cementing material) and carbonate rocks present in the geologic units. The Sundance aquifer has the highest selenium concentrations of all aquifers considered in this report.

Concentrations of common ions 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. Wells completed in alluvial deposits that do not overlie Cretaceous shales generally yield fresh water with a calcium bicarbonate or calcium magnesium bicarbonate type. Wells that are completed in alluvial deposits that overlie the Cretaceous shales generally yield slightly saline water with a mixed type or a type in which sodium and/or sulfate is dominant. Samples from alluvial aquifers may be high in uranium concentrations, especially in the southern Black Hills. About 17 percent of the samples from alluvial aquifers exceeded the MCL for uranium, and all samples exceeding this MCL were from the southern Black Hills.

Wells completed in alluvial deposits generally yield fresh water where they do not overlie shales and generally yield slightly saline water dominated by sodium and sulfate where they overlie shales.

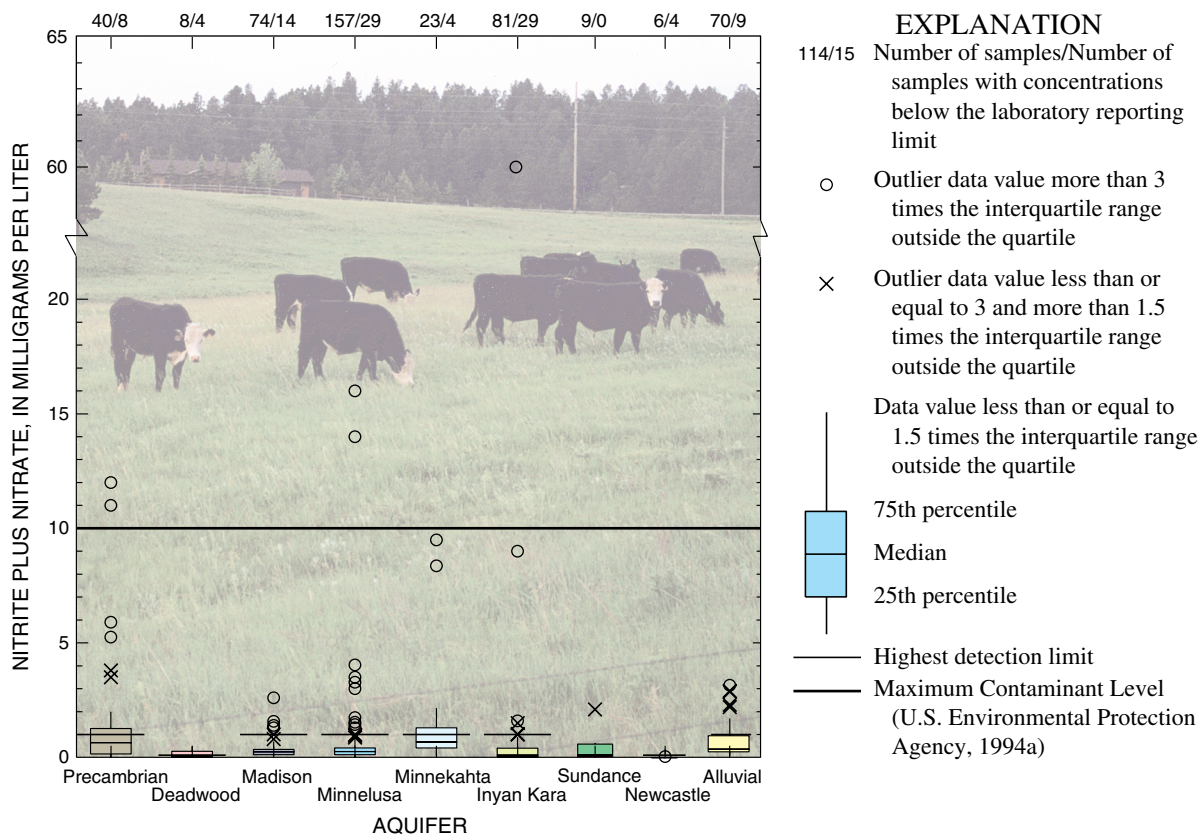


Figure 78. Concentrations of nitrite plus nitrate for selected aquifers (modified from Williamson and Carter, 2001).

Susceptibility to Contamination

The Black Hills Hydrology Study focused primarily on determination of natural water-quality characteristics, and investigation of contamination potential was not an objective of the study. The susceptibility of the aquifers to contamination in the study area is an important issue, however, and can be addressed to some extent.

Nitrite plus nitrate concentrations for various aquifers (fig. 78) can provide a general indication of possible human influence. Although nitrogen is essential for plant growth, high concentrations of nitrite plus nitrate can cause excessive plant growth and can be harmful to livestock and humans. Excessive concentrations of nitrite plus nitrate in drinking water are a health concern for pregnant women, children, and the elderly (may cause methemoglobinemia (blue-baby syndrome) in children). Nitrite plus nitrate in ground water can originate from natural processes or as potential contamination from nitrogen sources, such as fertilizers and sewage, on the land surface or in the soil zone (fig. 79). Nitrite plus nitrate concentrations in most ground-water samples in the Black Hills area generally are

low (fig. 78); however, samples approaching or exceeding the national nitrate background concentration of 2.0 mg/L (U.S. Geological Survey, 1999) may provide indications of possible human influence in a variety of land-use settings. The extreme values for nitrite plus nitrate in figure 78 are unusually high and may reflect poor well construction and surface contamination as opposed to aquifer conditions.

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).

Maps showing sensitivity of ground water to contamination were produced by Putnam (2000) for Lawrence County and by Davis and others (1994) for the Rapid Creek Basin. The most sensitive hydrogeologic units are limestones, unconsolidated sands

and gravels, and sandstones (Putnam, 2000). The least sensitive units include shales or units with interbedded shales. The Madison, Minnelusa, and Minnekahta aquifers are especially sensitive to contamination because of high secondary permeability and potential for streamflow recharge.

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.

Figure 79. Nitrite plus nitrate in ground water can originate from natural processes or as potential contamination from nitrogen sources. Nitrite plus nitrate can leach into the ground water from natural soil organic material or from nitrogen-fixing plants such as alfalfa (A). Contamination can result from both animal (B) and human waste, including wastewater-treatment plant effluent and that from septic tanks. Routine maintenance and pumping of septic tanks (E) can greatly reduce the potential for contamination from these potential sources. Agricultural and urban uses of fertilizer (D) also can contribute to nitrite plus nitrate in ground water. In drinking water (C), excessive concentrations of nitrite plus nitrate may cause methemoglobinemia (blue-baby syndrome) in children.

Nitrite plus nitrate concentrations in most ground-water samples in the Black Hills area generally are low; however, samples approaching or exceeding 2.0 milligrams per liter may provide indications of possible human influence in a variety of land-use settings.



In the Madison and Minnelusa aquifers, high concentrations of iron and manganese are the principal deterrents to water use. High concentrations of dissolved solids and sulfate in water from deep wells (greater than 1,000 to 2,000 feet) also may hamper use.

High concentrations of radium-226 and uranium in water from the Inyan Kara aquifer may preclude its use, primarily in the southern Black Hills.

Streamflow variability is highly influenced by geology, with distinctive characteristics identifiable for each of the five hydro-geologic settings in the Black Hills area.

Ground-Water Quality Relative to Water Use

Concentrations exceeding SMCL’s and MCL’s affect the use of water in some areas for many aquifers within the study area. Most concentrations exceeding standards are for various SMCL’s 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 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.

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 deter 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.

The principal properties or constituents in water from the Minnelusa aquifer that may hamper its use include hardness and high concentrations of iron and manganese. 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 revised MCL of 10 µg/L in some locations. Only a few samples exceeded the MCL’s for various radionuclides.

Samples from the Minnekahta aquifer are available only from shallow wells near the outcrop. Water from the Minnekahta aquifer is harder than that from any of the other major aquifers in the study area, and may require special treatment for certain uses. Water generally is suitable for all uses; few samples exceeded SMCL’s, and no samples available for this study from the Minnekahta aquifer exceeded drinking-water standards for any 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. Selenium concentrations in some places are an additional deterrent to the use of water from the Sundance aquifer. 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, but may not be in specific instances 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 shales. In the southern Black Hills, uranium concentrations in alluvial aquifers can be high in many locations.

The use of water from the minor aquifers may be hampered by hardness and concentrations of dissolved solids and sulfate.

Surface-Water Resources

The surface-water resources of the Black Hills area are summarized in this section of the report. Descriptions of streamflow characteristics and water-quality characteristics are included.

Streamflow Characteristics

Streamflow characteristics in the Black Hills area are influenced by geologic and climatic conditions. Streamflow variability is distinctly influenced by geologic conditions and yield characteristics are primarily influenced by climatic conditions, as described in the following sections of the report. More detailed discussions of this subject matter were presented by Miller and Driscoll (1998) and by Driscoll and Carter (2001).

Streamflow Variability

Streamflow variability is highly influenced by the hydrogeologic settings shown in figure 34 (presented in a previous section of the report describing the local hydrologic framework for surface water). Each of the five hydrogeologic settings in the Black Hills area have distinctive characteristics relative to variability of streamflow, as summarized in this section of the report.

Duration curves are presented in figure 80 that show variability in daily mean streamflow for streamflow-gaging stations representative of the five hydrogeologic settings. The duration curves show the percentage of time that a given flow is equalled or exceeded, with an example provided for the loss zone basins. Two graphs are provided for the crystalline core setting because of the large number of basins representative of this setting. Locations of representative streamflow-gaging stations are shown in figure 34 and generally include only streams where flow conditions are representative of natural conditions within a single hydrogeologic setting. For example, Rapid Creek is

excluded because flows are regulated by Deerfield and Pactola Reservoirs.

The duration curves (fig. 80) indicate that variability in daily flow is much smaller for the limestone headwater basins and the artesian spring basins than for any of the other settings. Flow variability for both of these settings is small because flow generally is dominated by ground-water discharge (springflow), with relatively small influence from direct runoff. The smallest variability in daily flow is at Cox Lake (station 06430540), where flow originates from an artesian spring within an extremely small (0.07 square mile) drainage basin. For this gaging station, measured daily flow during the period of record has been between 4 and 5 cubic feet per second almost 100 percent of the time. Among the limestone headwater basins, the smallest variability in flow is for Rhoads Fork (station 06408700), where measured daily flow has ranged almost exclusively between 3 and 10 cubic feet per second. Measured daily flows vary by less than an order of magnitude (factor of 10) for many streams in these settings.

Variability in daily flow is small for the limestone headwater and artesian spring basins because of dominance by ground-water discharge (springflow), which originates primarily from the Madison and Minnelusa aquifers. Measured daily flows vary by less than an order of magnitude for many streams in these settings.

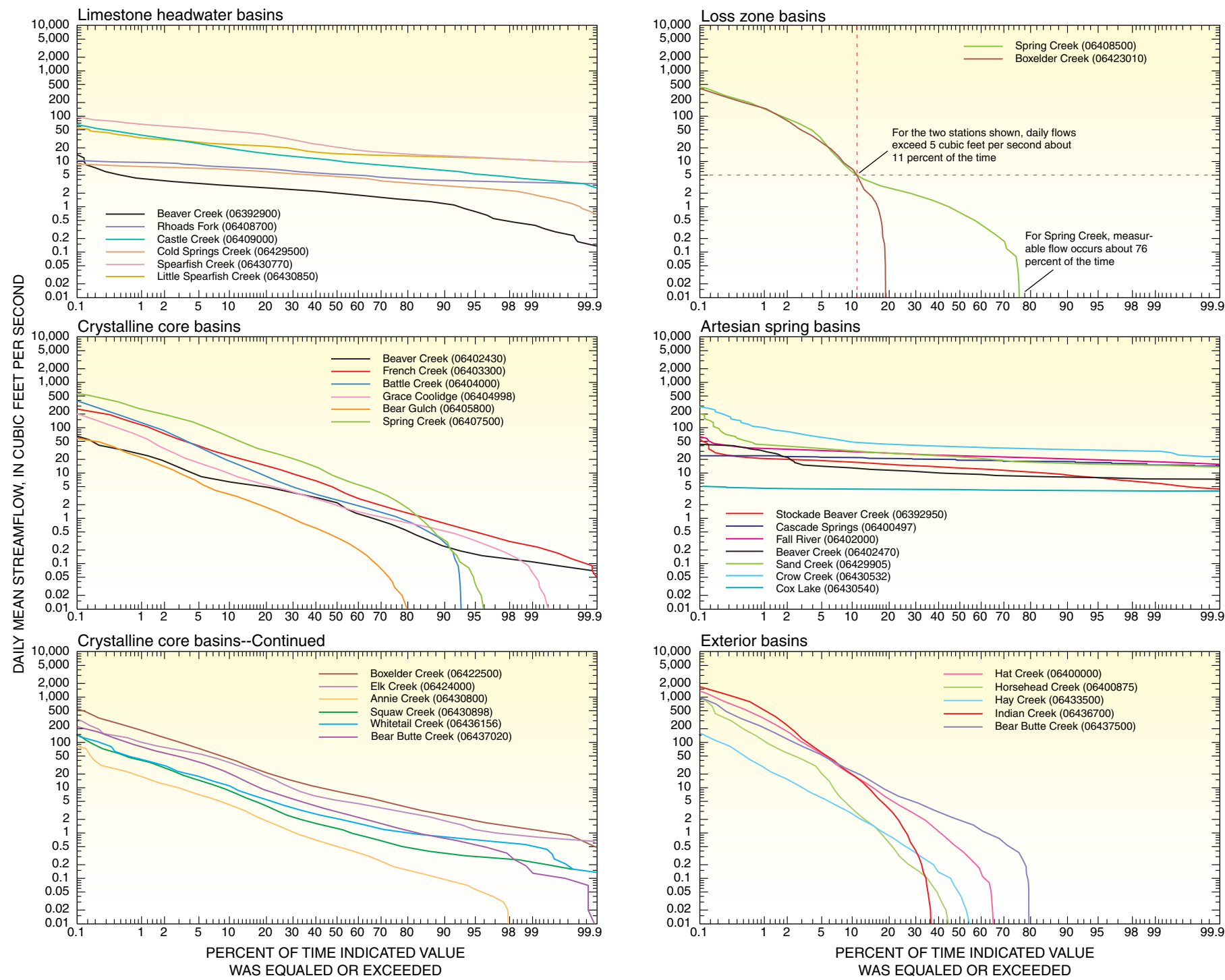


Figure 80. Duration curves of daily mean streamflow. An example showing the use of duration curves is provided for the loss zone basins. Locations of streamflow-gaging stations are shown in figure 34.

