Hydrologic Processes and Framework

This section of the report provides an overview of the hydrologic framework for the study area. A discussion of hydrologic processes is first provided for the benefit of readers with limited backgrounds in hydrology.

Hydrologic Processes

In the Black Hills area, potential evaporation generally exceeds precipitation.

The **hydrologic cycle** is the constant circulation of water from the atmosphere, to the sea and land, and its eventual return to the atmosphere by way of **transpiration** (plants) and **evaporation** from the sea and land surfaces (soil). The total water volume of the world is about 326 million cubic miles. Most of the water is stored in the oceans, frozen in glaciers, held in lakes, or stored underground. Following precipitation, water may flow swiftly to the sea in rivers, may evaporate quickly, or may be held in a lake for many years, in a glacier for thousands of years, or in the ground for even much longer periods of time.

A schematic diagram illustrating hydrologic processes in the Black Hills area is presented as figure 6. Precipitation falling on the earth's surface generally infiltrates into the soil horizon, unless the soil is **saturated** or the infiltration capacity is exceeded, in which case **overland flow** or **direct runoff** will occur after **depression storage** is filled. Some water may be returned from the soil horizon to the land surface through **interflow**, contributing to relatively short-term increases in streamflow. In the Black Hills area, **potential evaporation**, which is the maximum amount of water that would evaporate if unlimited moisture was available, generally exceeds precipitation. Thus, most of the precipitation in the Black Hills area eventually is returned to the atmosphere through **evapotranspiration**. Water infiltrating beyond the root zone may eventually recharge ground-water systems; however, ground-water **discharge** (in the form of springflow or seepage) also may contribute to streamflow.

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

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

Rock materials may be classified as consolidated rocks (often called bedrock) that may consist of **limestone**, **dolomite**, **sandstone**, siltstone, shale, or granite. Unconsolidated rock consists of granular material such as sand, gravel, and clay. The amount of ground water that can flow through soil or rock depends on the size of the spaces in the soil or rock and how well the spaces are connected. **Porosity** is the percentage of the soil or rock volume that is occupied by pore space, which is void of material. Permeability is the measure of how well the spaces are connected (fig. 7A). An estimated one million cubic miles of the world's ground water is stored within one-half mile below the land surface.

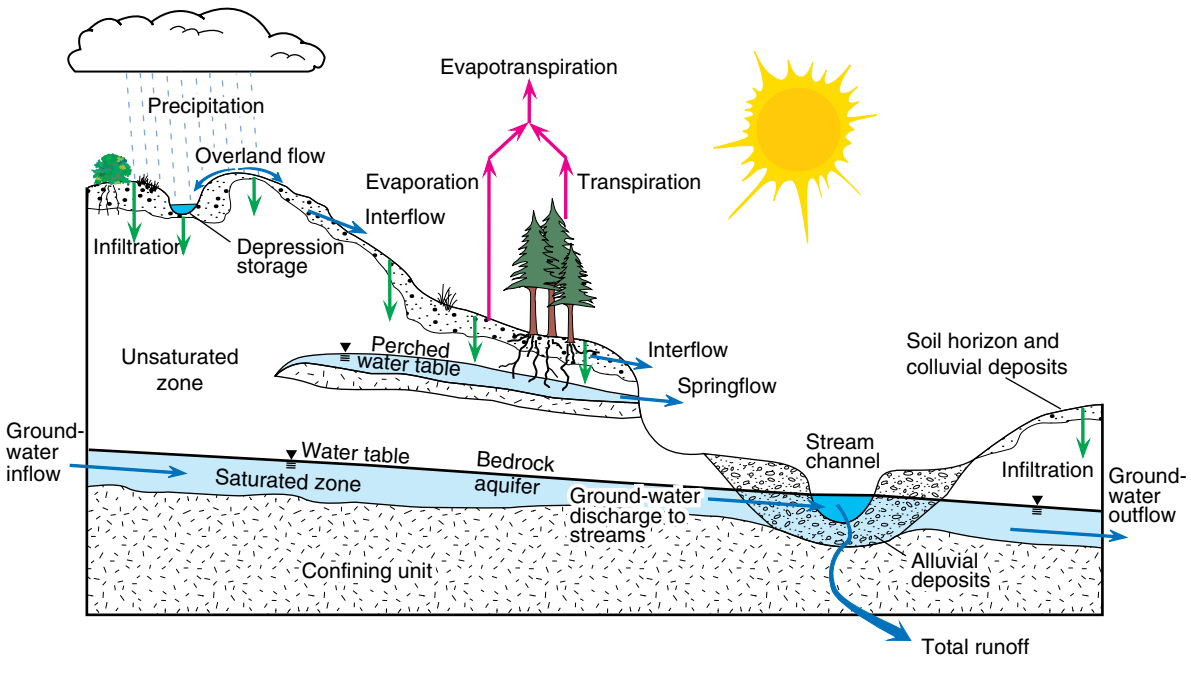


Figure 6. Schematic diagram illustrating hydrologic processes (modified from Driscoll and Carter, 2001).

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

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

Ground water can occur in aquifers under two different conditions. Where water-table conditions occur, water does not fill the aquifer material all the way to the top and the aquifer is considered **unconfined**. Where an aquifer is completely filled with water (fully saturated) and is overlain by a confining unit, the water can be **confined** under pressure and can rise above the top of the aquifer in an **artesian well** (fig. 7B) to a level representing the **potentiometric surface**. In the schematic shown in figure 7B, the potentiometric surface of the **confined** (**artesian**) **aquifer** is higher than the water table of the **unconfined aquifer**. Artesian wells will flow (fig. 8) where the potentiometric surface is above the land surface. **Semiconfining units** contain some layers with low permeability but may transmit some water to and from adjacent aquifers.

Photograph by Earl A. Greene

Figure 8. During development of the Lime Creek observation well in Rapid City, the well flowed about 400 gallons per minute under artesian pressure.

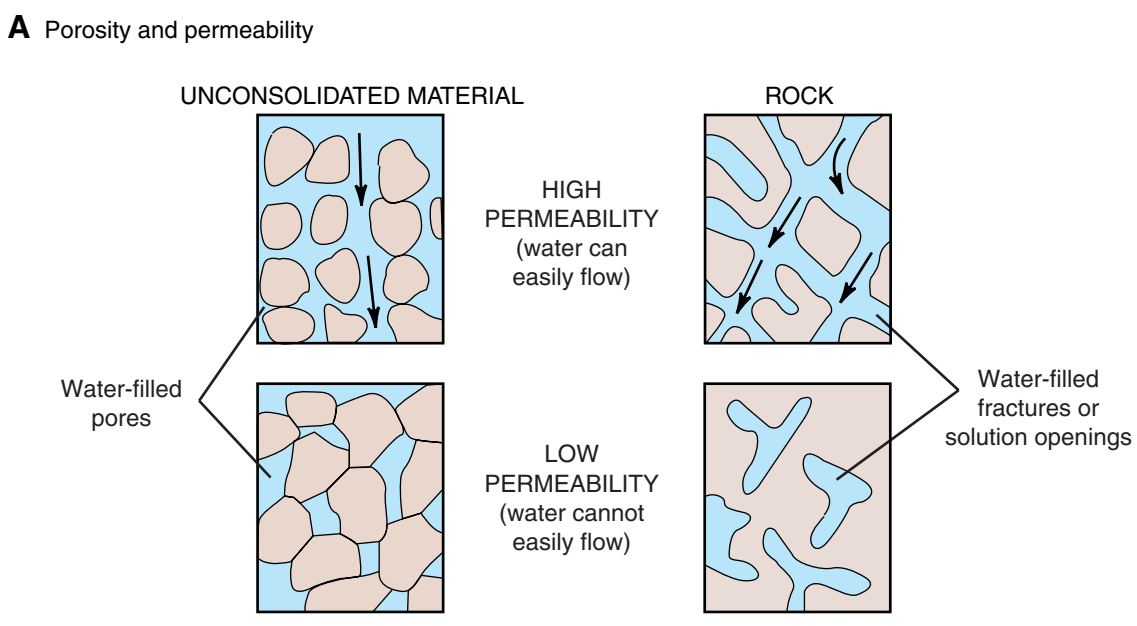


Figure 7. Schematic diagram showing (A) porosity and permeability (modified from Clark and Briar, 1993); and (B) aquifers and confining beds (modified from Heath,1983).

Local Hydrologic Framework

The hydrologic framework for the Black Hills area is presented in this section of the report. Descriptions of climate, geology, ground water, and surface water are presented.

Climate

The overall climate of the Black Hills area is continental, which is characterized generally by low precipitation amounts, hot summers, cold winters, and extreme variations in both precipitation and temperatures (Johnson, 1933). Local climatic conditions are affected by topography, with generally lower temperatures and higher precipitation at the higher altitudes. The average annual temperature is 43.9 degrees Fahrenheit (U.S. Department of Commerce, 1999) and ranges from 48.7 degrees at Hot Springs to approximately 37 degrees near Deerfield Reservoir.

Precipitation data sets used for this study generally were taken from Driscoll, Hamade, and Kenner (2000), who summarized available precipitation data for **water years** 1931-98 for the Black Hills area. These investigators compiled monthly precipitation records for 52 long-term precipitation gages operated by the National Oceanic and Atmospheric Administration (1998) and 42 short-term precipitation gages operated by the USGS. A **geographic information system** (GIS), which is a computer program that uses spatially related data, was used by Driscoll, Hamade, and Kenner (2000) to generate spatial distributions of monthly precipitation data. An example for October 1995 is shown in figure 9, which illustrates the large spatial variability in monthly precipitation that can occur. Monthly distributions were composited to produce annual distributions, both of which have been used extensively for various applications such as quantification of precipitation over **drainage areas** for streams and recharge areas for aquifers.

Figure 10 shows the distribution of average annual precipitation for water years 1950-98, which is the period commonly used for determining hydrologic budgets for the study. Land-surface (topographic) contours for the study area also are included in

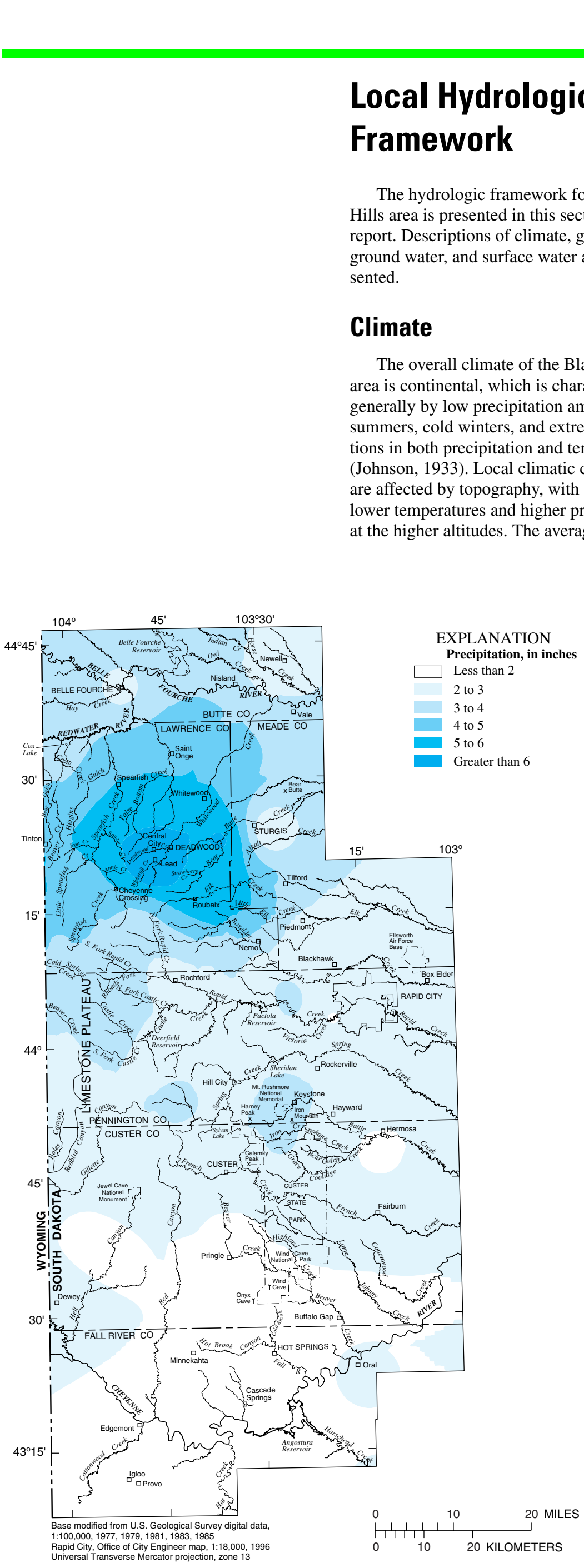


Figure 9. Monthly precipitation distribution for October 1995 (from Driscoll, Hamade, and Kenner, 2000).