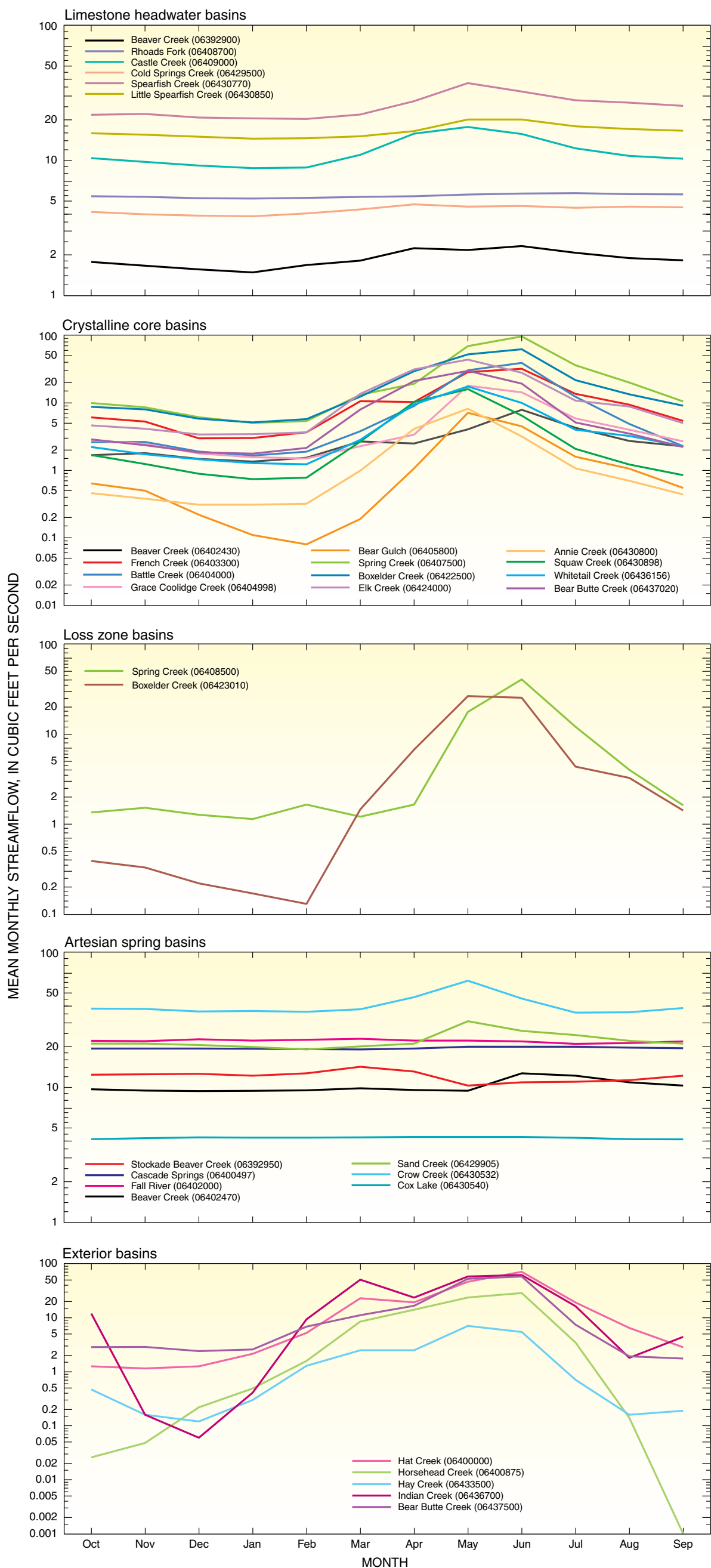


Figure 81. Mean monthly streamflow for basins representative of hydrogeologic settings. Locations of streamflow-gaging stations are shown in figure 34.

Flow variability is large for the loss zone basins (fig. 80), where zero-flow conditions are common because of the streamflow losses that occur where streams cross outcrops of the Madison Limestone and Minnelusa Formation. The example provided for the loss zone basins shows that daily flow at both gaging stations has exceeded 5 cubic feet per second only about 11 percent of the time. For Boxelder Creek, measurable flow occurs less than 20 percent of the time. Small springs within the alluvial deposits along Spring Creek maintain small but measurable streamflow about 76 percent of the time.

Flow variability is largest for the exterior basins (fig. 80), with daily flows varying by at least four orders of magnitude for all of the representative basins. Zero-flow conditions also are common for this setting. These characteristics indicate that streamflow for exterior basins is dominated primarily by direct runoff, with only minor influence from ground-water discharge.

Flow variability also is large for the crystalline core setting, where high-flow conditions commonly result from direct runoff. Low-flow conditions are common because ground-water discharge is small and tends to diminish rather quickly during periods of dry climatic conditions. Zero-flow conditions are relatively uncommon, however. Large topographic relief in this setting provides a mechanism for relatively rapid movement of shallow ground water to stream channels.

Zero-flow conditions are common for the loss zone setting because of streamflow losses that provide recharge to the Madison and Minnelusa aquifers. An example showing the use of daily duration curves is shown for this setting in figure 80.

Graphs showing variability in mean monthly streamflow for the five hydrogeologic settings are presented in figure 81. The limestone headwater and artesian spring basins, which are dominated by groundwater discharge, have only minor variability in mean monthly flow. Larger variability is apparent for the other settings because of larger influence from direct runoff that generally occurs during spring and summer when the largest precipitation amounts typically occur. For many basins, the smallest streamflow commonly occurs during winter months, when precipitation is small and may be stored as snowpack. Snowmelt in the exterior basins typically occurs earlier than in other settings because of lower altitudes.

Annual Yield Characteristics

The spatial distribution of average annual yield for selected drainage basins is shown in figure 82. Average annual **basin yield** is expressed in inches, which is obtained by dividing average annual flow by drainage area. Adjusting for the size of drainage areas allows direct comparison of yields between basins. Basin yields are highly influenced by climatic conditions, with the largest yields generally occurring in the highest altitudes of the northern Black Hills. These areas generally have the largest precipitation amounts (fig. 10) and also have smaller evapotranspiration rates, primarily because of lower temperatures.

Flow variability is large for the crystalline core and exterior basins, with daily flows typically spanning several orders of magnitude for most streams. High flows can result from heavy rainfall or snowmelt; however, low- and zero-flow conditions can develop quickly during dry periods.

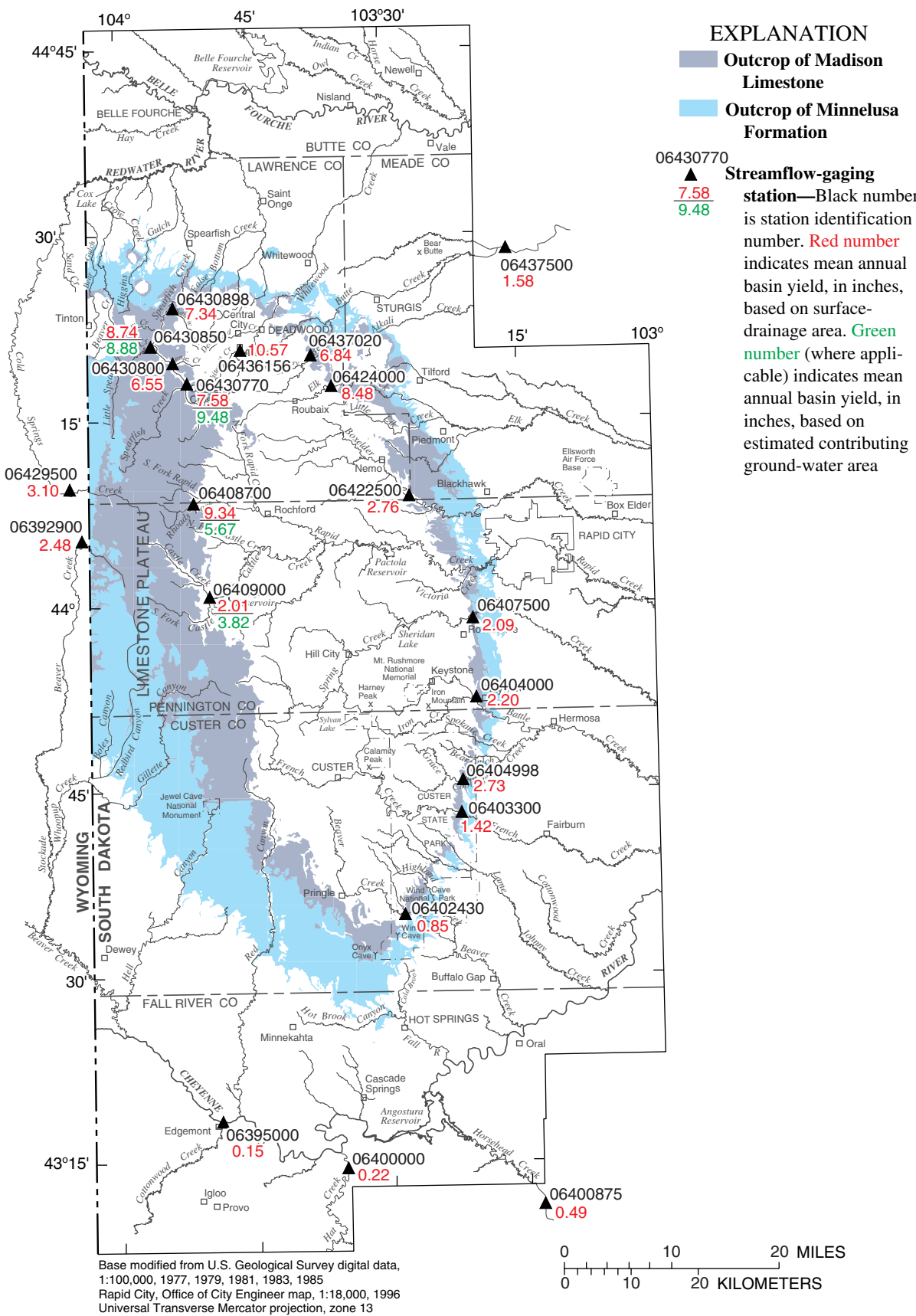


Figure 82. Basin yields for selected streamflow-gaging stations. For some stations, basin yields that are based on contributing ground-water areas estimated by Jarrell (2000a) also are shown. Basin yields are for periods of record, which are not the same for all stations.

In the Limestone Plateau area, ground-water flow directions are strongly influenced by confining units underlying the Madison aquifer. Thus, contributing ground-water areas for headwater springs do not coincide with surface drainages.

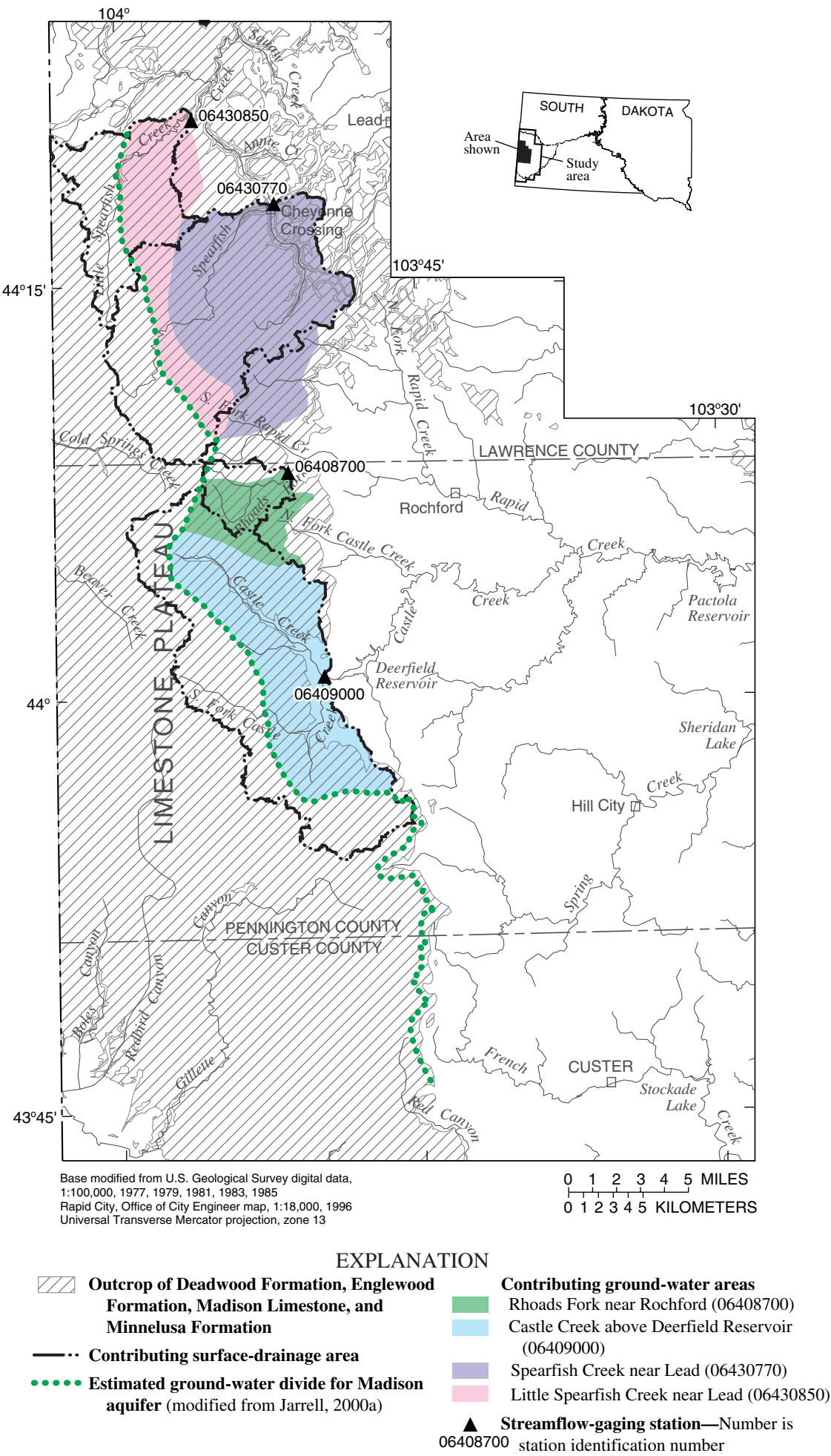


Figure 83. Comparison between surface-drainage areas and contributing ground-water areas for streamflow-gaging stations in Limestone Plateau area (modified from Jarrell, 2000a). Streamflow in the basins shown generally is dominated by ground-water discharge of headwater springs. Recharge occurring in areas west of the ground-water divide does not contribute to headwater springflow east of the divide.

Calculated yields for basins dominated by ground-water discharge are not necessarily representative of actual yield because the contributing ground-water areas are not necessarily congruent with surface drainages. Six of the streamflow-gaging stations shown in figure 82 are representative of the limestone headwater setting and are heavily influenced by ground-water discharge. Four of these gaging stations are located in South Dakota, and contributing ground-water areas were identified by Jarrell (2000a), as shown in figure 83. For these gaging stations, yields that are based on estimated ground-water areas also are included in figure 82, along with the yields that are based on surface drainages. Contributing ground-water areas have not been identified for the two gaging stations located in Wyoming.

The approximate location of a ground-water divide that was identified by Jarrell (2000a) is shown in figure 83. This divide coincides with the western extent of the contributing ground-water areas for the four gaging stations that are shown. West of the ground-water divide, **infiltration** of precipitation results in ground-water recharge that is assumed to flow to the west, contributing to regional flowpaths in the Madison and Minnelusa aquifers that wrap around the northern or southern flanks of the uplift (fig. 45). East of the divide, recharge is assumed to contribute to headwater springflow along the eastern edge of the Limestone Plateau.

The ground-water divide extends about 10 miles south of the Castle Creek Basin and approximately coincides with the western extent of the Spring and French Creek surface drainages in this vicinity. The ground-water divide is not defined south of this point because the surface drainages contribute to Red Canyon, which flows to the south and provides streamflow recharge to the Madison and Minnelusa aquifers along the western flank of the uplift. Immediately northwest of the ground-water divide, the Madison and Minnelusa aquifers are absent because of Tertiary intrusive units; thus, westerly ground-water flow directions are not possible.

The contributing ground-water area for Rhoads Fork (station 06408700) includes areas to the south of the surface drainage (fig. 83), but does not include the northern part of the surface drainage. The contributing

ground-water area is slightly larger than the surface drainage; thus, the adjusted yield (fig. 82) for the contributing ground-water area (5.67 inches) is smaller than the yield based on the surface drainage (9.34 inches). For Castle Creek (station 06409000), the contributing ground-water area is smaller than the surface drainage, which results in a larger adjusted yield. The adjusted annual yields for these two basins are quite similar and are consistent with a general pattern of increasing yields in a northerly direction for the Black Hills area.

Contributing ground-water areas for the two basins along the northern part of the ground-water divide (fig. 83) also are much different than the surface drainages. Adjusted yields for these basins also are shown in figure 82 and are generally consistent with yields for other nearby basins. The calculated yield for Annie Creek (station 06430800) is somewhat lower than for other basins, which may result from consumptive water use for extensive mining operations within the basin (Carter, Driscoll, Hamade, and Jarrell, 2001).

The information summarized in this section of the report was used extensively by Driscoll and Carter (2001) in developing hydrologic budgets for the Black Hills area. As previously discussed, adjusted yields for limestone headwater basins dominated by ground-water discharge are similar to yields for streams dominated by surface influences. This similarity was used by Carter, Driscoll, and Hamade (2001) in developing a method for estimating precipitation recharge for the Madison and Minnelusa aquifers. An important initial assumption was that in areas of comparable precipitation, evapotranspiration for outcrops of the Madison Limestone and Minnelusa Formation is similar to evapotranspiration for crystalline core settings, where recharge to regional flow systems is considered negligible. A further assumption was made that streamflow originating from direct runoff is negligible for Madison and Minnelusa outcrops, which is supported by the daily flow characteristics for gaging stations representative of the limestone headwater setting. These assumptions resulted in a concept that precipitation recharge to the Madison and Minnelusa aquifers can be approximated by streamflow in the crystalline core setting. This concept is schematically illustrated in figure 84.

Recharge to regional flow systems is considered negligible in the crystalline core setting of the central Black Hills. Direct runoff (streamflow) is very uncommon in outcrops of the Madison Limestone and Minnelusa Formation. Thus, evapotranspiration rates are assumed to be similar in areas of comparable precipitation, and annual streamflow within the crystalline core setting is assumed to approximate precipitation recharge to the Madison and Minnelusa aquifers.

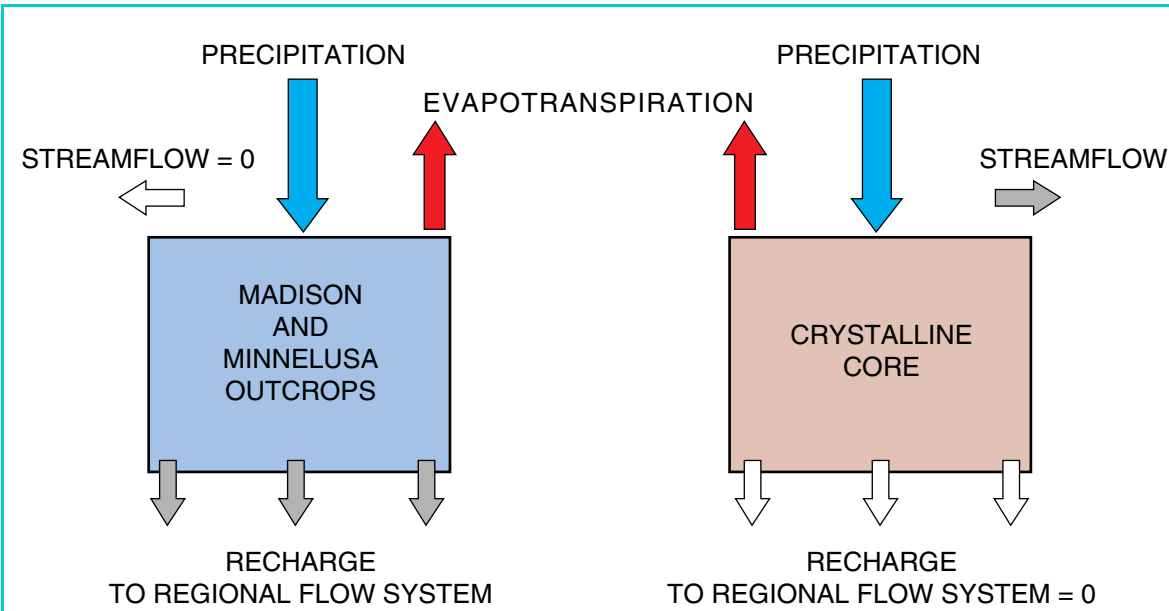


Figure 84. Schematic diagram illustrating recharge and streamflow characteristics for selected outcrop types (modified from Carter, Driscoll, and Hamade, 2001).

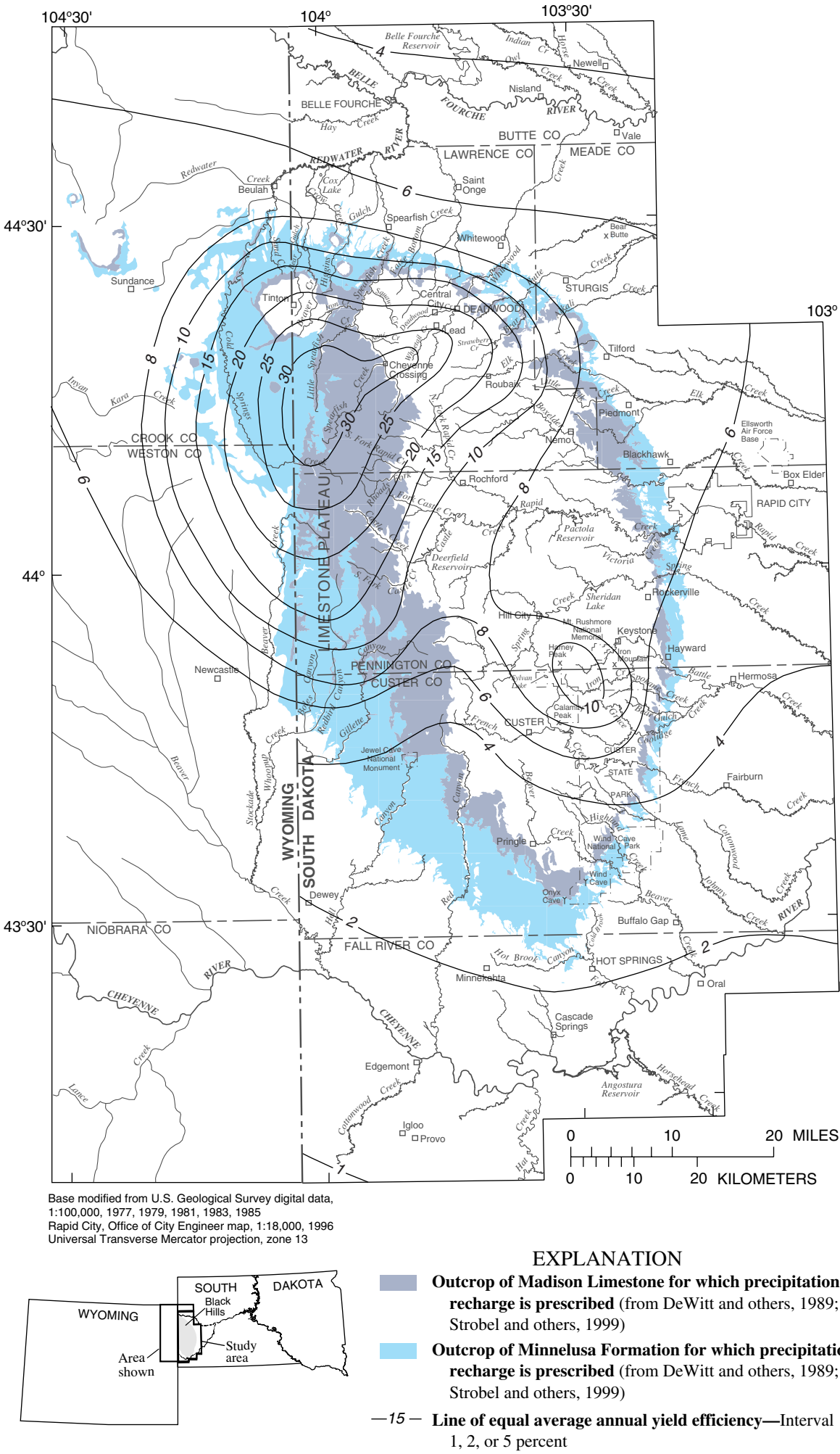


Figure 85. Generalized average annual yield efficiency, water years 1950-98 (from Carter, Driscoll, and Hamade, 2001). Yield efficiency represents the percentage of annual precipitation that becomes streamflow or recharge.

The previous concepts were used by Carter, Driscoll, and Hamade (2001) in developing a map of generalized average **yield efficiency** for the Black Hills area (fig. 85). Yield efficiency is the ratio of annual yield to annual precipitation, expressed as a percent. Average yield efficiency can exceed 30 percent of annual precipitation in the higher altitudes of the Black Hills. In the southern part of the study area, average yield efficiency is less than 2 percent of annual precipitation.

These concepts were further used to develop a map of annual yield potential (fig. 86), which represents average annual yield (in inches) that is likely to occur in a given location. This yield generally occurs as streamflow for outcrop areas that are considered confining units, but may occur as recharge in aquifer outcrops. In some areas, yield potential may consist of a combination of aquifer recharge and streamflow. Average annual recharge from infiltration of precipitation on outcrops of the Madison Limestone and Minnelusa Formation, including outcrop areas in Wyoming, is shown as an example. Average yield potential is less than 1 inch per year in much of the southern part of the study area, but may exceed 8 inches per year in the higher altitudes of the northern Black Hills.

A “yield-efficiency algorithm” was developed by Carter, Driscoll, and Hamade (2001) for estimating annual recharge to the Madison and Minnelusa aquifers, based on yield-efficiency characteristics and annual precipitation. This **algorithm** (procedure) also was used by Driscoll and Carter (2001) for estimating recharge for other aquifers and for estimating basin yields for surface-water budgets. Results of these efforts are presented in a subsequent section of the report summarizing hydrologic budgets for the Black Hills area.

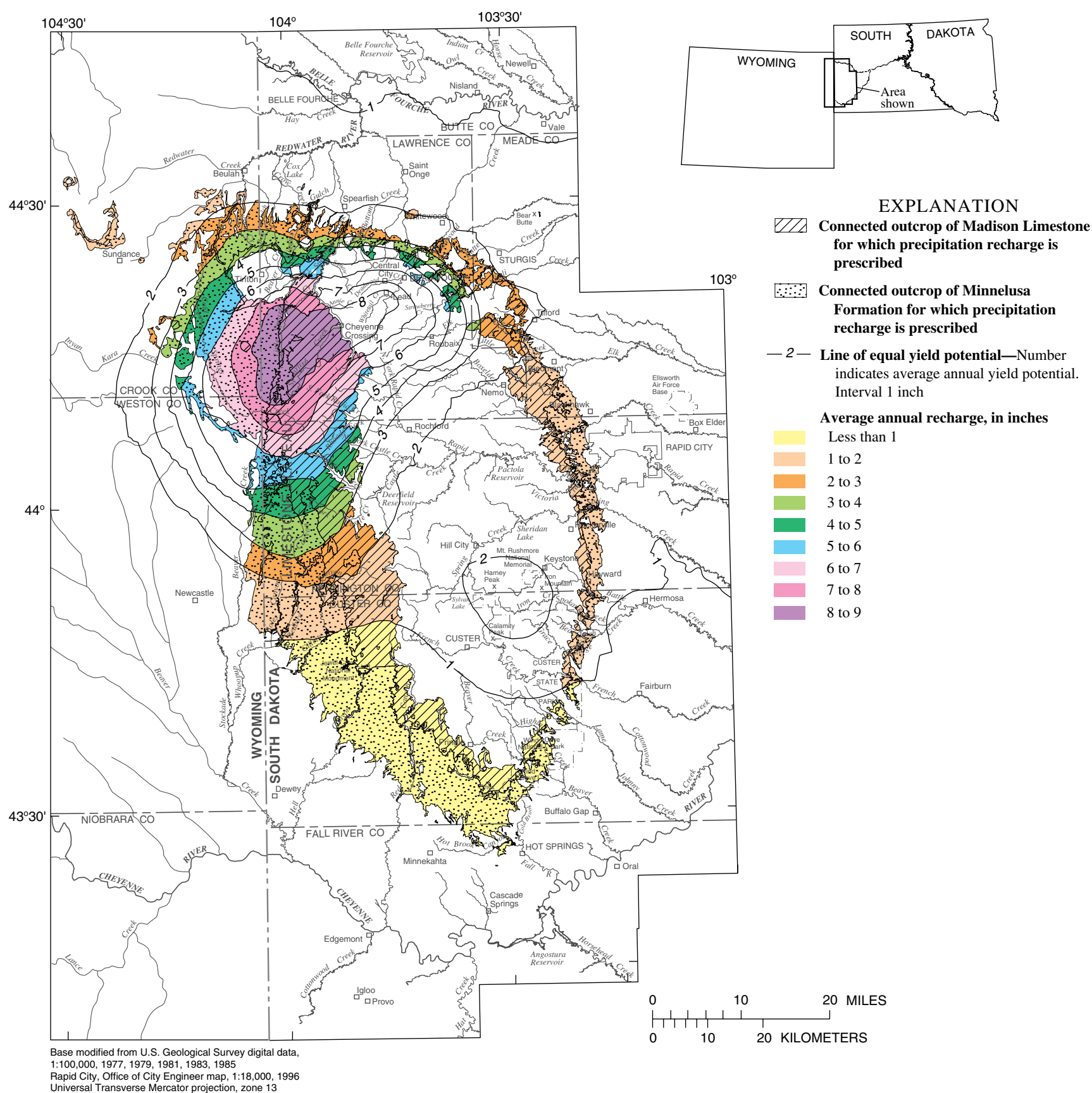


Figure 86. Estimated annual yield potential for the Black Hills area, water years 1950-98 (from Carter, Driscoll, and Hamade, 2001). Yield potential represents the average depth (in inches) of annual yield, which may occur as streamflow or recharge. Average annual recharge from precipitation on outcrops of the Madison Limestone and Minnelusa Formation is shown as an example.