Precipitation amounts generally are largest in the higher altitudes of the northern Black Hills. Lawrence County receives a larger proportion of its annual precipitation during winter months than other counties in the Black Hills area.

figure 10, which shows the influence of **orographic** effects (increasing precipitation with increasing altitude). Most areas with altitudes exceeding 6,000 feet above sea level have average annual precipitation in excess of 19 inches, with the largest amounts occurring in the northern Black Hills near Lead, where the average annual precipitation exceeds 28 inches. Orographic effects also are apparent in the high-altitude areas near Harney Peak.

Local conditions also are affected by regional climatic patterns, with the northern Black Hills influenced primarily by moist air currents out of the northwest, and the southern Black Hills influenced primarily by drier air currents out of the south-southeast. As a result, annual precipitation averages about 16 to 17 inches for most of Fall River County (fig. 10), which is much less than parts of Lawrence and Meade Counties that have comparable altitudes. Boxplots showing the distribution of annual precipitation for the study area and for counties within the study area during water years 1931-98 are presented in figure 11. For the study area, the long-term average of 18.61 inches is slightly larger than the **median** (or 50th percentile) of 17.96 inches. The 90th percentile indicates that annual precipitation over the study area is less than about 23.70 inches 90 percent of the time. Annual precipitation for both Butte and Fall River Counties is less than the long-term average for the study area about 75 percent of the time.

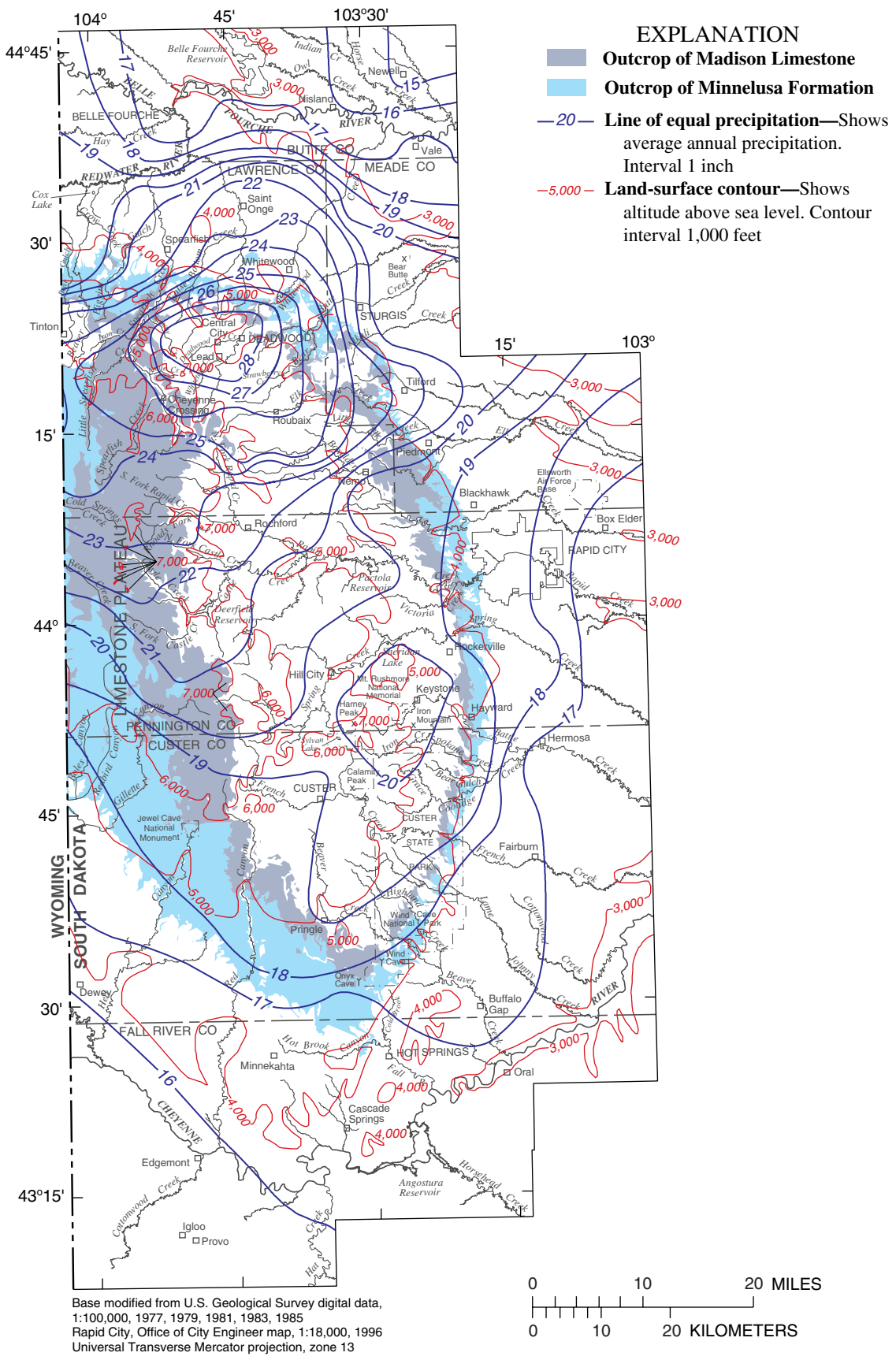


Figure 10. Distribution of average annual precipitation for the Black Hills area, water years 1950-98 (from Carter, Driscoll, and Hamade, 2001).

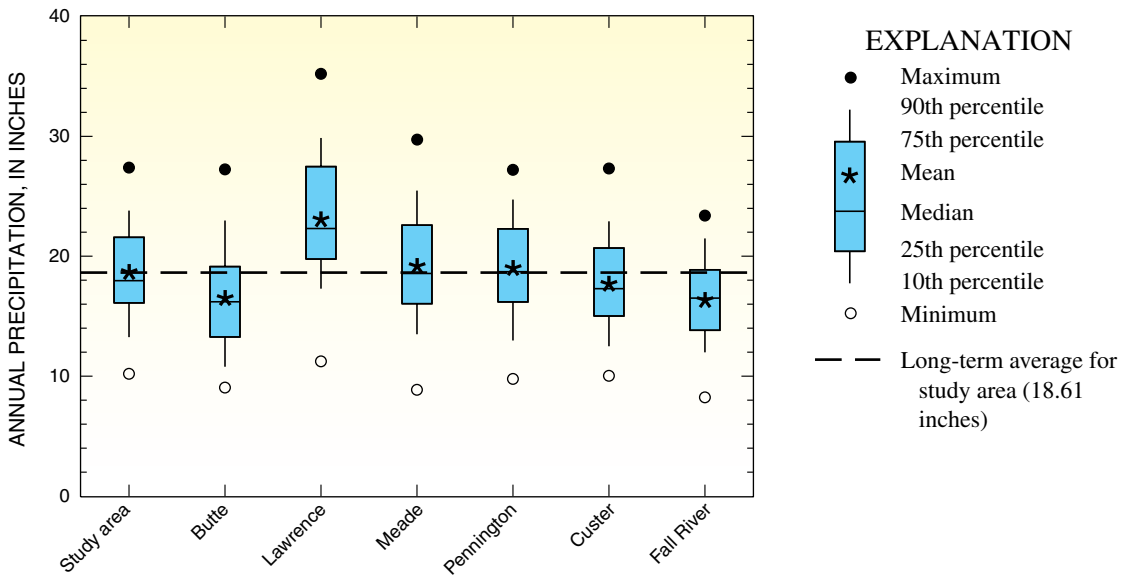


Figure 11. Distribution of annual precipitation for the study area and counties within the study area, water years 1931-98 (modified from Driscoll and Carter, 2001).

The largest precipitation amounts typically occur during May and June, with the smallest amounts typically occurring during November through February (fig. 12). The most variable month is May, during which precipitation ranges from a minimum of about 0.4 inch to a maximum of 8.5 inches. The seasonal distribution of precipitation is fairly uniform throughout the study area; however, Lawrence County receives slightly larger proportions of its annual precipitation during winter months than the other counties (fig. 13).

Long-term (water years 1931-98) trends in precipitation for the study area are illustrated in figure 14. Graph A shows that annual precipitation for the study area averages 18.61 inches and has ranged from 10.22 inches in 1936 to 27.39 inches in 1995. Graph B shows that the associated departures (from the average) have ranged from a deficit (-) of 8.39 inches to a surplus (+) of 8.78 inches. The cumulative trends are readily apparent from graph C, with the most pronounced trends identified by the longest and steepest line segments. Sustained periods of generally deficit precipitation occurred during 1931-40 and 1948-61. Sustained periods of generally surplus precipitation occurred during 1941-47, 1962-68, and 1993-98. The middle to late 1990's stand out as the wettest period since 1931, which has caused potential for bias towards wet conditions in extensive hydrologic data collection in the Black Hills area during this period. This potential bias has been addressed in analysis of hydrologic data throughout the course of the study, and has been balanced to