Generalized maps of average annual yield efficiency (fig. 85) and yield potential (fig. 86) have been developed for the study area. In the southern Black Hills, average yield efficiency is less than 2 percent of annual precipitation, with corresponding yields of less than 1 inch per year. In the high altitudes of the northern Black Hills, yield efficiency can exceed 30 percent, with yields in excess of 8 inches per year.

Surface-Water Quality

This section of the report summarizes water-quality characteristics for surface water within the study area. More detailed discussions regarding surface-water quality in the Black Hills area are presented in Williamson and Carter (2001). Standards and criteria that apply to surface waters are presented in the following section of the report, after which general characteristics, human influences on water quality, and a summary of water quality relative to water use are discussed.

Standards and Criteria

The water quality of streams and lakes can be compared to a number of standards and criteria. In-stream standards and criteria consist of two basic categories: **beneficial-use criteria** and **aquatic-life criteria** (table 7). Each standard or criterion is established for specific reasons. In-stream water-quality standards are different from drinking-water standards because they apply to water prior to treatment for human consumption or to conditions for aquatic life such as plants, fish, and insects. Streams and lakes within the State of South Dakota have been assigned beneficial uses, which are based on considerations such as physical location and condition of a water body. These beneficial uses establish the minimum use for a water body that needs to be protected. For example, if a stream has a beneficial use of “cold-water permanent fisheries,” then an industry may not discharge to the stream in such a way that the temperature would exceed 65 degrees Fahrenheit (table 7).

All streams in South Dakota are designated for the beneficial uses of irrigation and of wildlife propagation and stock watering.

Additional beneficial uses are assigned to stream segments as applicable; other common designations in the Black Hills area include fish-life propagation waters and immersion recreation waters. Designated beneficial uses for specific stream segments are indicated by South Dakota Department of Environment and Natural Resources (2001a).

The highest beneficial-use designation is for domestic water supply. Several stream segments within the Black Hills that are used for public water supplies are designated for domestic water supply and include portions of Alkali Creek, Cold Brook Creek, Hot Brook Creek, Rapid Creek, and Spearfish Creek. The significance of selected physical properties and constituents and any related U.S. Environmental Protection Agency drinking-water standards were presented previously in table 6. The drinking-water standards apply to finished waters that are used for public consumption and, thus, do not apply directly to surface waters. These standards do provide another useful basis for comparison, however.

Aquatic-life criteria are estimates of the highest concentrations in surface water to which aquatic life can be exposed without adverse effects and are established to provide protection from either acute or chronic toxicity. The **acute criteria** are based on concentrations at which short-term exposures may cause adverse effects. The **chronic criteria** are based on concentrations that may cause adverse effects with longer term exposures. The acute criteria concentrations are higher than the chronic criteria concentrations. The aquatic-life criteria for several trace elements vary with stream hardness with toxicity generally decreasing as stream hardness increases.

Photograph by Joyce E. Williamson



Aquatic-life criteria are established to provide protection for fish and other aquatic life from either short-term exposure to high concentrations or long-term exposures to lower concentrations of constituents that may cause adverse effects.

Table 7. Surface-water-quality standards for selected physical properties and constituents

[All constituents in milligrams per liter unless otherwise noted. µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; °F, degrees Fahrenheit; °C, degrees Celsius; ≥, greater than or equal to; --, no data available]

Property or constituent	Beneficial-use criteria ¹										Aquatic-life criteria for fisheries ¹ (acute/chronic) (µg/L)
	Domestic water supply	Coldwater permanent fisheries	Coldwater marginal fisheries	Warm-water permanent fisheries	Warm-water semi-permanent fisheries	Warm-water marginal fisheries	Immersion waters	Limited contact waters	Wildlife propagation and stock-watering waters	Irrigation waters	
Specific conductance (µS/cm)	--	--	--	--	--	--	--	--	² 4,000/7,000	² 2,500/4,375	--
pH range (standard units)	6.5-9.0	6.6-8.6	6.5-8.8	6.5-9	6.5-9	6.5-9	--	--	6.0-9.5	--	--
Temperature °F/°C (maximum)	--	65/18.3	75/24	80/27	90/32	90/32	--	--	--	--	--
Dissolved oxygen (minimum)	--	≥6.0 ≥7 during spawning	≥5.0	≥5.0	≥5.0	≥4.0	≥5.0	≥5.0	--	--	--
Dissolved solids	² 1,000/1,750	--	--	--	--	--	--	--	² 2,500/4,375	--	--
Total suspended solids	--	² 30/53	² 90/158	² 90/158	² 90/158	² 150/263	--	--	--	--	--
Sodium-adsorption ratio	--	--	--	--	--	--	--	--	--	10	--
Chloride	² 250/438	² 100/175	--	--	--	--	--	--	--	--	--
Fluoride	4.0	--	--	--	--	--	--	--	--	--	--
Sulfate	² 500/875	--	--	--	--	--	--	--	--	--	--
Nitrate (as N)	10	--	--	--	--	--	--	--	² 50/88	--	--
Un-ionized ammonia (as N)	--	0.02	0.02	0.04	0.04	0.05	--	--	--	--	--
Cyanide (free)	--	--	--	--	--	--	--	--	--	--	22/5.2
Dissolved arsenic	--	--	--	--	--	--	--	--	--	--	360/190
Dissolved barium	1.0	--	--	--	--	--	--	--	--	--	--
Dissolved cadmium	--	--	--	--	--	--	--	--	--	--	³ 3.7/ ³ 1.0
Dissolved copper	--	--	--	--	--	--	--	--	--	--	³ 17/ ³ 11
Dissolved lead	--	--	--	--	--	--	--	--	--	--	³ 65/ ³ 2.5
Dissolved mercury	--	--	--	--	--	--	--	--	--	--	2.1/ ⁴ 0.012
Dissolved selenium	--	--	--	--	--	--	--	--	--	--	20/5
Dissolved zinc	--	--	--	--	--	--	---	--	--	--	³ 110/ ³ 100

¹South Dakota Department of Environment and Natural Resources, 2001a.
²30-day average/daily maximum.
³Hardness-dependent criteria; value given is an example based on hardness of 100 milligrams per liter as CaCO₃.
⁴Chronic criteria based on total recoverable concentration.

Dissolved solids concentrations and specific conductance are highest for sites representative of the exterior setting. The lowest concentrations tend to occur at sites representative of the crystalline core and limestone headwater settings.

General Characteristics

Surface-water quality in the study area is highly influenced by geology. Within this section of the report, selected sites (fig. 34) are used to characterize the geological influences based on the hydrogeologic settings (limestone headwater, crystalline core, artesian spring, and exterior settings) discussed previously. The loss zone setting is not characterized because the primary hydrologic influence is on streamflow, not water quality.

Concentrations of dissolved solids are important for applications such as consideration of beneficial-use criteria. Dissolved solids data are not always readily available; however, specific conductance can provide an excellent indication of dissolved solids concentrations in surface water (fig. 87). Because a relation exists between dissolved solids and specific conductance, specific conductance measurements (which are easily collected) can be used to estimate the dissolved solids within a stream.

The relation between dissolved solids and specific conductance generally varies from site to site and among hydrogeologic settings (fig. 87). Some sites, especially those representative of the limestone headwater and artesian spring settings, tend to have small variability in dissolved solids concentrations and specific conductance. Sites representative of the crystalline core and exterior settings tend to have more variability in dissolved solids concentrations and specific conductance than the other hydro-

geologic settings. Dissolved solids concentrations and specific conductance are highest for sites representative of the exterior setting. The lowest concentrations tend to occur at sites representative of the crystalline core and limestone headwater settings.

Water-quality variability also is influenced by streamflow, with specific conductance values (and dissolved solids concentrations) generally decreasing with increasing streamflow, primarily because of dilution by direct runoff. Figure 88 provides an example site from each hydrogeologic setting. Relations between streamflow and specific conductance are different for each of the example sites (fig. 88) because of the different geologic and streamflow characteristics. Cox Lake near Beulah (06430540, representative of the artesian spring setting) has small variability in both streamflow and specific conductance. This provides an indication that dissolved solids (and other constituent concentrations) at this site also would have low variability. Variability in specific conductance at Spearfish Creek near Lead (06430770, representative of the limestone headwater setting) also is small, which indicates generally low variability in constituent concentrations. Battle Creek near Keystone (06404000, representative of the crystalline core setting) and Cheyenne River at Edgemont (06395000, representative of the exterior setting) have large variability in both streamflow and specific conductance and generally would have more variability in constituent concentrations than sites representative of the other hydrogeologic settings.

Figure 89 presents a diagram of median ion concentrations for each hydrogeologic setting, which provides a way of comparing concentrations among the different settings. The common ion concentrations in water can

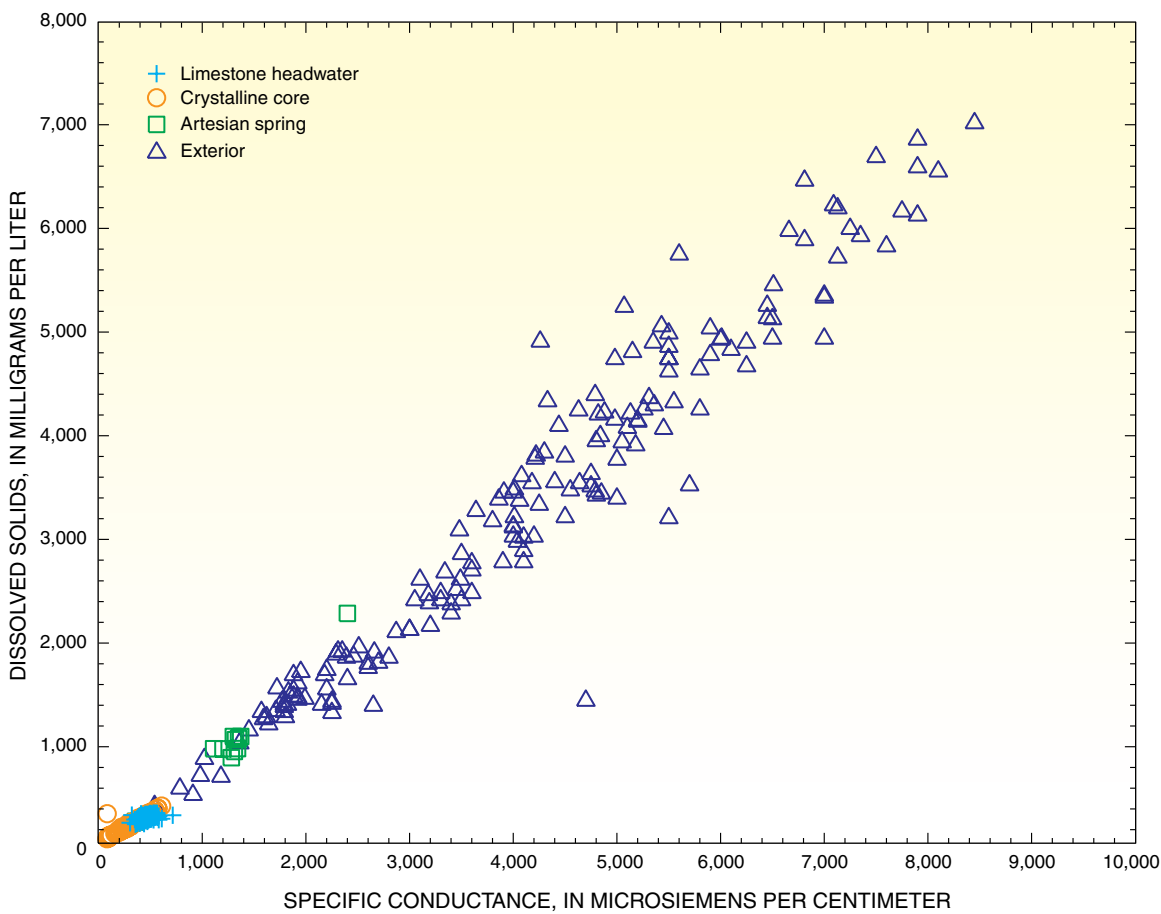


Figure 87. Relations between dissolved solids and specific conductance by hydrogeologic setting (modified from Williamson and Carter, 2001). Dissolved solids concentrations are highest among exterior sites and lowest among crystalline core sites. Specific conductance, which is relatively easy to measure, can provide estimates of the dissolved solids concentrations.

provide indications of water source as well as possible limitations to use, which is discussed later in this section of the report. The diagrams for the limestone headwater and crystalline core settings are very similar with low concentrations for most common ions; however, the median concentration of bicarbonate is slightly lower for the crystalline core setting.

Sulfate concentrations are notably higher for the artesian spring setting than for the limestone headwater and crystalline core settings. Most water discharged by artesian springs probably originates primarily from the Madison and/or Minnelusa aquifers (Naus and others, 2001). The high sulfate concentrations probably result from the dissolution of anhydrite in the Minnelusa Formation. Other potential sulfate sources may be exposure to shale confining units such as the Spearfish Formation. Several artesian springs with low sulfate concentrations are located upgradient from the anhydrite transition zone in the Minnelusa aquifer (fig. 76).

The diagram for the exterior setting (fig. 89) generally shows much higher sodium, chloride, magnesium, and sulfate concentrations than the diagrams for the other hydrogeologic settings. The higher sulfate and sodium concentrations for the exterior setting correspond to the much higher specific conductance and dissolved solids concentrations for this setting. Although no stream reaches within the exterior setting are classified for domestic water supply, most samples for exterior sites have dissolved solids concentrations that exceed the 30-day average and maximum criteria of 1,000 and 1,750 mg/L, respectively (table 7). The criteria for wildlife propagation and stock watering also are exceeded for many samples.

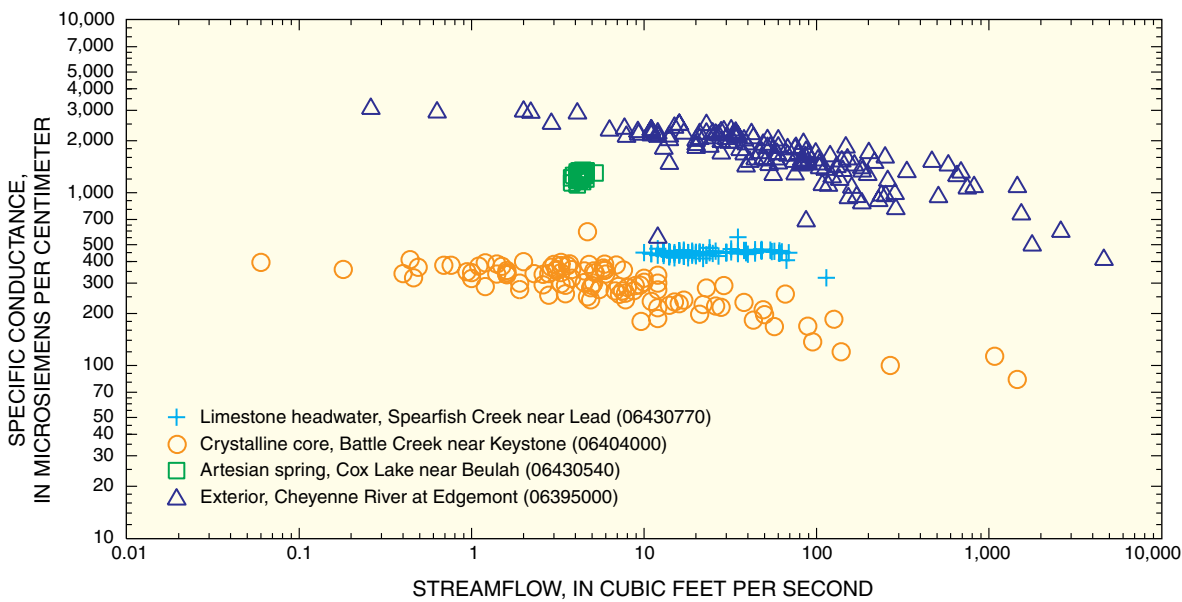


Figure 88. Relations between specific conductance and streamflow for a selected site within each hydrogeologic setting (modified from Williamson and Carter, 2001). Locations of sites are shown in figure 34.

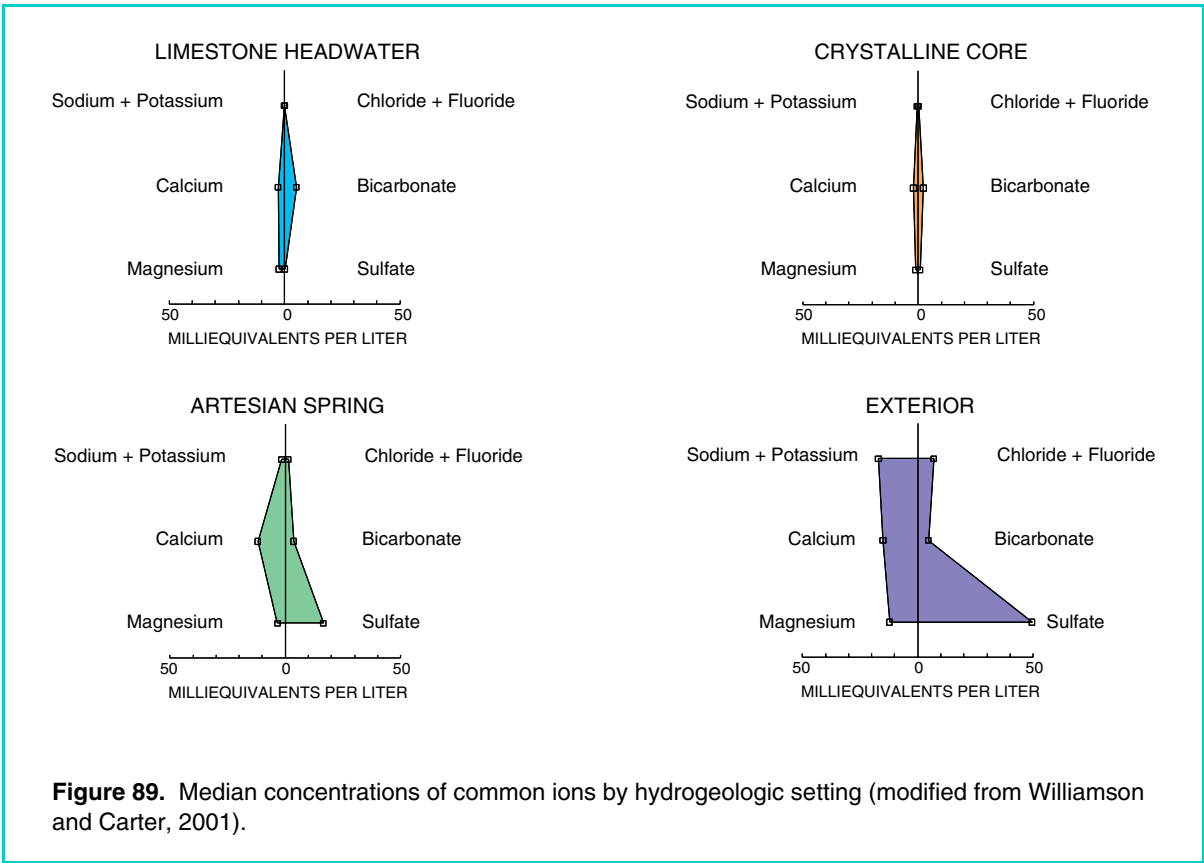


Figure 89. Median concentrations of common ions by hydrogeologic setting (modified from Williamson and Carter, 2001).

Samples from sites in the exterior setting generally have the highest sulfate concentrations of the hydrogeologic settings. Sulfate can affect the taste of water.

Figure 90 presents median sulfate concentrations for selected surface-water samples in the study area, including numerous sites in addition to those that are representative of the hydrogeologic settings. Sulfate concentrations throughout most of the study area generally are less than 330 mg/L, except in the exterior setting where concentrations commonly are much higher. Some streams that typically have high sulfate concentrations include the Belle Fourche River, Beaver Creek, Cheyenne River, Elk Creek, and Redwater River. The higher concentrations of sulfate generally are due to contact of streams with the Cretaceous shales within

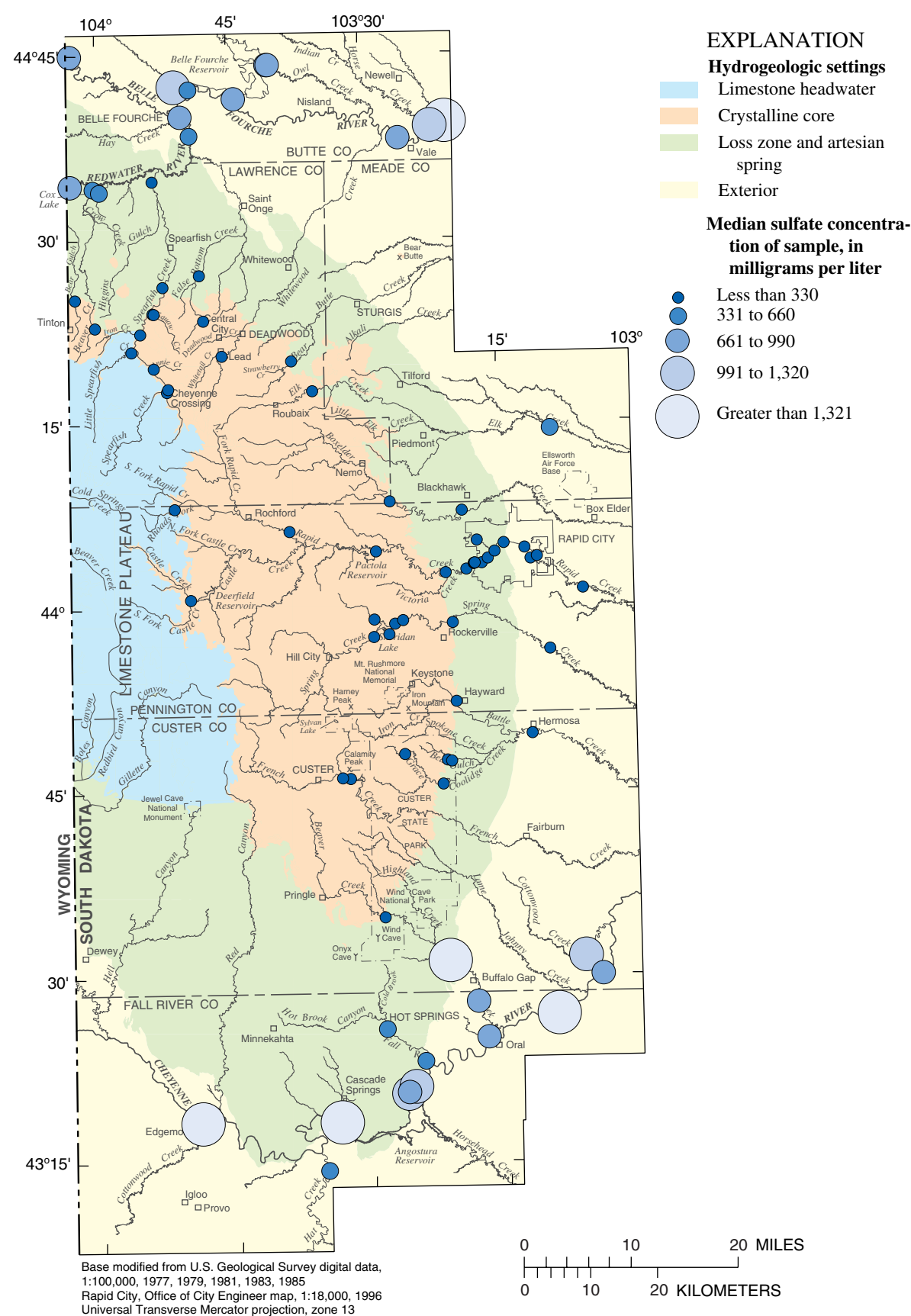


Figure 90. Median sulfate concentrations in surface water (modified from Williamson and Carter, 2001).

this area. Several streams such as Crow Creek and Fall River also have relatively high sulfate concentrations from influence of artesian springs.

Uranium is fairly common in locations within the outcrop of Inyan Kara Group, and uranium was historically mined in the southern Black Hills, especially near Edgemont. Figure 91 presents the median concentrations of uranium in surface water and shows that higher uranium concentrations occur downstream from the outcrop of the Inyan Kara Group relative to the rest of the study area.

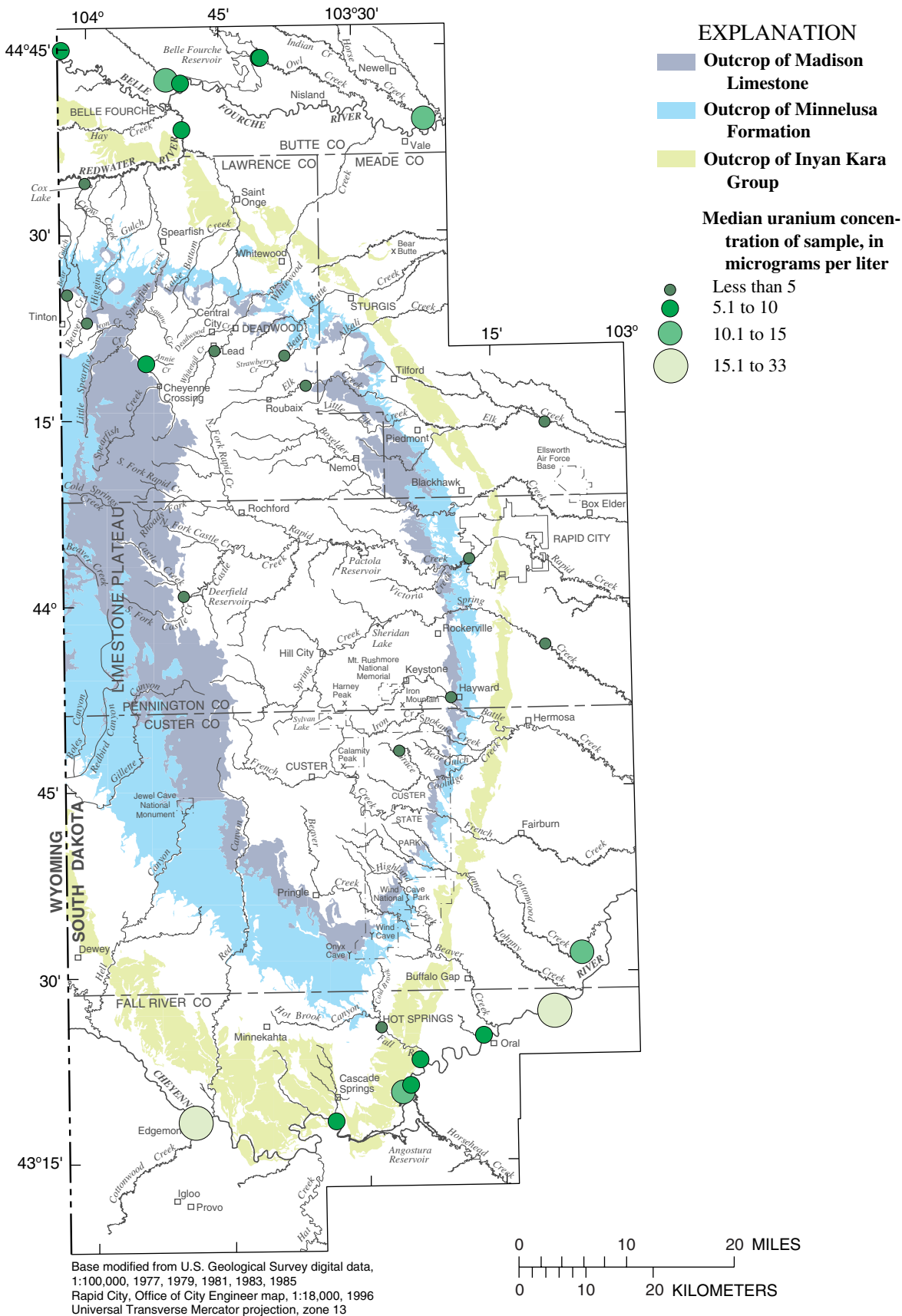


Figure 91. Median uranium concentrations in surface water (modified from Williamson and Carter, 2001).