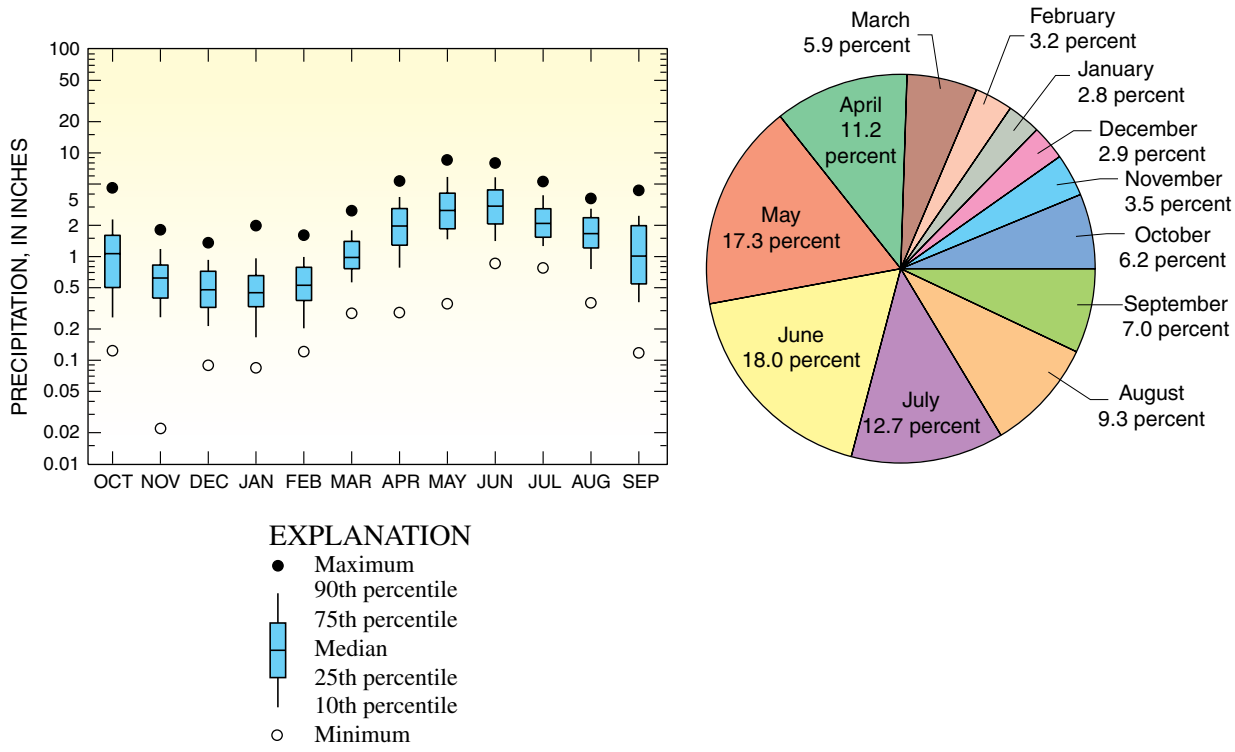


Figure 12. Distribution of monthly precipitation for the study area, water years 1931-98 (from Driscoll, Hamade, and Kenner, 2000). Pie chart shows monthly distribution of average annual precipitation of 18.61 inches.

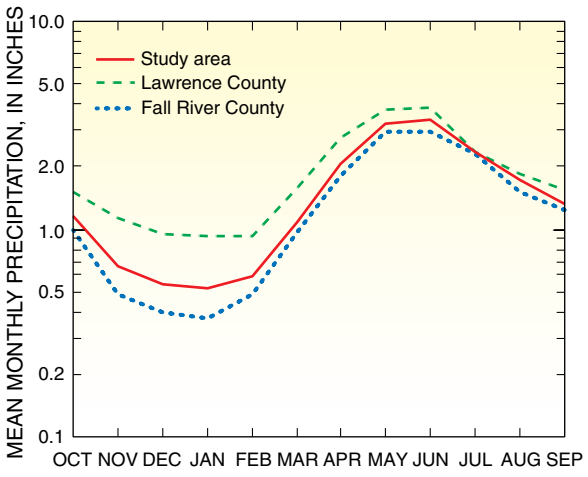


Figure 13. Mean monthly precipitation for the study area and selected counties, water years 1931-98 (from Driscoll and Carter, 2001).

The middle to late 1990's, during which extensive hydrologic data were collected, has been the wettest period since 1931. Only limited hydrologic data are available for the extremely dry conditions that occurred during the 1930's and 1950's.

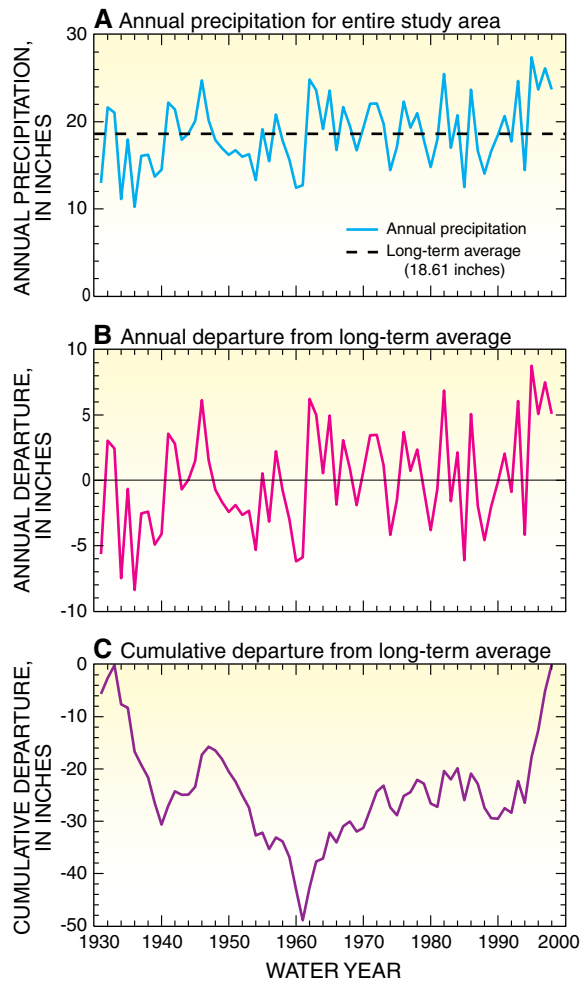


Figure 14. Long-term trends in precipitation for the Black Hills area, water years 1931-98 (from Driscoll, Hamade, and Kenner, 2000). Graph A shows annual precipitation for the study area relative to the long-term average of 18.61 inches. Graph B shows annual departures (calculated as annual precipitation minus the average). Graph C shows cumulative departures (calculated as the running sum of annual departures).

some extent by relatively dry conditions during the late 1980's and early 1990's.

Average annual potential evaporation (measured in evaporation pans) exceeds average precipitation throughout most of the study area. Thus, evapotranspiration generally is limited by precipitation amounts and availability of soil moisture. Average pan evaporation for April through October is about 30 inches at Pactola Reservoir and about 50 inches at Oral (U.S. Department of Commerce, 1999).

Geology

The geology of the Black Hills area is very complex. Throughout geologic time, the area experienced periods of frequent inundation by seas, extended erosion, mountain building (known as **orogeny**), and **intrusion** by **igneous rocks**. An overview of the geologic history of the Black Hills area is presented in table 3. The **geologic time scale** is divided into four eras (table 3) and spans from the Precambrian Era (earliest) to the **Cenozoic** Era (latest). A **stratigraphic column**, which portrays the vertical (or chronological) sequence of geologic units of the Black Hills, is shown in figure 15.

Uplift of the Black Hills began about 62 million years ago during the Laramide orogeny. Erosion removed approximately 7,500 feet of sedimentary rock and exposed the Precambrian rocks in the crystalline core. Previous altitudes are unknown because uplift and erosion probably occurred simultaneously; however, maximum altitudes probably approached current altitudes of some peaks in the Rocky Mountains.

Table 3. Geologic history of the Black Hills area

[Modified from Gries (1996) and Paterson and Kirchner (1996). m.y., million years before present]

Era	System	Epoch	Ages (in million years before present)	Activity
Cenozoic	Quaternary	Holocene	0.01 - 0	Erosion. Fluvial deposition of sands and gravels.
		Pleistocene	2 - 0.01	Erosion. Fluvial deposition of sands and gravels.
	Tertiary	Pliocene	5 - 2	Erosion. Fluvial deposition of terrace gravels.
		Miocene	24 - 5	Continued fluvial deposition of light-colored sands and clays, including the White River Group.
		Oligocene	38 - 24	Fluvial deposition of light-colored sands and clays over the region.
		Eocene	55 - 38	Erosion. The Black Hills were at their highest by about 48 m.y. and had much of their present shape by about 37 m.y. Igneous activity formed Devils Tower (west of the Black Hills area) and Bear Butte.
		Paleocene	63 - 55	Uplift of the Black Hills (beginning about 62 m.y.) and igneous activity in the northern areas occurred.
Mesozoic	Cretaceous		138 - 63	The Rocky Mountains began to form. Sand deposits during fluvial and marginal marine conditions formed the Inyan Kara Group. Thick mud deposits during marine conditions formed the Pierre Shale and other shales in the area.
	Jurassic		205 - 138	Erosion through Middle Jurassic, followed by advance of shallow seas that deposited sandstones and shales.
	Triassic		240 - 205	Deposition of red beds (Spearfish Formation) began in the Late Permian and extended into Early Triassic. From Middle Triassic to Middle Jurassic, major erosion occurred for about 50 million years.
Paleozoic	Permian		290 - 240	Following deposition of the Minnelusa Formation, the Opeche Shale was deposited under desert playa conditions above sea level. Then, a shallow sea flooded the region and deposited the Minnekahta Limestone. At the end of the Permian period, a major extinction occurred when about 90 percent of all animal species became extinct.
	Pennsylvanian		330 - 290	Erosion followed by deposition of sandstones, carbonates, and evaporites (Minnelusa Formation) by shallow seas. Numerous transgressions and regressions of the seas occurred.
	Mississippian		365 - 330	Deposition of carbonates (Englewood Formation and Madison Limestone) by shallow seas followed by about 50 million years of erosion, which allowed for the development of karst features.
	Devonian		410 - 365	Erosion followed by deposition of carbonates in shallow marine environment.
	Silurian		435 - 410	Erosion.
	Ordovician		500 - 435	Seas covered area. Deposition of sand and shale (Winnipeg Formation) followed by deposition of limestone (Whitewood Formation).
	Cambrian		570 - 500	Erosion followed by deposition of sand and shale in beach and shallow marine environments (Deadwood Formation).
Precambrian	Proterozoic		1,715 - 570	Long period of erosion.
			2,500 - 1,715	Emplacement of Harney Peak Granite; deposition of marine sands and clays.
	Archean		4,600 - 2,500	Intrusion of Little Elk Granite; deposition of shales interrupted by periods of mountain building and volcanic activity.

ERATHEM	SYSTEM	ABBREVIATION FOR STRATIGRAPHIC INTERVAL	GEOLOGIC UNIT	THICKNESS IN FEET	DESCRIPTION
CENOZOIC	QUATERNARY & TERTIARY (?)	QTac	UNDIFFERENTIATED ALLUVIUM AND COLLUVIUM	0-50	Sand, gravel, boulders, and clay.
	TERTIARY	Tw	WHITE RIVER GROUP	0-300	Light colored clays with sandstone channel fillings and local limestone lenses.
		Tui	INTRUSIVE IGNEOUS ROCKS	--	Includes rhyolite, latite, trachyte, and phonolite.
MESOZOIC	CRETACEOUS	Kps	PIERRE SHALE	1,200-2,700	Principal horizon of limestone lenses giving teepee buttes. Dark-gray shale containing scattered concretions. Widely scattered limestone masses, giving small teepee buttes. Black fissile shale with concretions.
			NIOBRARA FORMATION	[1]80-300	Impure chalk and calcareous shale.
			CARLILE SHALE	[1]350-750	Light-gray shale with numerous large concretions and sandy layers. Dark-gray shale.
			GREENHORN FORMATION	225-380	Impure slabby limestone. Weathers buff. Dark-gray calcareous shale, with thin Orman Lake limestone at base.
			GRANEROS GROUP: BELLE FOURCHE SHALE	150-850	Gray shale with scattered limestone concretions. Clay spur bentonite at base.
			GRANEROS GROUP: MOWRY SHALE	125-230	Light-gray siliceous shale. Fish scales and thin layers of bentonite.
			GRANEROS GROUP: MUDDY SANDSTONE / NEWCASTLE SANDSTONE	0-150	Brown to light-yellow and white sandstone.
			GRANEROS GROUP: SKULL CREEK SHALE	150-270	Dark-gray to black siliceous shale.
		Kik	INYAN KARA GROUP: FALL RIVER FORMATION	10-200	Massive to thin-bedded, brown to reddish-brown sandstone.
			INYAN KARA GROUP: LAKOTA FORMATION	35-700	Yellow, brown, and reddish-brown massive to thinly bedded sandstone, pebble conglomerate, siltstone, and claystone. Local fine-grained limestone and coal.
	JURASSIC	Ju	MORRISON FORMATION	0-220	Green to maroon shale. Thin sandstone.
			UNKPAPA SS	0-225	Massive fine-grained sandstone.
			SUNDANCE FORMATION	250-450	Greenish-gray shale, thin limestone lenses. Glauconitic sandstone; red sandstone near middle.
			GYPSUM SPRING FORMATION	0-45	Red siltstone, gypsum, and limestone.
	TRIASSIC	TrPs	SPEARFISH FORMATION	375-800	Red silty shale, soft red sandstone and siltstone with gypsum and thin limestone layers. Gypsum locally near the base.
PALEOZOIC	PERMIAN	Pmk	MINNEKAHTA LIMESTONE	[1]25-65	Thin to medium-bedded, fine grained, purplish-gray laminated limestone.
		Po	OPECHE SHALE	[1]25-150	Red shale and sandstone.
	PENNSYLVANIAN	PIPm	MINNELUSA FORMATION	[1]375-1,175	Yellow to red cross-bedded sandstone, limestone, and anhydrite locally at top. Interbedded sandstone, limestone, dolomite, shale, and anhydrite. Red shale with interbedded limestone and sandstone at base.
	MISSISSIPPIAN	MDme	MADISON (PAHASAPA) LIMESTONE	[1]<200-1,000	Massive light-colored limestone. Dolomite in part. Cavernous in upper part.
	DEVONIAN		ENGLEWOOD FORMATION	30-60	Pink to buff limestone. Shale locally at base.
	ORDOVICIAN	Ou	WHITEWOOD (RED RIVER) FORMATION	[1]0-235	Buff dolomite and limestone.
			WINNIPEG FORMATION	[1]0-150	Green shale with siltstone.
	CAMBRIAN	O€d	DEADWOOD FORMATION	[1]0-500	Massive to thin-bedded brown to light-gray sandstone. Greenish glauconitic shale, flaggy dolomite, and flat-pebble limestone conglomerate. Sandstone, with conglomerate locally at the base.
PRECAMBRIAN		p€u	UNDIFFERENTIATED IGNEOUS AND METAMORPHIC ROCKS		Schist, slate, quartzite, and arkosic grit. Intruded by diorite, metamorphosed to amphibolite, and by granite and pegmatite.

[1] Modified based on drill-hole data

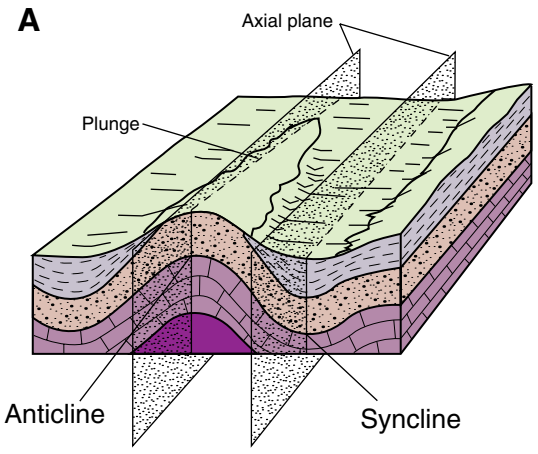
Modified from information furnished by the Department of Geology and Geological Engineering, South Dakota School of Mines and Technology (written commun., January 1994)

Figure 15. Stratigraphic column for the Black Hills.

Photograph by J. Foster Sawyer, South Dakota Department of Environment and Natural Resources

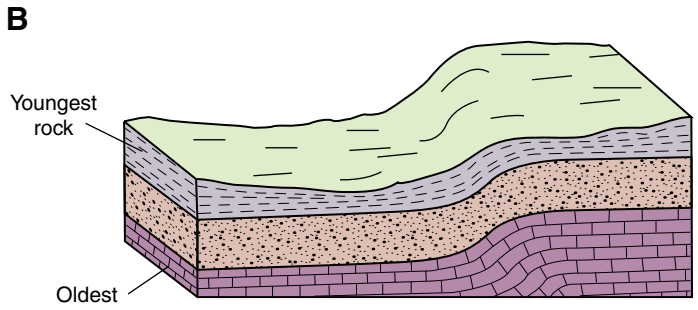
Figure 16. Folds and fractures in Precambrian rock near Rochford.

Uplift of the Black Hills began about 62 million years ago during the Laramide orogeny and probably continued in the Eocene Period (Redden and Lisenbee, 1996). Numerous **structural features**, such as **folds** and fractures (fig. 16), were created by the deformation and displacement of rocks during the uplift. These structural features are schematically illustrated in figure 17. Pairs of large **anticlines** (folds in which the strata dip away from the axis like an arch) and **synclines** (folds in which the strata dip toward the axis like a trough) occur on the northern and southern flanks of the Black Hills and plunge away from the uplift into the surrounding plains. Numerous domes, **faults,** and **monoclines** also occur in the Black Hills. Igneous intrusions, such as Bear Butte (fig. 18), were emplaced on the northern flanks of the uplift during the Tertiary Period.



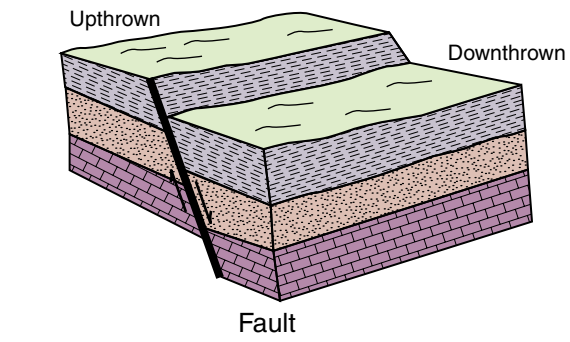
Photograph by Janet M. Carter

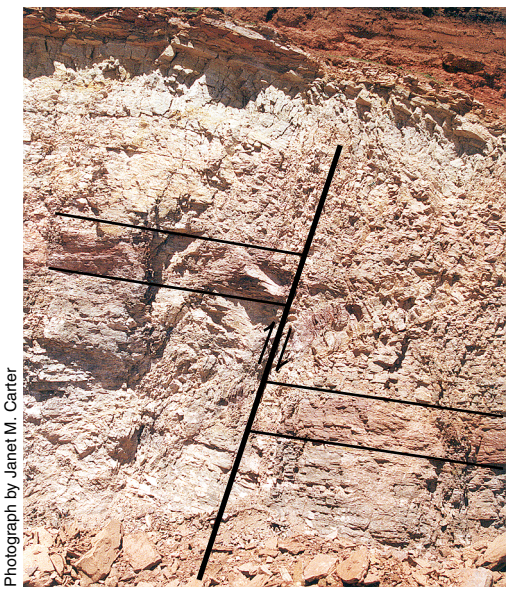
Broad anticline in the Minnekahta Limestone near Rapid City.



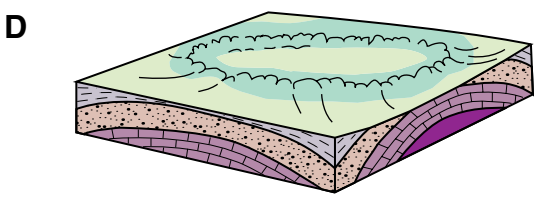
Photograph by Joyce E. Williamson

At the Whitegates monocline near Piedmont, the Madison Limestone dips steeply.




Photograph by Janet M. Carter

Small fault in the Minnekahta Limestone near Rapid City, where the dark red layer to the left of the fault has been thrust up relative to the dark red layer to the right of the fault.



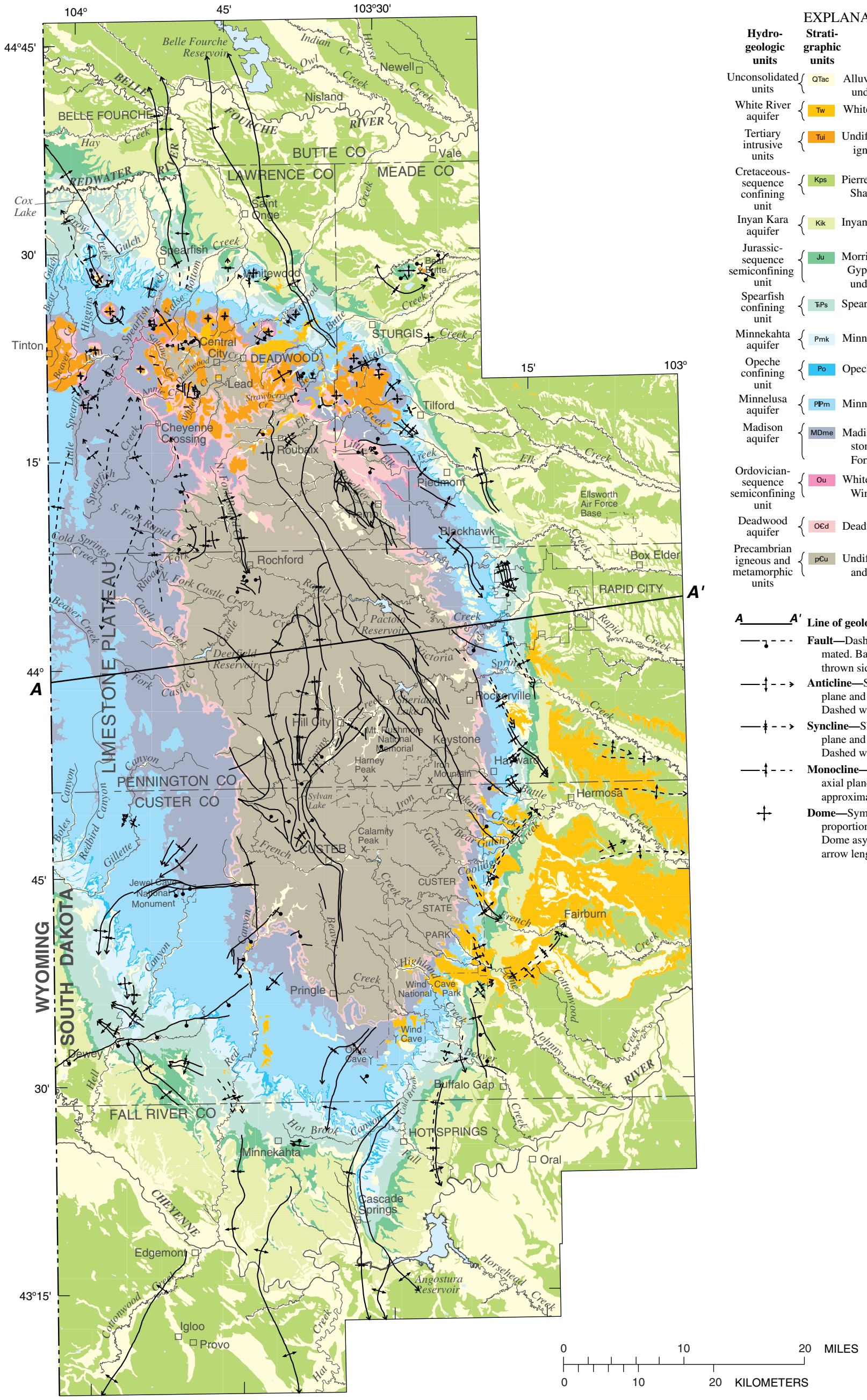
Photograph by Joyce E. Williamson

Green Mountain near Sundance, Wyoming, is a dome.