The highest uranium concentrations in surface water in the Black Hills area generally occur downstream from the outcrop of the Inyan Kara Group. Uranium is a potential carcinogen and can be a chemical and radiological hazard.

Human Influences on Water Quality

The water quality of streams can be influenced by many human activities in the area including agriculture, mining, and urban/suburban development (fig. 92). Some of these influences can be quantified to a certain extent, whereas in other cases the impacts are difficult to separate from naturally occurring influences. Water-quality sampling for the Black Hills Hydrology Study was performed primarily for the purpose of identifying baseline water-quality conditions; extensive investigations to evaluate influences from human activities were not performed as part of the study. Much of the information summarized in this section of the report was obtained from results of site-specific studies by previous investigators. A detailed summary of previous investigations is provided in Williamson and Carter (2001).

Ranches and farms are common throughout the Black Hills and primarily are owned and operated as family businesses rather than large-scale corporate businesses. Irrigation is

common where sufficient water supplies exist. Several irrigation projects are located in the Black Hills area and include the Angostura Reclamation Unit south of Hot Springs, the Belle Fourche Reclamation Project west of Belle Fourche, and the Rapid Valley Water Conservancy District east of Rapid City.

Selenium has been a special concern of the National Irrigation Water Quality Program because of its toxicity and prevalence in irrigation areas in the western United States. Selenium can be transported in irrigation **return flows** at concentrations higher than would be expected under natural conditions. Selenium is abundant in the Cretaceous shales surrounding the Black Hills area (fig. 19), which is reflected in the maximum selenium concentrations measured at selected sites within the study area (fig. 93). Selenium concentrations below the laboratory reporting limit of 1 µg/L have been reported for numerous additional sites (not shown in fig. 93), most of which are located within the limestone headwater,

Photograph by Mark. A. Keenihan, South Dakota Department of Environment and Natural Resources



Photograph by Joyce E. Williamson



Figure 92. Water quality can be degraded by human activity including mining activity (upper photograph), agricultural practices (left photograph), and urban/suburban influences (lower photograph). How these activities are managed determines to a large extent the impact they potentially may have on surface-water quality.

Photograph by Joyce E. Williamson



crystalline core, or artesian spring settings. Studies to investigate selenium and other trace elements in irrigation areas were conducted during the late 1980's at the Angostura and Belle Fourche irrigation projects (Greene and others, 1990; Roddy and others, 1991). A follow-up study based on 1994 sampling concluded that selenium routinely occurs in concentrations that could be problematic, both upstream and downstream from both irrigation projects (Sando and others, 2001). High concentrations of selenium upstream from the irrigation projects reflect background concentrations; however, additional sediment might be contributed to the Belle Fourche River in return flows in Horse Creek.

Fertilizers and pesticides also can impact water quality. Regional studies have not determined that fertilizers or pesticides are major concerns in the Black Hills area (Greene and others, 1990; Roddy and others, 1991), although localized problems may exist.

Samples from sites along the Belle Fourche River and the Cheyenne River occasionally have exceeded the selenium aquatic-life chronic criterion of 5 micrograms per liter and the aquatic-life acute criterion of 20 micrograms per liter.

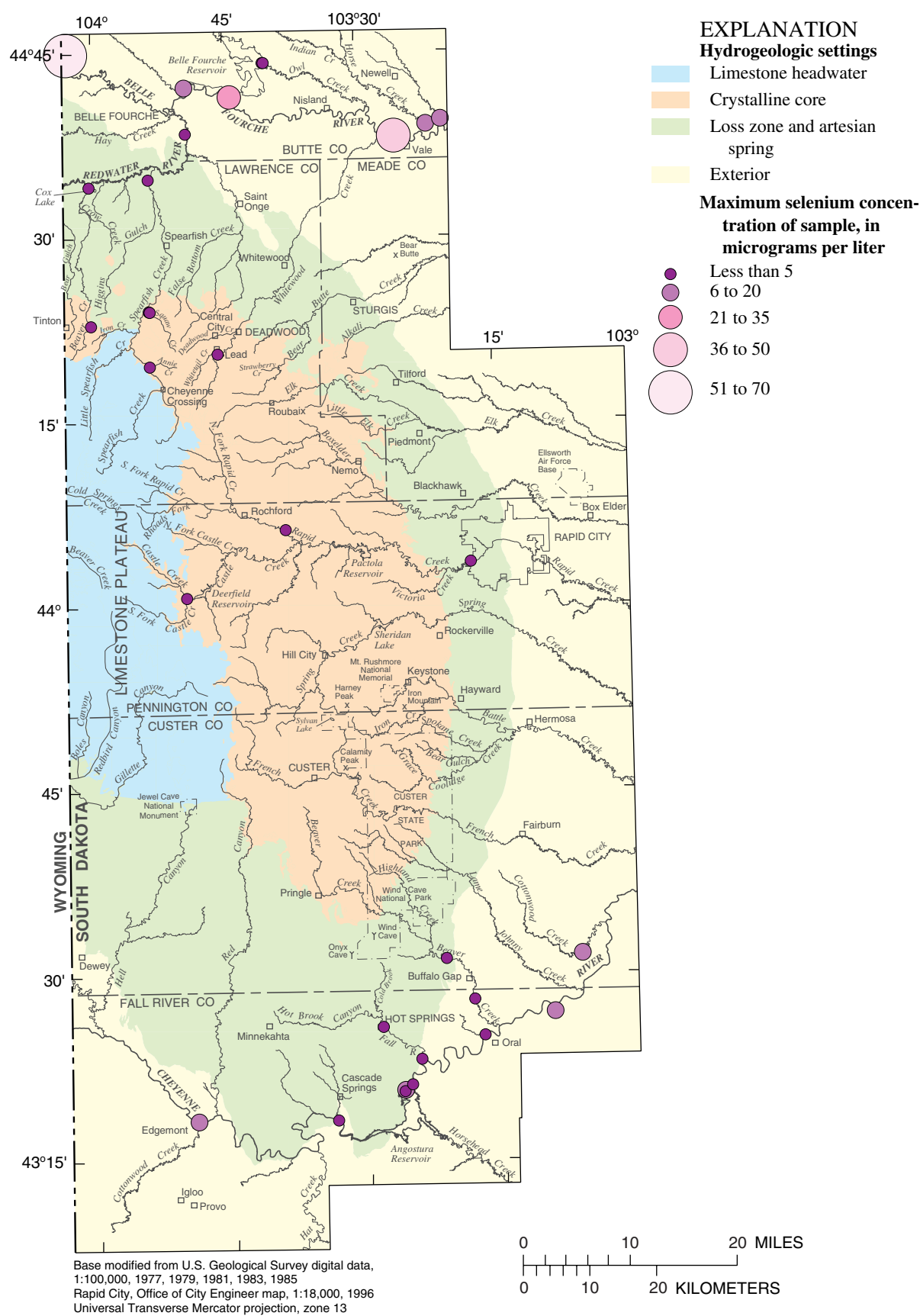


Figure 93. Maximum selenium concentrations in surface water (modified from Williamson and Carter, 2001). Many sites along the Belle Fourche River and Cheyenne River occasionally have exceeded aquatic criteria for selenium. Selenium is toxic to humans and animals.

Approximately 900 abandoned or inactive mines exist throughout the Black Hills. Efforts are underway by Federal, State, and private individuals and companies to remediate problematic sites.

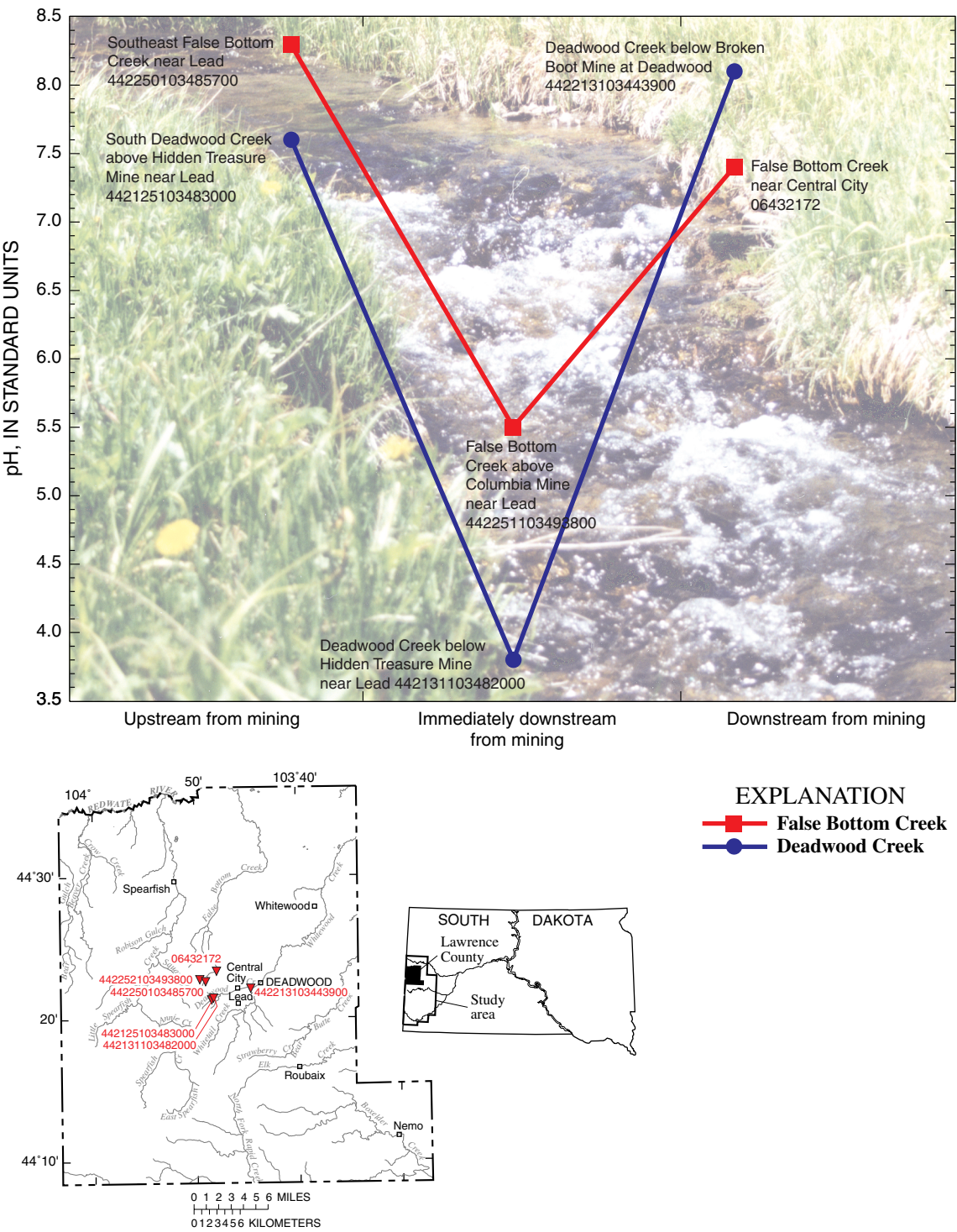
Mining has historically been a very important industry in the Black Hills area. Mining activities generally have been most extensive in the northern Black Hills, primarily in the vicinity of Tertiary intrusives (fig. 19) where the largest deposits of gold ores tend to be located. Effects of mining activity on water quality can be difficult to quantify because natural influences in these **mineralized areas** may have similar effects on water quality.

Approximately 900 abandoned or inactive mines exist throughout the Black Hills (South Dakota Department of Environment and Natural Resources, 2001b). One of the potential impacts from abandoned mines is that low pH can occur from the weathering of the discarded rock and tailing piles that can have high sulfide content. Low pH creates the potential for acid-mine drainage problems including acidic water, high concentrations of metals, sulfate, and dissolved solids, and possible detrimental aquatic effects. Efforts are underway by Federal, State, and private individuals and companies to remediate problematic sites.

Measured pH values for several sites in a downstream progression along False Bottom Creek and Deadwood Creek are presented in figure 94, which shows low pH at locations immediately downstream of historic mining operations. The pH levels usually increase farther downstream as a result of contact with carbonate minerals. Similar areas of low pH also exist in naturally occurring bog-iron areas (fig. 95). Drainage from these bog-iron areas, commonly found near Rochford and Iron Mountain (Luza, 1969; Rice, 1970), have very similar effects of decreasing the stream pH locally, but pH levels usually increase farther downstream. For both situations, low pH can increase the solubility of various metals such as iron, lead, copper, and zinc. High metal concentrations can impact aquatic life if concentrations are outside recommended ranges for aquatic life.

Acid-mine drainage has been a problem at the Gilt Edge mine (a large, open-pit, heap-leach-recovery gold mine that was operated during 1986-98), which was listed as a **Superfund** site in 2000 (South Dakota Department of Environment and Natural Resources, 2001c). The mine area is drained by Strawberry Creek, which is a tributary to Bear Butte Creek downstream of the confluence with Strawberry Creek show a trend of increasing dissolved solids concentrations since 1994, primarily from increases in sodium and sulfate concentrations (Williamson and Carter, 2001) (fig. 96). Copper concentrations frequently have exceeded aquatic criteria in parts of Bear Butte Creek (fig. 97).

Acid-mine drainage from the Richmond Hill Mine resulted in depressed pH levels in headwater reaches of Squaw Creek (Durkin, 1996). This condition resulted in a need for substantial reclamation efforts in closing the mine, which consisted of capping large deposits of sulfide minerals to prevent exposure to air and water.



Low pH can increase the solubility of various metals, which can have detrimental effects on aquatic life.

Figure 94. Downstream progression of pH for selected streams influenced by acid-mine drainage (modified from Williamson and Carter, 2001). Acidic water (pH less than 7) can have detrimental effects on aquatic life.

Photograph by Joyce E. Williamson



Photograph courtesy of South Dakota Department of Environment and Natural Resources



Photograph by Joyce E. Williamson



Figure 95. Abandoned mines are present throughout the northern Black Hills (upper photograph) and low pH levels can result in acid-mine drainage (middle photograph of Minnesota Ridge Mine). Naturally occurring bog-iron areas near Rochford (lower photograph) and Iron Mountain produce similar effects.