Figure 17. Schematic diagrams and photographs showing (A) anticline and syncline, (B) monocline, (C) fault, and (D) dome. Schematic diagrams modified from Spencer (1988) and Hamblin (1989).

Figure 18. Bear Butte is an igneous intrusion that rises more than 1,200 feet above the adjacent prairie. The butte was formed from molten magma about 51 million years ago. The high slope on the right is a block of the Madison Limestone, which was uplifted 4,500 to 5,000 feet by the intrusion (Gries, 1996).

Photograph by Michael T. Carter



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

Figure 19. Distribution of hydrogeologic units (modified from Strobel and others, 1999).

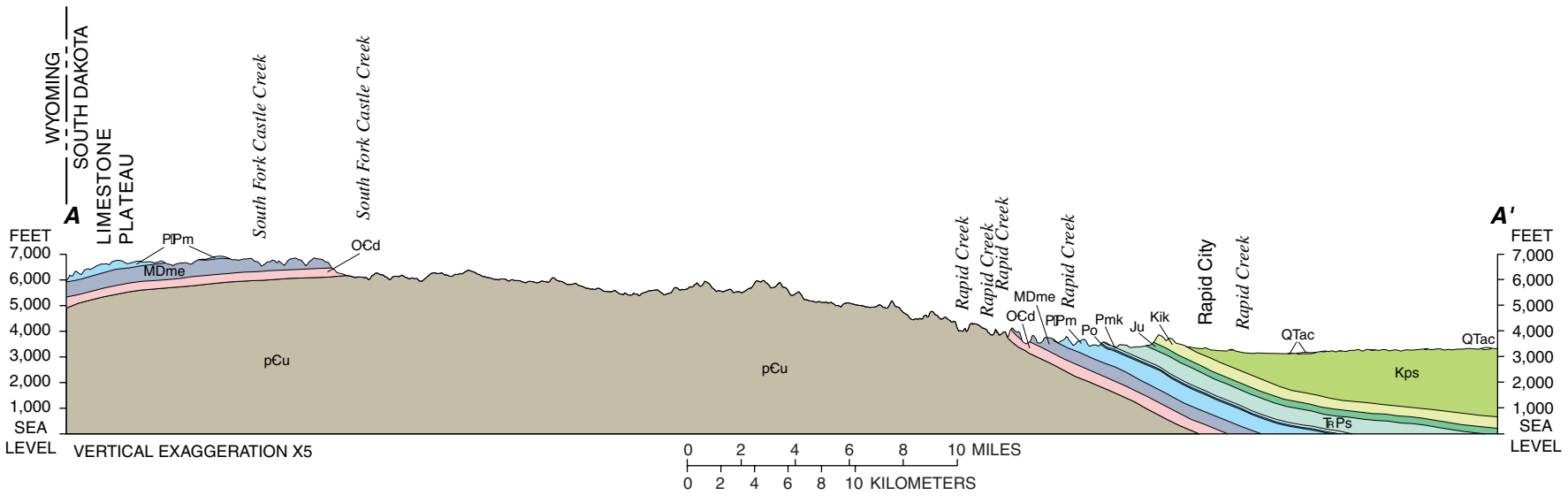


Figure 20. Geologic cross section A-A' (modified from Strobel and others, 1999). Location of section is shown in figure 19. Abbreviations for stratigraphic intervals are explained in figure 15.

The geologic units discussed in this section of the report are shown in the stratigraphic column (fig. 15). The geologic units are grouped into stratigraphic intervals representing hydrogeologic units comprising various aquifers, confining units, and semi-confining units, as shown in the explanation for figure 19 and discussed in the next section of the report. Figure 19 shows outcrops of the hydrogeologic units and locations of numerous structural features (anticlines, synclines, domes, faults, and monoclines) in the study area.

The oldest geologic units in the study area are the Precambrian igneous and **metamorphic** rocks (fig. 15), which underlie the **Paleozoic**, **Mesozoic**, and Cenozoic rocks and sediments. These Precambrian rocks are highly variable in composition and range in age from 1.7 to about 2.5 billion years. At the beginning of the Paleozoic Era, the Precambrian rocks were eroded to a gentle undulating plain (Gries, 1996). Then the Paleozoic and Mesozoic rocks were deposited on the Precambrian rocks as nearly horizontal beds. During the Laramide orogeny, the area was uplifted to form the Black Hills. An extensive period of erosion occurred during and after the uplift that removed approximately 7,500 feet of **sedimentary rocks** (Gries, 1996) and exposed the Precambrian **crystalline rocks** in the central core of the Black Hills. Previous altitudes are unknown because uplift and erosion probably occurred simultaneously; however, maximum altitudes probably approached current altitudes of some peaks in the Rocky Mountains. The exposed Precambrian rocks commonly are referred to as the crystalline core. Many of the Paleozoic and Mesozoic sedimentary rocks are exposed in roughly concentric rings around this crystalline core.

The layered series of sedimentary rocks surrounding the crystalline core includes outcrops of the Madison Limestone (also locally known as the Pahasapa Limestone) and the Minnelusa Formation, as shown in figure 19. A geologic **cross section**, which shows the geologic units in a vertical cut along the line A-A′ in figure 19, is shown in figure 20. The bedrock sedimentary units typically **dip** away from the uplifted Black Hills (fig. 20) at angles that can approach or exceed 15 to 20 degrees near the outcrops, and decrease with distance from the uplift to less than 1 degree. Following are descriptions for the Paleozoic and Mesozoic sedimentary units in the Black Hills area.

The oldest sedimentary unit in the study area is the Cambrian- and Ordovician-age Deadwood Formation (fig. 21), which is composed primarily of brown to light-gray sandstone, shale, limestone, dolomite, and local **basal conglomerate** (Strobel and others, 1999). These sediments were deposited on top of a relatively level plain of Precambrian rocks in beach and shallow marine environments. The thickness of the Deadwood Formation increases from south to north in the study area and ranges from 0 to 500 feet (Carter and Redden, 1999e). In the northern and central Black Hills, the Deadwood Formation is overlain by Ordovician rocks, which include the Whitewood and Winnipeg Formations. In the southern Black Hills, the Whitewood and Winnipeg Formations are absent, so the Deadwood Formation is overlain by the Englewood Formation, which generally is present throughout the Black Hills area except in the crystalline core. The Englewood Formation is overlain by the Madison Limestone.

Photograph by Janet M. Carter

Figure 21. Towering cliff of the Deadwood Formation in Deadwood, consisting mostly of sandstone and shale.

Photograph by Joyce E. Williamson

Photograph by Janet M. Carter

Figure 22. Outcrops of the Madison Limestone in Spearfish Canyon (upper photograph) and east of Custer (lower photograph).

Numerous caves and fractures occur in the upper part of the Madison Limestone, which have important hydrologic implications.

The Mississippian-age Madison Limestone (fig. 22) is a **massive**, gray to buff limestone with some dolomite (Strobel and others, 1999). The Madison Limestone was deposited by shallow seas and then was exposed above land surface for approximately 50 million years. During this period of extensive erosion, rainwater, made slightly acidic during its passage through the air, infiltrated slowly down through the limestone, dissolving caves in the rocks (Gries, 1996). As the caves collapsed, many of them broke through to the land surface, creating sinkholes. This process is called karstification, which results in a type of topography (with caves and sinkholes) called **karst**. Numerous caves (fig. 23) and fractures occur within the upper part of the Madison Limestone (Peter, 1985). The thickness of the Madison Limestone increases from south to north in the study area and ranges from almost zero in the southeast corner of the study area (Rahn, 1985) to 1,000 feet east of Belle Fourche (Carter and Redden, 1999d). The Madison Limestone is overlain by the Minnelusa Formation.

Photographs by Marc J. Ohms, National Park Service

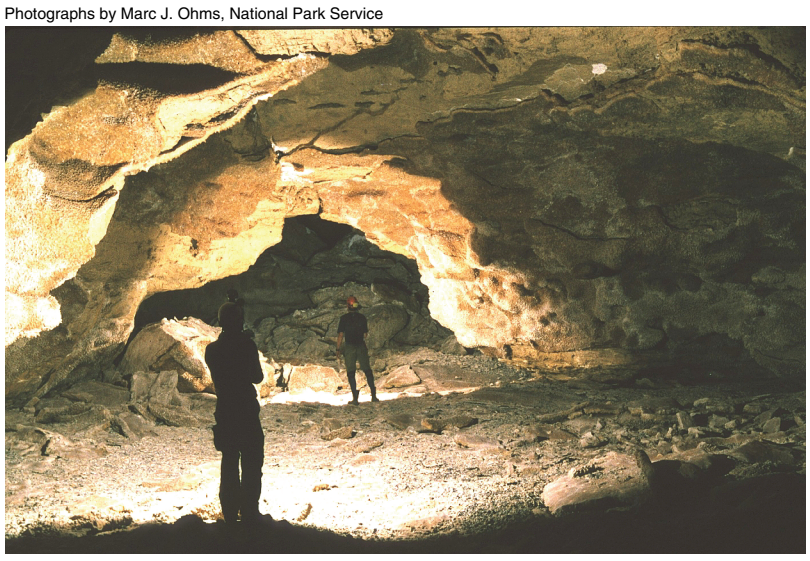


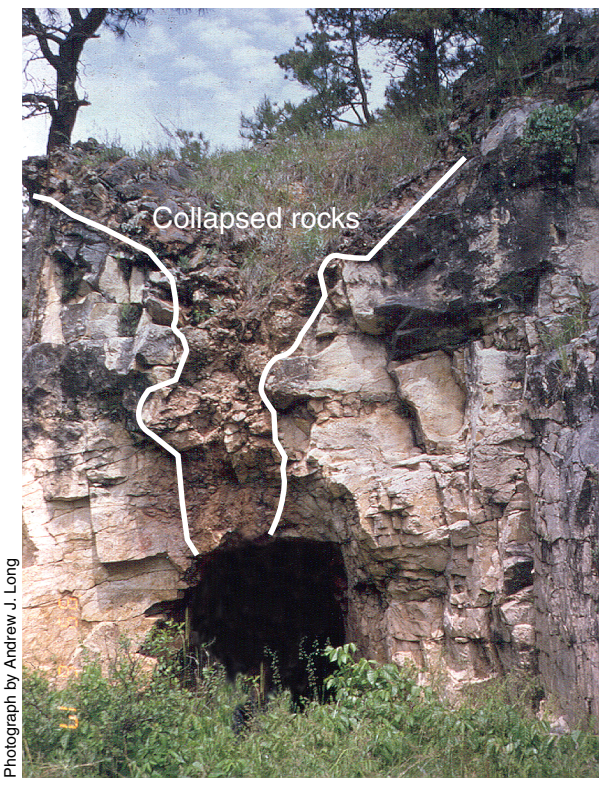
Figure 23. Large cave openings in the Madison Limestone at Jewel Cave.

The Pennsylvanian- and Permian-age Minnelusa Formation (fig. 24) consists mostly of yellow to red sandstone, limestone, dolomite, and shale (Strobel and others, 1999). In addition to sandstone and dolomite, the middle part of the formation contains **anhydrite,** which can be easily dissolved by water, and shale (DeWitt and others, 1986). The upper part of the Minnelusa Formation also may contain anhydrite, which generally has been dissolved in or near the outcrop areas, occasionally forming collapse features filled with rock fragments known as **breccia** (fig. 25) (Braddock, 1963). Numerous breccia pipes (fig. 25), which are cylindrical chimneys filled with breccia, exist in the southern Black Hills. The Minnelusa Formation was deposited in a coastal environment, and dune structures at the top of the formation may represent beach sediments (Gries, 1996). The thickness of the Minnelusa Formation increases from north to south in the study area and ranges from 375 feet near Belle Fourche to 1,175 feet near Edgemont (Carter and Redden, 1999c). The Minnelusa Formation is overlain by the Opeche Shale, which is overlain by the Minnekahta Limestone.

Photograph by Janet M. Carter

Figure 24. Outcrop of the Minnelusa Formation at Ranch A near Beulah, Wyoming.

Collapse features filled with breccia are common in the Minnelusa Formation.



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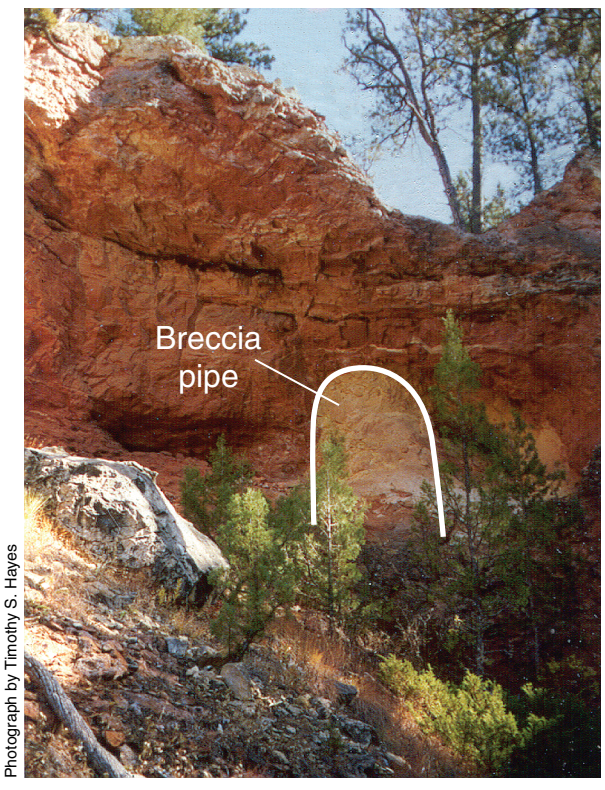

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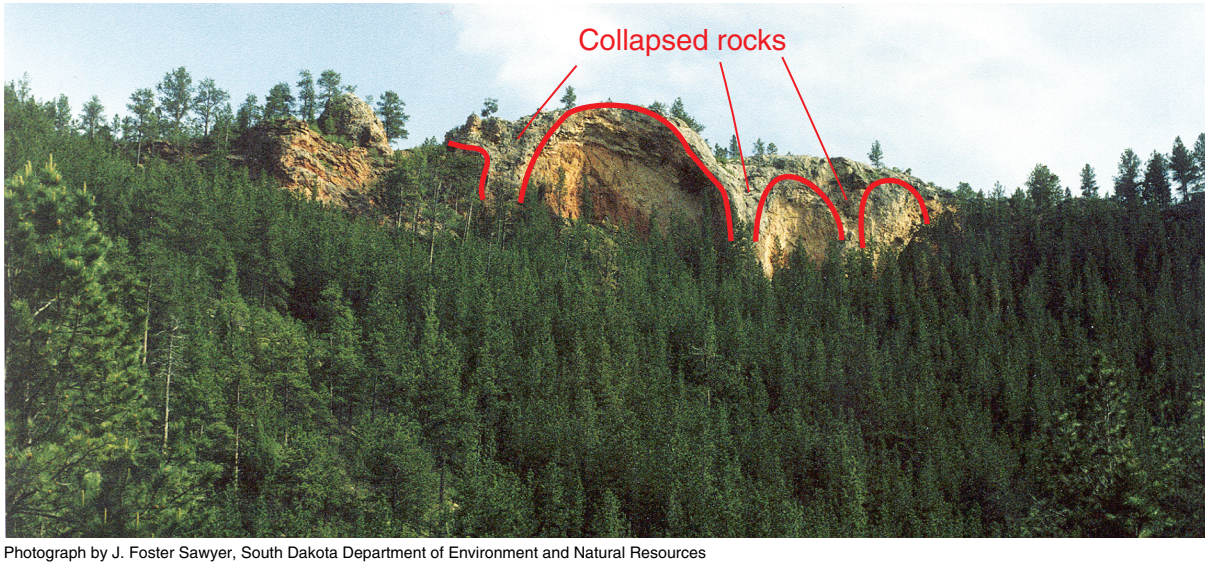


Photograph by J. Foster Sawyer, South Dakota Department of Environment and Natural Resources

Figure 25. Collapse breccia in the Minnelusa Formation in Redbird Canyon (lower photograph) and above Onyx Cave (upper left photgraph). Numerous breccia pipes, such as the one pictured in Hell Canyon (right photograph), exist in the southern Black Hills.

Photograph by Janet M. Carter

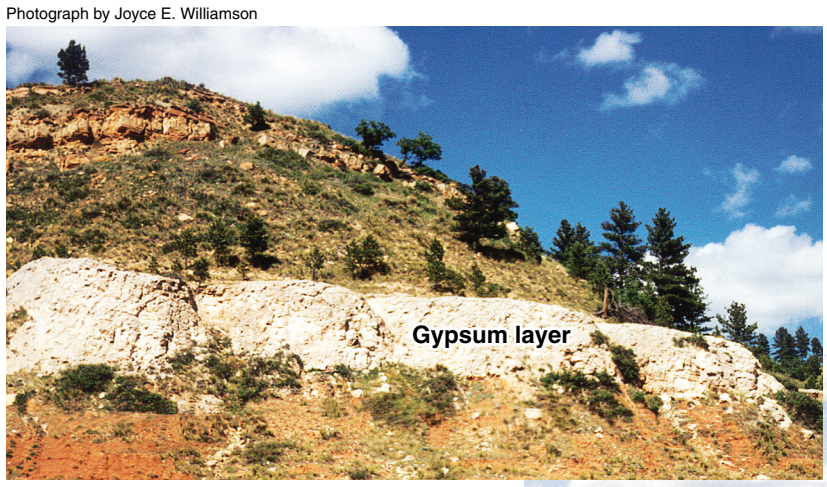
Figure 26. Outcrop of the Minnekahta Limestone near Beulah, Wyoming.

Photograph by J. Foster Sawyer, South Dakota Department of Environment and Natural Resources

Figure 27. Red cliffs of the Spearfish Formation west of Spearfish near the Wyoming border.

The dissolution of anhydrite in the Minnelusa Formation and gypsum in the Spearfish Formation can lead to the development of sinkholes and other collapse features.

Photograph by Joyce E. Williamson



Photograph by Joyce E. Williamson

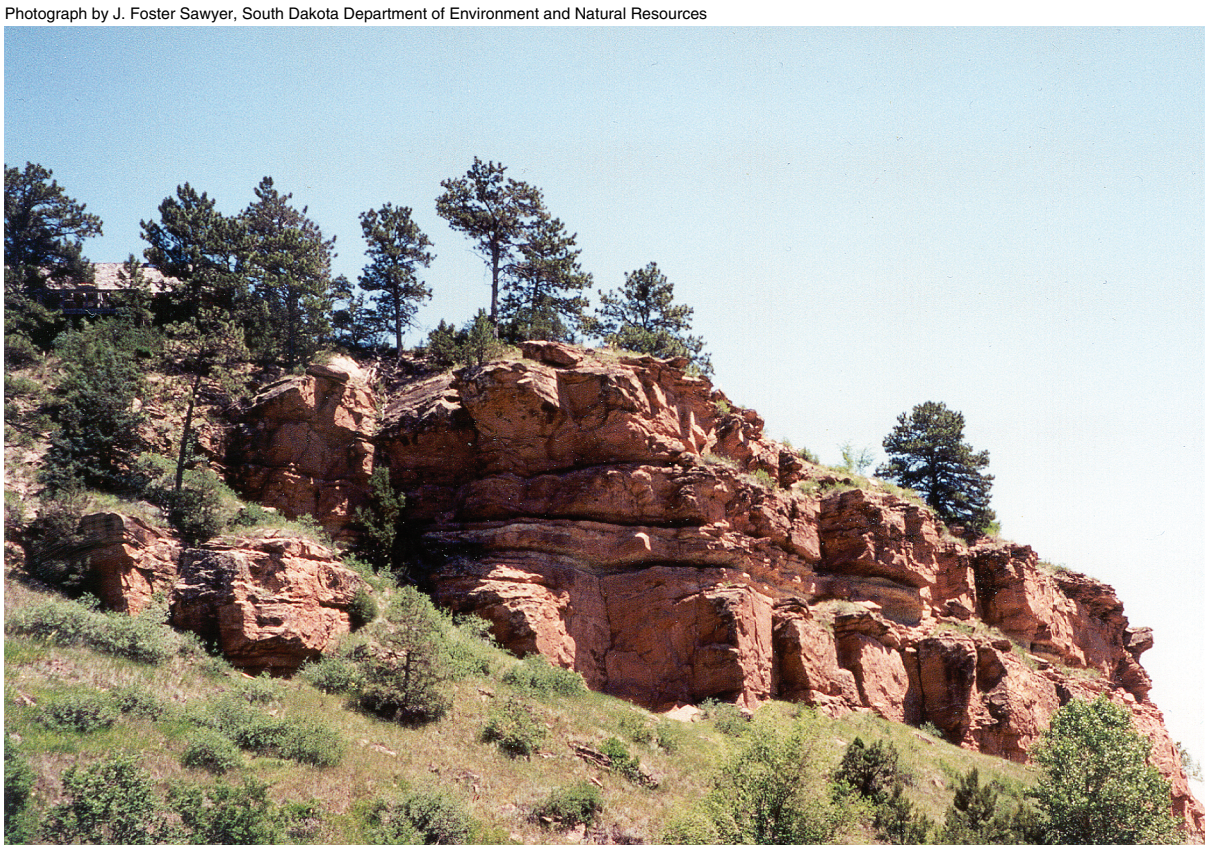
Figure 28. As water dissolves the massive gypsum (upper photograph) in the Spearfish Formation, sinkholes like this one just west of Beulah, Wyoming (lower photograph), can develop.

The Permian-age Minnekahta Limestone (fig. 26) is a fine-grained, purple to gray **laminated** limestone (Strobel and others, 1999), which ranges in thickness from 25 to 65 feet in the study area. The Minnekahta Limestone is overlain by the Spearfish Formation.

The Spearfish Formation (fig. 27) is a red, silty shale with interbedded red sandstone and siltstone, which ranges in thickness from about 375 to 800 feet (Strobel and others, 1999). The Spearfish Formation contains massive **gypsum** deposits (fig. 28) scattered throughout**.** Because gypsum is easily dissolved by water, numerous sinkholes in the Spearfish Formation have developed (fig. 28), especially in the northern Black Hills (Epstein, 2000). The process of dissolving minerals and rock materials is called **dissolution**. Overlying the Spearfish Formation are Mesozoic-age units that are composed primarily of shale, siltstone, and sandstone deposits, and include the Cretaceous-age Inyan Kara Group.