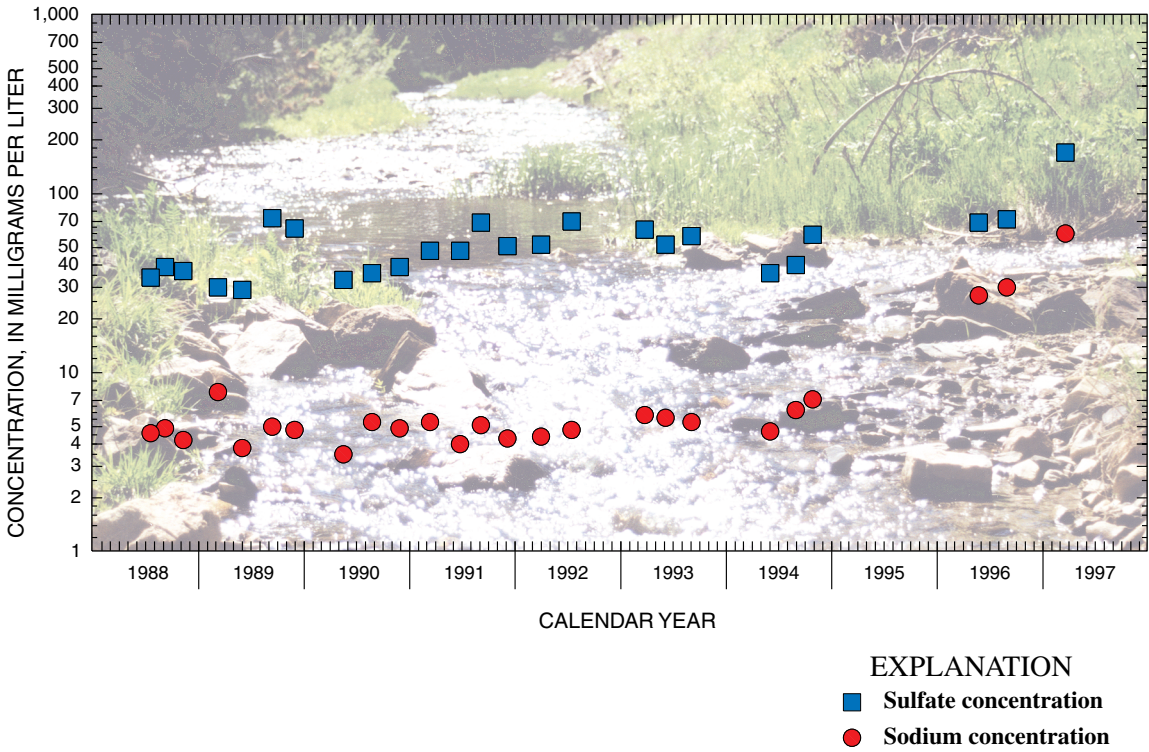


Figure 96. Changes in sulfate and sodium concentrations at Bear Butte Creek near Deadwood (06437020) (modified from Williamson and Carter, 2001). Increases in sulfate and sodium concentrations between 1994 and 1997 probably results from mining activities on a tributary to Bear Butte Creek. Location of site is shown in figure 34.

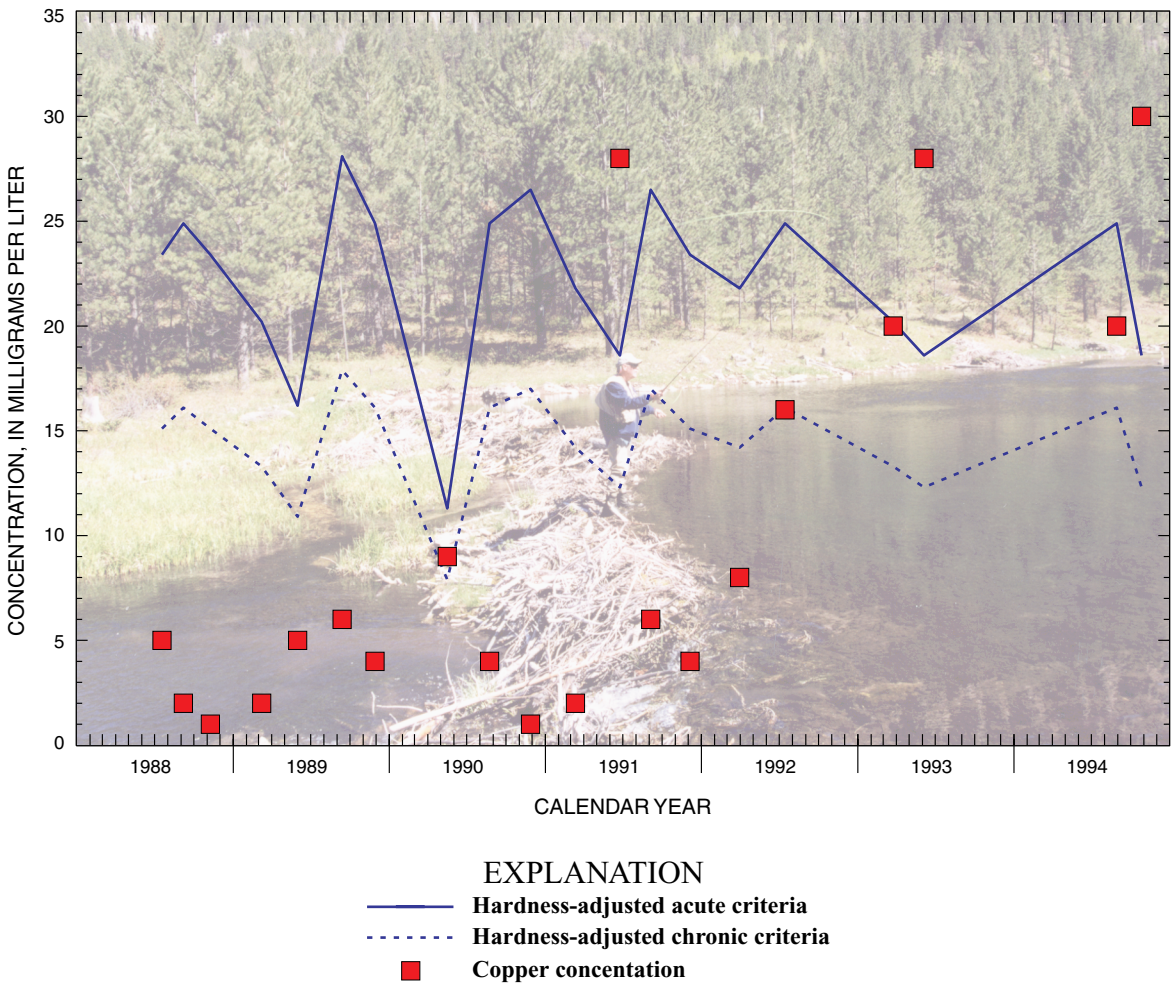
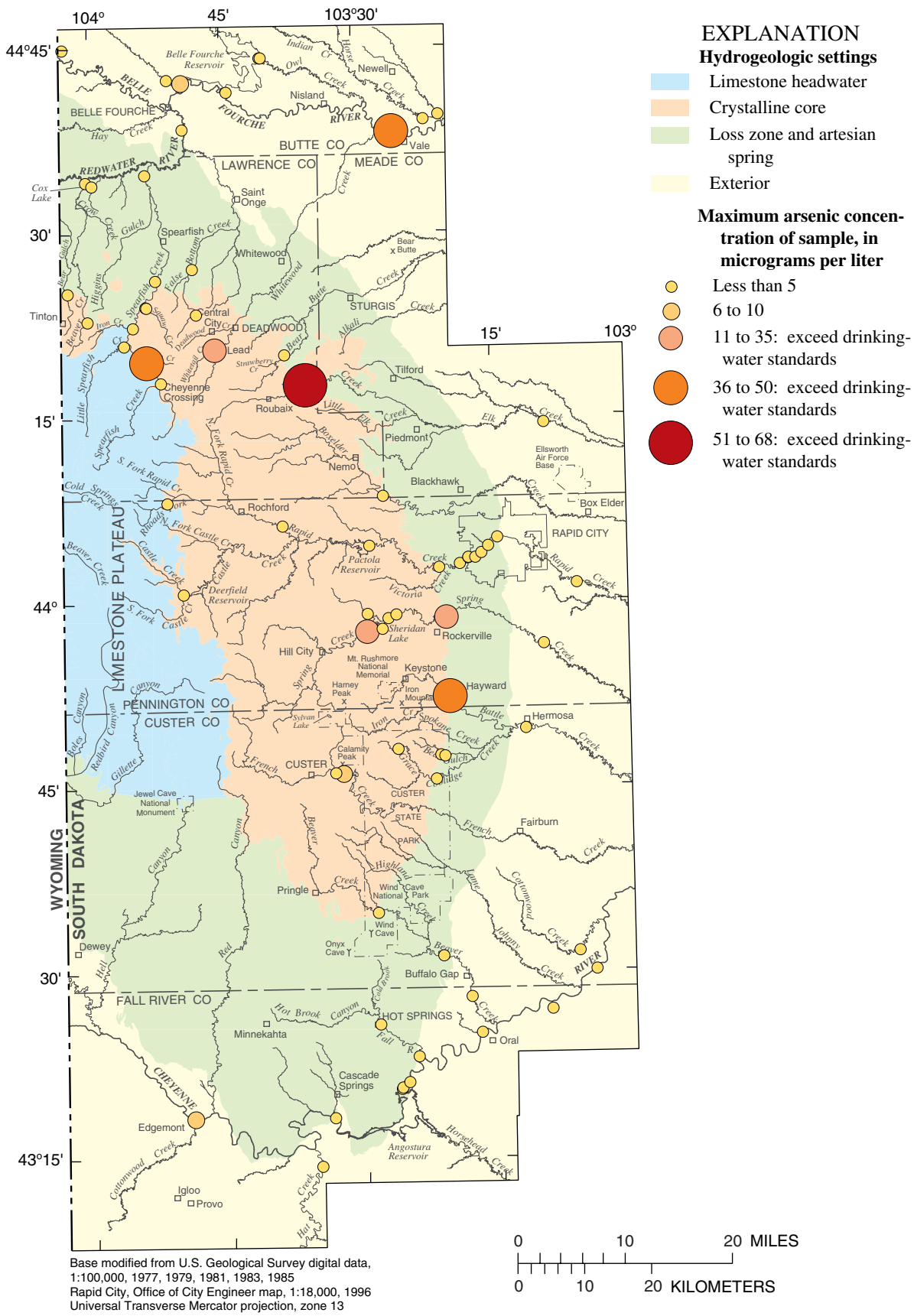


Figure 97. Comparison of dissolved copper concentrations to hardness-adjusted chronic and acute aquatic criteria for Bear Butte Creek near Deadwood (06437020) (modified from Williamson and Carter, 2001). During 1992 through 1994, copper concentrations generally exceeded chronic criteria and occasionally exceeded acute criteria. Concentrations exceeding aquatic criteria have the potential to impact aquatic life in streams. In the Black Hills area, many streams such as Rhoads Fork (background photograph) have beneficial use designations for fisheries. Location of site is shown in figure 34.

The spatial distribution of maximum arsenic concentrations for the study area is shown in figure 98. None of the samples have exceeded the aquatic-life criteria (table 7); however, concentrations exceeding the revised MCL of 10 µg/L (table 6) have been measured at seven sites. A single sample exceeding 50 µg/L has been collected. Concentrations below the laboratory reporting limit of 1 µg/L have been reported for numerous additional sites that are not shown in figure 98. Arsenic commonly is associated with gold ores, with most of the elevated concentrations occurring within the crystalline core setting in locations where mining activities have occurred. Arsenic also is relatively abundant in the Cretaceous shales surrounding the Black Hills area, with concentrations above 5 µg/L measured at upstream locations on the Cheyenne and Belle Fourche Rivers.

Potential effects of mining operations on arsenic concentrations generally cannot be quantified because background samples (prior to mining activities) are not available. Elevated arsenic concentrations in White-wood Creek and downstream reaches of the Belle Fourche River have been attributed to long-term discharge of mine tailings, which resulted in designation of an 18-mile reach as a Superfund site in 1983 (Goddard, 1989). Other constituents of concern along White-wood Creek include cadmium, copper, cyanide, iron, manganese, mercury, and silver. The largest concentrations of dissolved arsenic typically occur during storm-flow recessions and result from seepage from tailing deposits in the adjacent flood plain. Concentrations of total arsenic exceeding 100 µg/L are common during storm flows when sediments are mobilized.

Trends in Annie Creek indicate an increase in nitrite plus nitrate concentrations associated with mining operations, with two samples exceeding the MCL of 10 µg/L in 1995 and 1996 (fig. 99). The concentrations probably result from the breakdown of blasting agents (ammonium nitrate mixed with diesel fuel) and cyanide. Cyanide is used in the gold-extraction process and is highly toxic but breaks down relatively quickly to



Elevated nitrite plus nitrate concentrations attributed to mining impacts have occurred in Annie Creek. The breakdown of blasting agents and cyanide, which is used in the extraction process, are sources of nitrite plus nitrate to streams draining mining areas.

Figure 98. Maximum arsenic concentrations in surface water (modified from Williamson and Carter, 2001). A few sites in the mineralized areas of the Black Hills have approached or exceeded drinking-water standards of 10 micrograms per liter for arsenic.

nitrate. Water-treatment facilities were installed within the Annie Creek Basin in 1997 and have been effective in reducing nitrite plus nitrate concentrations (South Dakota Department of Environment and Natural Resources, 1998).

Elevated nitrite plus nitrate concentrations also can occur from a variety of other influences including fertilizers, animal and human waste, and natural processes that occur along stream channels. Nitrite plus nitrate concentrations by hydrogeologic setting are shown in figure 100. In this figure, Annie Creek is separated from other crystalline core sites because of the substantial influence from mining operations, as previously discussed. Concentrations for most sites representative of the hydrogeologic settings generally are less than 1 $\mu\text{g/L}$, whereas concentrations in Annie Creek generally are greater than 1 $\mu\text{g/L}$. Numerous samples for sites that are not representative of the hydrogeologic settings are included in an “other sites” category. Most of the elevated nitrite plus nitrate concentrations for this category were collected prior to 1980 from Horse Creek near Vale (Williamson and Carter, 2001), which is influenced by irrigation return flows.

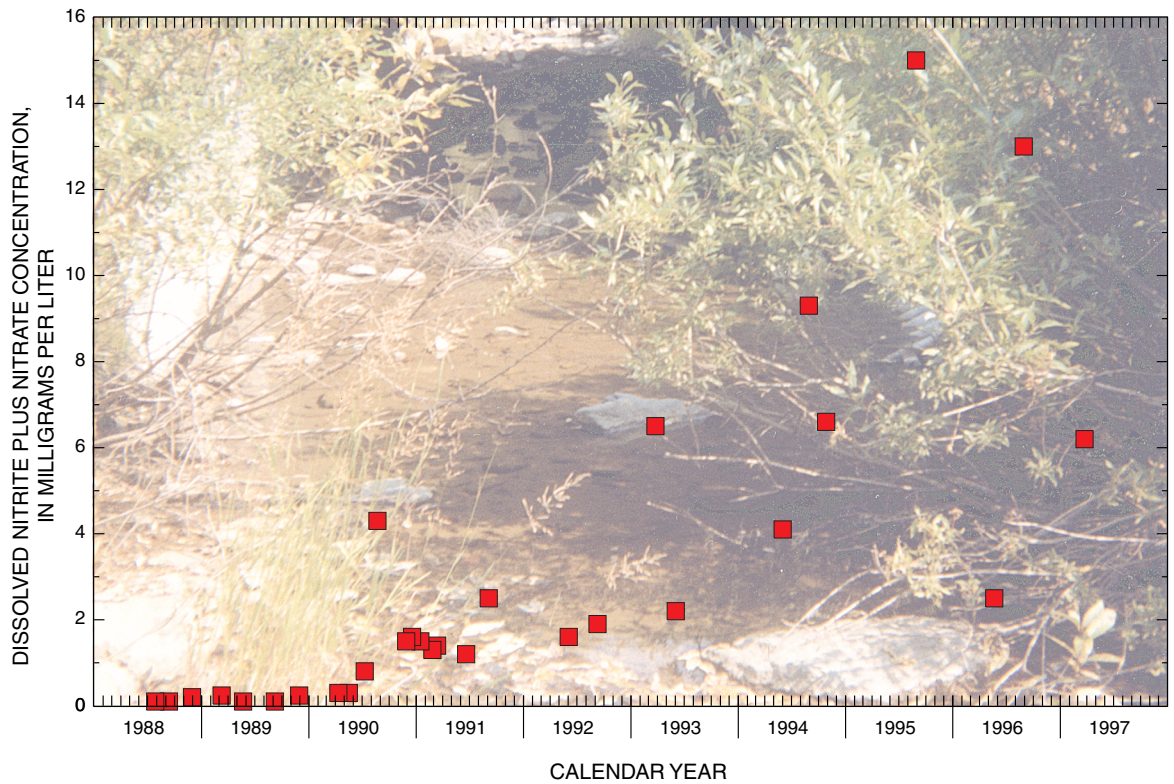


Figure 99. Nitrite plus nitrate concentrations in Annie Creek near Lead (06430800), 1988-97 (modified from Williamson and Carter, 2001). Elevated nitrite plus nitrate concentrations in the 1990's have been attributed to mining activities within the Annie Creek Basin. Water treatment has been implemented to reduce the nitrite plus nitrate concentrations in recent years. Location of site is shown in figure 34.

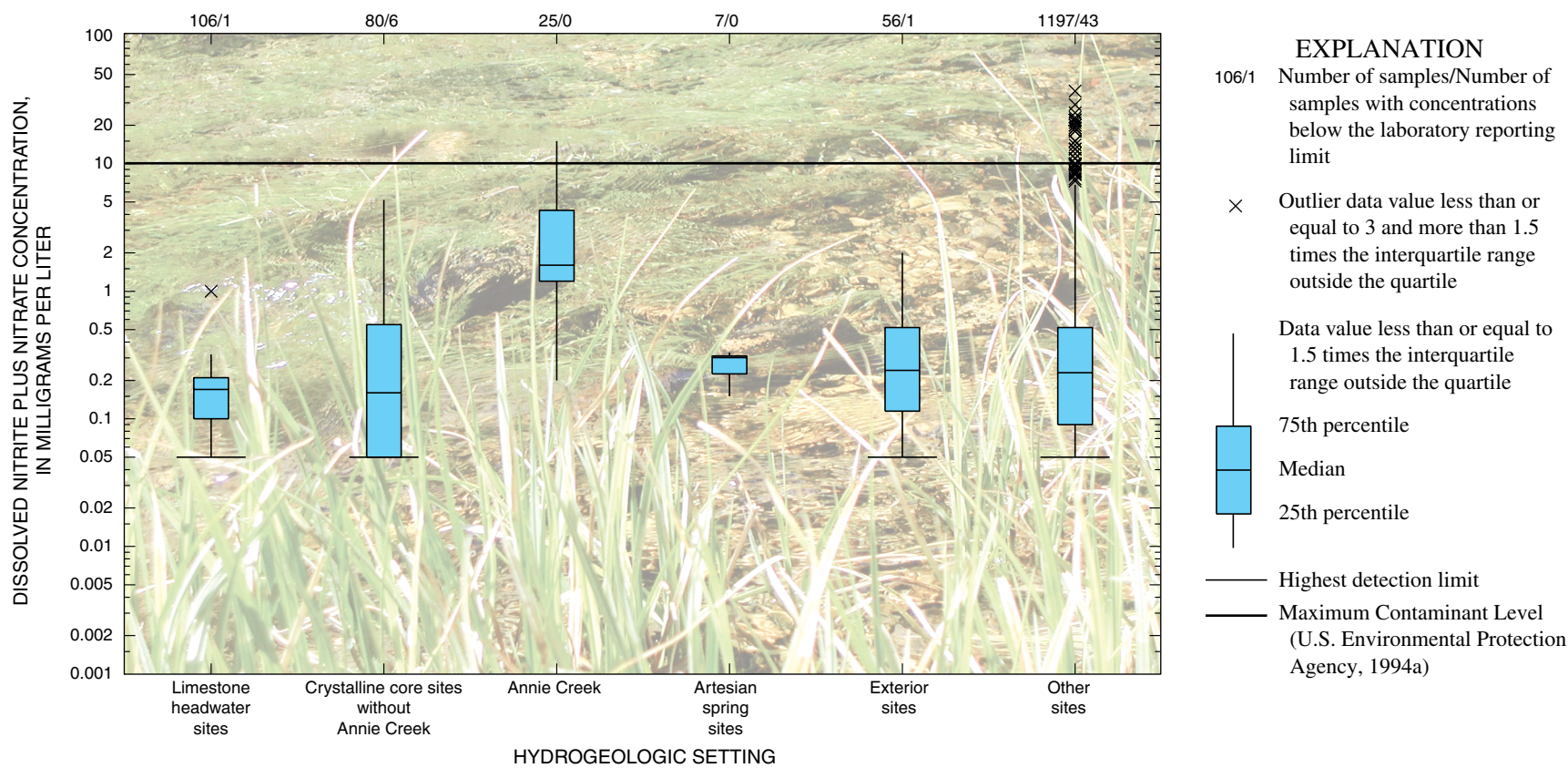


Figure 100. Concentrations of dissolved nitrite plus nitrate by hydrogeologic setting, with Annie Creek separated from other crystalline core sites. Nitrite plus nitrate concentrations generally are less than 1 milligram per liter, whereas concentrations in Annie Creek generally are greater than 1 milligram per liter.

Nitrite plus nitrate concentrations for selected sites within the Rapid Creek Basin are presented in figure 101. Concentrations for the farthest site upstream (06409000, Castle Creek above Deerfield) generally are slightly higher than for the next two sites downstream. One possible nitrogen source, based on land-use activities, is cattle grazing upstream from the site. Rapid Creek at Rapid City (06414000) shows minor influences of nitrite plus nitrate from various possible urban sources. Concentrations at Rapid Creek near Farmingdale (06421500) increase markedly, reflecting various possible influences including nonpoint urban/suburban sources, effluent discharge from the Rapid City municipal wastewater treatment plant, and various possible influences from agricultural activities.

Numerous constituents in addition to nitrite plus nitrate can influence water quality in urban environments. Williamson and others (1996) documented increased concentrations of various trace metals contributed to Rapid Creek by the Rapid City municipal wastewater treatment plant. Goddard and others (1989) summarized data collected during a National Urban Runoff Program study in the Rapid City area. In an interpretation of this data set, Harms and others (1983) documented increases in numerous

constituents in Rapid Creek associated with urban runoff.

Surface-Water Quality Relative to Water Use

In some instances, the quality of water can affect the use of that water. Low pH conditions in streams in the mineralized areas of the Black Hills may be associated with mining activities or naturally occurring processes especially in areas with bog-iron deposits (Luza, 1969). Occasional occurrences of pH values exceeding the desirable range (table 7) have been noted in the limestone headwater and crystalline core settings (Williamson and Carter, 2001).

Beneficial uses for some stream reaches also can be limited by temperature and dissolved oxygen concentrations. Aquatic life, especially spawning fish, prefer certain temperature ranges, and water temperatures heavily influence the species of fish found within a stream reach. High temperatures and low dissolved oxygen concentrations can affect fish populations, resulting in stress, disease, or death. In-stream temperatures exceeding beneficial-use criteria for fisheries (table 7) occasionally occur, especially during low-flow conditions. Concentrations of dissolved oxygen below desirable ranges also can occur occasionally,

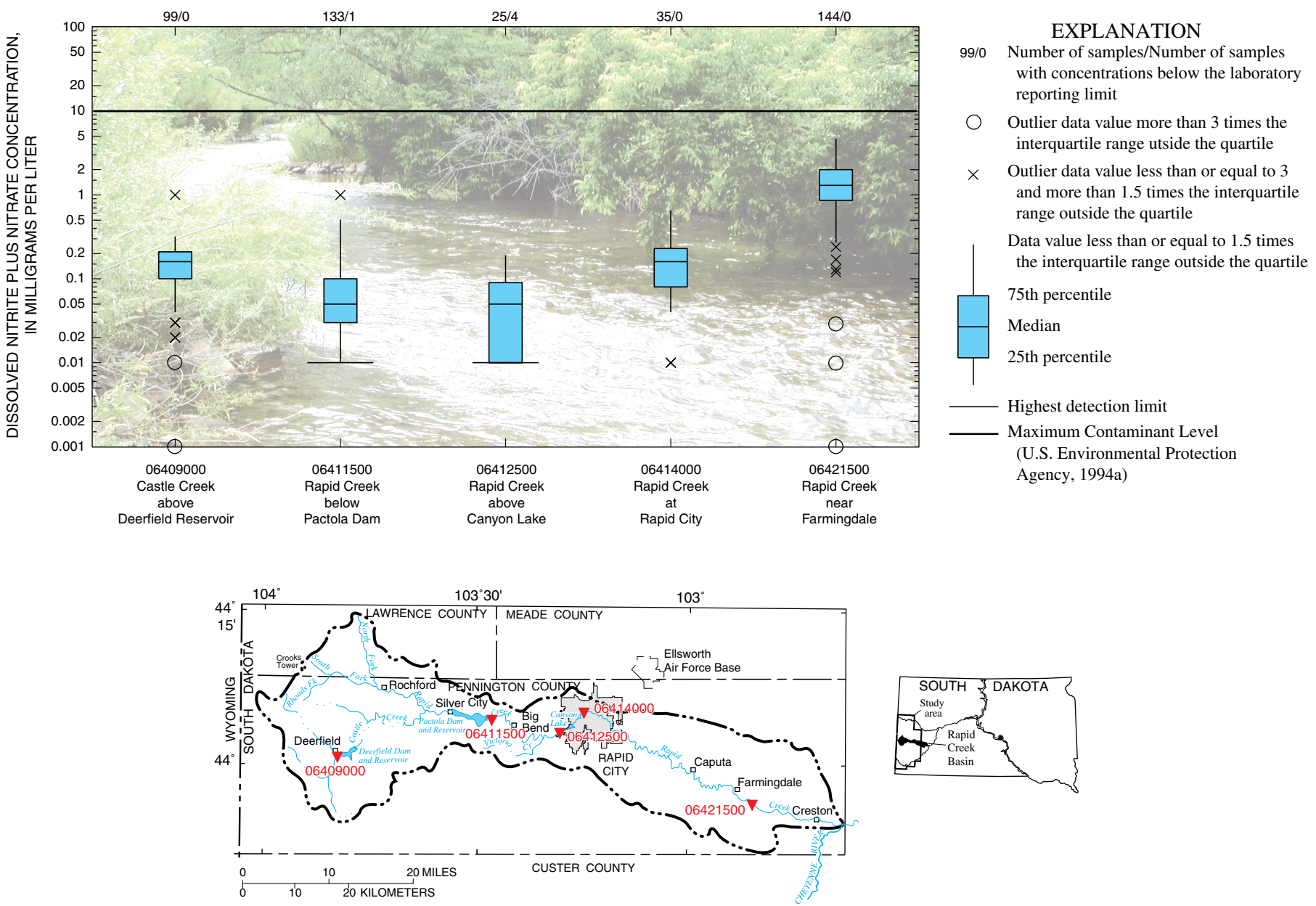


Figure 101. Concentrations of dissolved nitrite plus nitrate within the Rapid Creek Basin. Nitrite plus nitrate concentrations at Rapid Creek near Farmingdale increase, reflecting various possible influences from nonpoint urban/suburban impacts, wastewater discharge, nonpoint cattle-grazing impacts, and irrigation return flows.

especially during low-flow conditions and when elevated water temperatures reduce oxygen solubility. Low concentrations of dissolved oxygen associated with urban runoff also have been documented (Harms and others, 1983).

Concentrations of suspended solids exceeding beneficial-use criteria are relatively common in the Black Hills area. The largest (and most frequent) exceedances typically occur in the exterior setting, where fine-grained particulates associated with clay soils are easily mobilized during high-flow conditions. High concentrations of suspended solids also typically occur during urban runoff events (Harms and others, 1983).

Constituent concentrations in samples from artesian springs generally do not approach drinking-water or beneficial-use criteria. Artesian springs may have high concentrations of sulfate and dissolved solids, which can affect the taste of the water. About 66 percent of the samples from exterior sites had sulfate concentrations that exceeded 1,000 mg/L, which is primarily a concern for drinking-water supplies. Sodium can limit the use of water for irrigation, but high sodium concentrations in surface water usually are not a problem in the Black Hills area.

High nitrite plus nitrate concentrations resulting from mining operations have occurred in Annie Creek but have been reduced by installation of water-treatment facilities. High nitrite plus nitrate concentrations are a health concern for pregnant women, children, and the elderly. Annie Creek is not a drinking-water source, and concentrations have not exceeded beneficial-use criteria.

Arsenic concentrations at several sites in the crystalline core settings have exceeded the revised MCL of 10 µg/L. These sites include Annie Creek, Battle Creek, Elk Creek, Spring Creek, and Whitewood Creek. Concentrations exceeding the SMCL's for iron and manganese are common in some streams, but these streams generally are not used for drinking-water sources. Concentrations exceeding the aquatic-life criteria for selenium and SMCL's for iron and manganese occur at some exterior sites. Higher uranium concentrations occur at some exterior sites downstream from the Inyan Kara Group outcrop relative to the rest of the Black Hills area. Copper concentrations exceeding the acute and chronic aquatic-life criteria in Bear Butte Creek were documented during 1992-94.

Photograph by South Dakota Tourism



Photograph by Michael T. Carter