The Inyan Kara Group (fig. 29) consists of the Lakota Formation and overlying Fall River Formation. A resistant ridge of Cretaceous sandstones, mostly of the Lakota Formation, completely encircles the Black Hills and stands hundreds of feet above the surrounding prairie. This ridge, known as the Cretaceous **hogback**, forms a general boundary between the Black Hills and the prairie (Gries, 1996). The Lakota Formation consists of yellow, brown, and reddish-brown massive to thinly bedded sandstone, pebble conglomerate, siltstone, and claystone that were deposited by rivers (Gott and others, 1974); locally there are lenses of limestone and coal. The Fall River Formation is a brown to reddish-brown, fine-grained sandstone, thin bedded at the top and massive at the bottom (Strobel and others, 1999). The thickness of the Inyan Kara Group ranges from 135 to 900 feet in the study area (Carter and Redden, 1999a). The Inyan Kara Group is overlain by a thick sequence of various shale units with some interbedded sandstone units.

Photograph by J. Foster Sawyer, South Dakota Department of Environment and Natural Resources



Photograph by Janet M. Carter

Figure 29. The Inyan Kara Group is exposed in the Cretaceous hogback in the Skyline Drive area of Rapid City (left photograph) and in Fall River Canyon (upper photograph). The outcrop of the Inyan Kara Group forms the general boundary of the Black Hills.

Ground Water

An overview of the ground-water framework is presented in this section of the report. Additional information is presented in a subsequent section of the report describing the ground-water resources.

The hydrologic setting of the Black Hills area is schematically illustrated in figure 30, and the distribution of the hydrogeologic units was presented previously in figure 19. The major bedrock aquifers in the Black Hills area are the Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara aquifers. Minor bedrock aquifers occur in other units, including confining units, due to fracturing and interbedded permeable layers. Infiltration of precipitation on outcrops is the primary source of recharge to most bedrock aquifers. The unconsolidated units, which includes alluvium and **colluvium**, are considered aquifers where saturated.

The major bedrock aquifers in the Black Hills area are the Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara aquifers.

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

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

The Precambrian basement rocks generally have low permeability and form the lower confining unit for the series of sedimentary aquifers (fig. 30). However, localized aquifers occur in many locations in the crystalline core of the Black Hills where **secondary permeability** (developed after the rock was formed) has resulted from weathering and fracturing. Water-table (unconfined) conditions generally occur in these localized aquifers, and topography can strongly control ground-water flow directions.

Overlying the Precambrian rocks is the Deadwood aquifer, which is contained within the Deadwood Formation and is used primarily near outcrop areas. Regionally, the Precambrian rocks act as an underlying confining unit to the Deadwood aquifer, and the Whitewood and Winnipeg Formations, where present, act as overlying semiconfining units (Strobel and others, 1999). Where the Whitewood and Winnipeg Formations are absent, the Deadwood aquifer is in contact with the overlying Englewood Formation, which was included as part of the Madison aquifer for this study.

The Madison aquifer generally occurs within the karstic upper part of the Madison Limestone, where numerous fractures and solution openings (fig. 31) have created

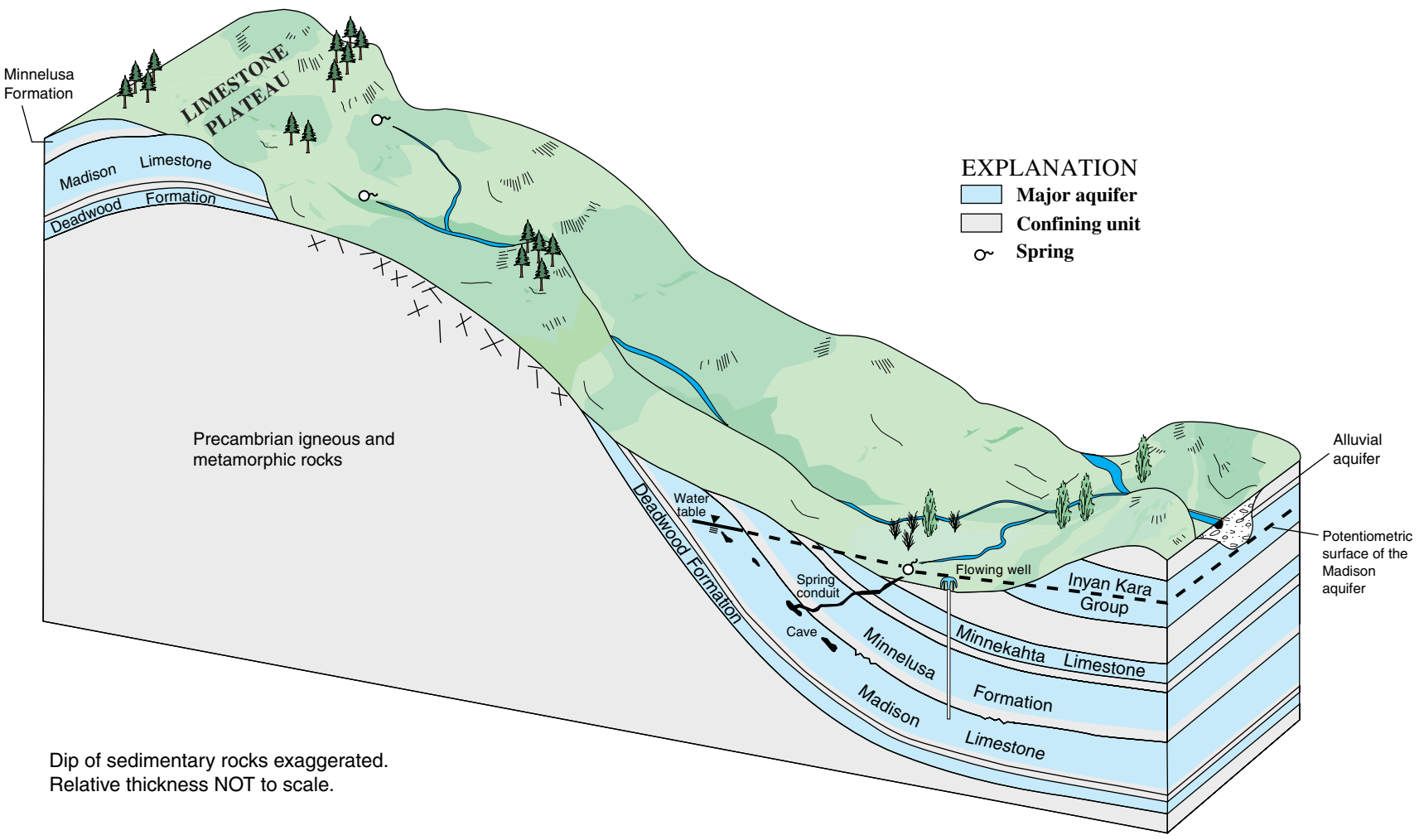


Figure 30. Schematic diagram showing simplified hydrologic setting of the Black Hills area. Schematic diagram generally corresponds with geologic cross section shown in figure 20.

Photographs by Earl A. Greene

Figure 31. Large solution openings, such as these in the Madison Limestone, provide conduits that store and transmit large volumes of water. Six large lakes, including Windy City Lake in the left photograph, have been discovered in Wind Cave about 500 feet below land surface. In the right photograph, the staff gage measures the water depth, which is about 1½ feet deep in a cave lake near Rapid City.

extensive **secondary porosity** and permeability. The entire Madison Limestone and the Englewood Formation were included in the delineation of the Madison aquifer for this study. Thus, in this report, outcrops of the Madison Limestone and Englewood Formation (fig. 19) are referred to as the outcrop of the Madison Limestone for simplicity. The Madison aquifer receives recharge from streamflow losses and precipitation on the outcrop. Low-permeability layers in the lower part of the Minnelusa Formation generally act as an upper confining unit to the Madison aquifer. However, karst features in the top of the Madison Limestone may have reduced the effectiveness of the overlying confining unit in some locations.

The Minnelusa aquifer occurs within layers of sandstone, dolomite, and anhydrite in the lower portion of the Minnelusa Formation and sandstone and anhydrite in the upper portion. Shales in the lower portion of the Minnelusa Formation act as confining layers to the underlying Madison aquifer; however, the extent of hydraulic separation between the two aquifers varies greatly between locations and is not well defined. Collapse breccia associated with dissolution of interbedded anhydrite in the Minnelusa Formation may enhance secondary porosity in the aquifer (Long and others, 1999). The Minnelusa aquifer receives significant recharge from streamflow losses and precipitation on the outcrop. Streamflow recharge to the Minnelusa aquifer generally is less than to the Madison aquifer because much streamflow is lost to the Madison aquifer before reaching the outcrop of the Minnelusa Formation. The Minnelusa aquifer is confined by the overlying Opeche Shale.

Secondary porosity and permeability have been enhanced by fractures and solution openings in the Madison aquifer and by collapse breccia in the Minnelusa aquifer.

Five hydrogeologic settings have been identified for the Black Hills area that have distinctive influences on streamflow and water-quality characteristics. The settings include the limestone headwater, crystalline core, and exterior settings, as well as the loss zone and artesian spring settings, which share a common area.

Photograph by Michael T. Carter

Figure 32. Cox Lake, which is South Dakota's deepest natural lake, is an artesian spring originating mostly from the Madison aquifer. Cox Lake occupies a large sinkhole in the Spearfish Formation that is more than 60 feet deep (Epstein, 2000).

Photograph by J. Foster Sawyer, South Dakota Department of Environment and Natural Resources

Figure 33. The Pierre Shale, as shown here near Buffalo Gap, is one of many Cretaceous shales that confine aquifers in the Mesozoic rock interval. In general, shales have very low permeability and impede ground-water flow. Many landfills and sewage lagoons are constructed in shales, which provide a natural barrier against leakage of potential contaminants to aquifers and streams.

The Madison and Minnelusa aquifers are distinctly different aquifers, but are connected hydraulically in some areas. Many of the artesian springs (fig. 32) have been interpreted as originating at least partially from upward leakage from the Madison aquifer; however, the overlying Minnelusa aquifer and other aquifers probably contribute to springflow in many locations.

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

Within the Mesozoic rock interval, the Inyan Kara aquifer is used extensively, and aquifers in various other formations are used locally. The Inyan Kara aquifer receives recharge primarily from precipitation on the outcrop. The Inyan Kara aquifer also may receive recharge from leakage from the underlying Paleozoic aquifers (Swenson, 1968; Gott and others, 1974). As much as 4,000 feet of Cretaceous shales, including the Pierre Shale (fig. 33), act as the upper confining unit to aquifers in the Mesozoic rock interval.

Surface Water

Surface water, mainly streamflow, is highly influenced by geologic conditions. Five hydrogeologic settings have been identified for the Black Hills area that have distinctive influences on surface water. The five settings, which are shown in figure 34, are represented by four areas, because two of the settings (loss zone and artesian spring) are considered to share a common area. Locations of streamflow-gaging stations that are used to identify representative streamflow characteristics (subsequently referred to as representative gaging stations) are included in figure 34. Representative water-quality sampling sites also are shown in figure 34. The hydrogeologic settings influence both streamflow and water-quality characteristics, as described in subsequent sections of the report. Within this section, the basic framework for the surface-water hydrology of the area is described.

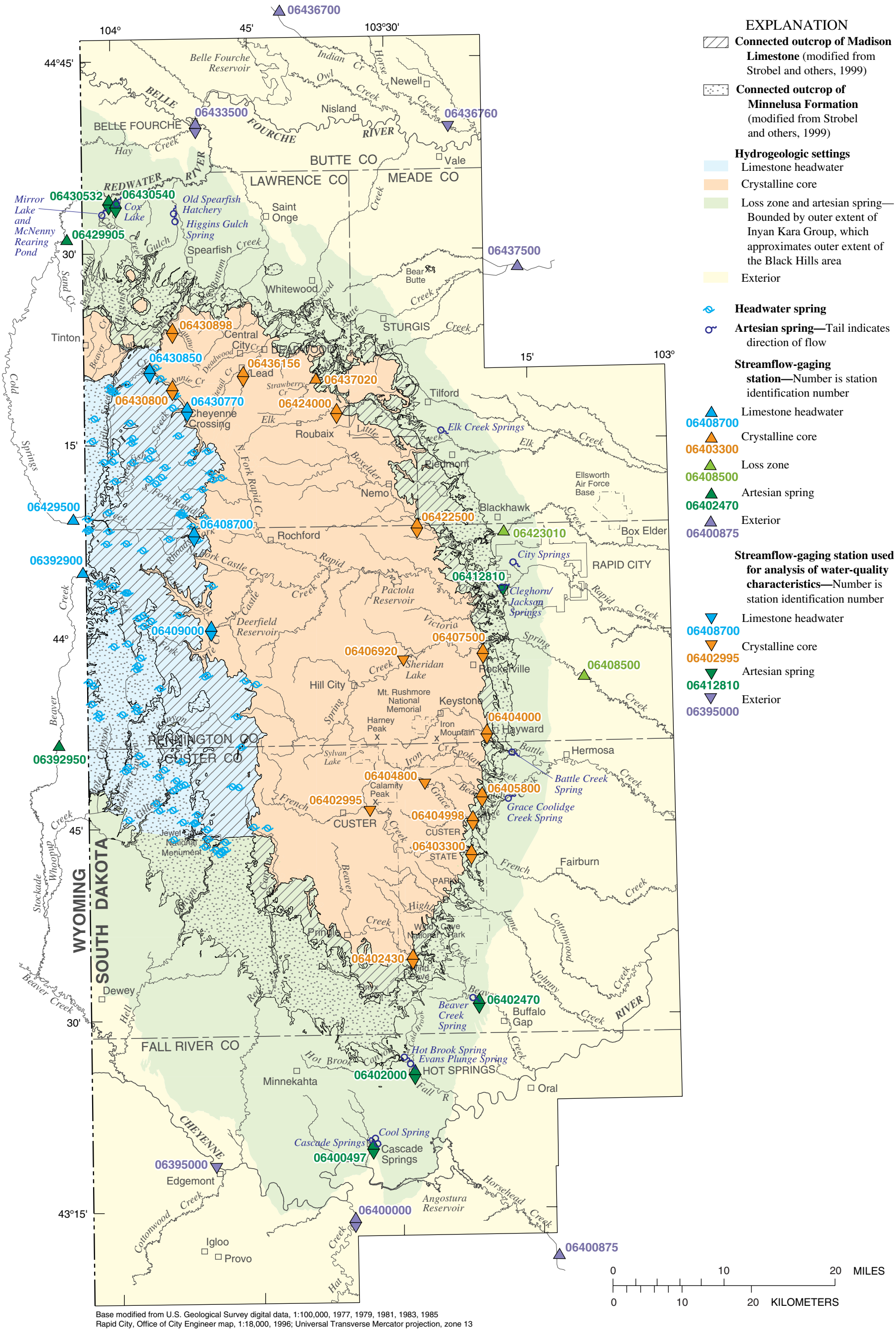


Figure 34. Hydrogeologic settings for the Black Hills area. Locations of streamflow-gaging stations representative of the settings also are shown.

Photograph by Van A. Lindquist, West Dakota Water Development District

Photograph by Janet M. Carter

Figure 35. Substantial headwater springflow occurs in the Limestone Plateau area along two creeks that flow west into Wyoming. Beaver Creek (upper photograph) and Cold Springs Creek (lower photograph) have perennial flowing reaches in South Dakota; however, flow of both streams is lost within outcrops of the Minnelusa Formation farther downstream in Wyoming.

Outcrops of the Madison Limestone and Minnelusa Formation that are shown in figure 34 have been modified (for simplicity) to include only "connected" outcrops of these formations. The connected outcrops exclude "**erosional remnants**" of these formations that are isolated from the regional ground-water flow systems for the associated aquifers (Carter, Driscoll, and Hamade, 2001).

The limestone headwater setting is considered to be within or near the "Limestone Plateau" area (fig. 19), where large outcrops of the Madison Limestone and Minnelusa Formation occur in a high-altitude area of generally low relief, along the South Dakota-Wyoming border. Ground-water discharging from this area (springflow) becomes surface water, which is carried as streamflow to downstream locations. Numerous water-table springs (fig. 34) occur along the eastern edge of the Limestone Plateau, especially within the headwaters of Castle Creek, Rapid Creek, and Spearfish Creek. Most of the largest springs are located upstream from the gaging stations representative of this setting. Substantial springs also are located upstream from the two gaging stations on Beaver Creek and Cold Springs Creek (fig. 35), along the Wyoming border.

Most of the limestone headwater springs occur near the eastern edge of the Limestone Plateau (fig. 36), primarily in areas where the contact between the Madison Limestone and underlying geologic units (fig. 15) is

For the limestone headwater setting, streamflow is dominated by water-table springs draining the eastern edge of the Limestone Plateau. The largest headwater springs occur in Castle Creek, Rapid Creek, and Spearfish Creek. Within this setting, sustained streamflow is uncommon; however, small perched springs occur in many locations.

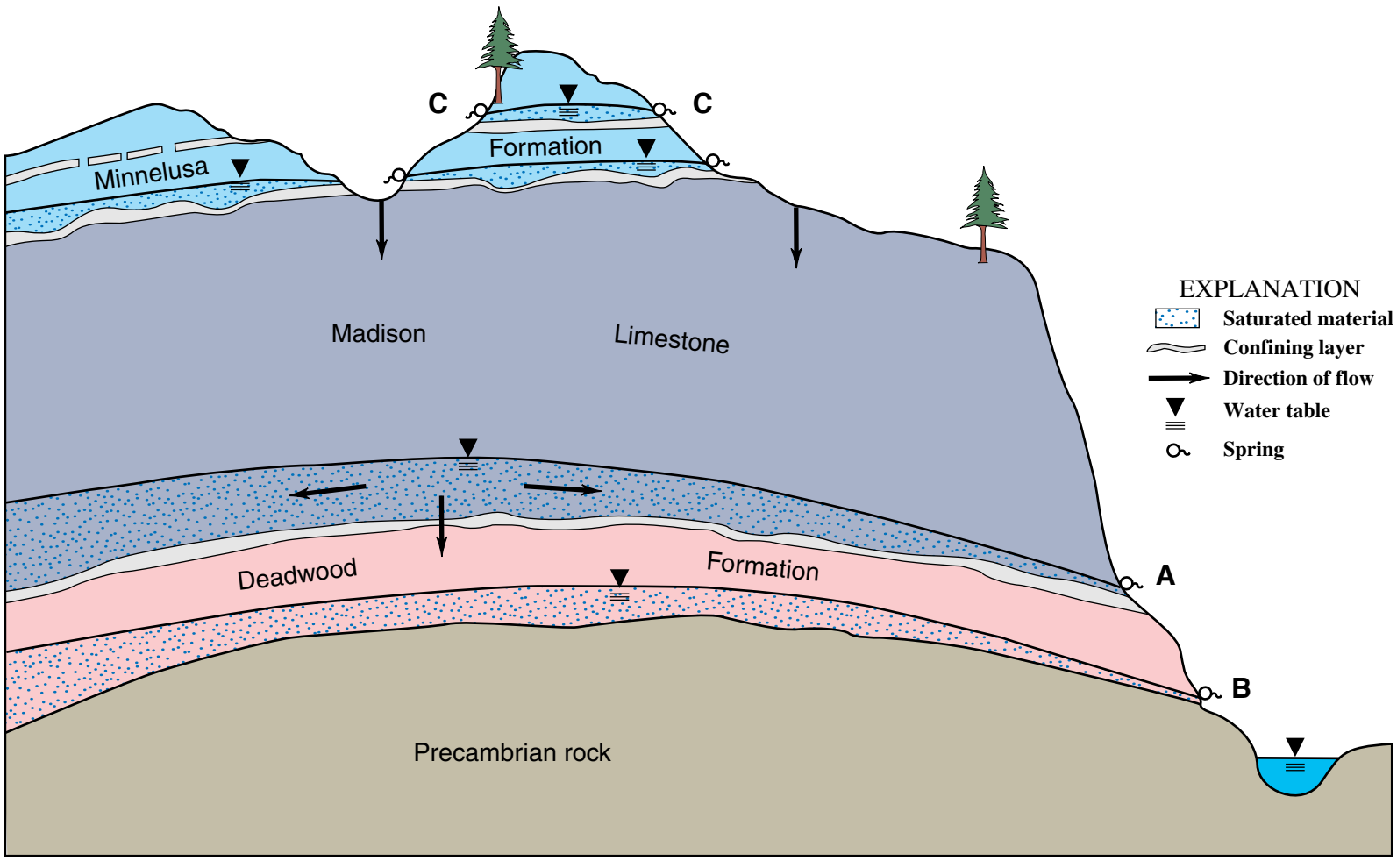
exposed. Various low-permeability layers in the underlying units can act as confining layers (fig. 37), which result in lateral movement of ground water prior to discharge as springflow.

Upon the Limestone Plateau, sustained streamflow is very uncommon and generally occurs only in limited areas where low permeability "perching" layers occur (fig. 37). Such conditions probably exist in the vicinity of the two Wyoming gaging stations, where streamflow is sustained for short distances downstream of the gaging stations. Small **perched springs** are common, however, especially within outcrops of the Minnelusa Formation. Locations of mapped springs obtained from the USGS Ground Water Site Inventory (GWSI) database are shown in figure 34.

The crystalline core setting (fig. 34) consists primarily of igneous and metamorphic rocks within the central part of the Black Hills (fig. 19). Most of the gaging stations representative of this setting are located along the northern and eastern flanks of the uplift, immediately upstream from the outcrop of the Madison Limestone. Only gaging stations with minor influence from limestone headwater springs are considered representative of this setting. For example, numerous gaging stations along Rapid Creek are not considered representative of the crystalline core setting because of large influence from limestone headwater springs.

Photograph by Van A. Lindquist, West Dakota Water Development District

Figure 36. Headwater springflow at the eastern edge of the Limestone Plateau provides flow to Rhoads Fork.



Relative thinkness NOT to scale

Figure 37. Schematic diagram showing various spring types found in the limestone headwater area. In this area, most springs occur where hillsides intersect water tables. The largest springs (A) generally occur in incised channels near the base of the Madison Limestone, which is the predominant outcrop. Springs near the base of the Deadwood Formation (B) generally are smaller because of limited outcrop area. Perched springs (C) are common within outcrops of the Minnelusa Formation, in which minor, low-permeability confining layers are common.

Streamflow losses occur in most streams in crossing outcrops of the Madison Limestone and Minnelusa Formation. These losses are an important source of recharge for the Madison and Minnelusa aquifers. Farther downstream, confined (artesian) conditions generally occur within the Madison and Minnelusa aquifers, and in some locations artesian springs originating from these aquifers contribute to streamflow.

The loss zone setting consists of areas that are heavily influenced by streamflow losses that occur as streams cross outcrops of the Madison Limestone and Minnelusa Formation. The outer extent of this area is represented by the outer extent of the Inyan Kara Group (fig. 34). The same area is used to represent the artesian spring setting because many artesian springs are located along stream channels that also are influenced by streamflow. Locations of selected artesian springs are shown in figure 34.

No artesian springs are known to be located beyond the outcrop of the Inyan Kara Group; thus, the area beyond this outcrop is considered to be the exterior setting. Many streams in the exterior setting are influenced by upstream streamflow losses, artesian springs, or both. The gaging stations that are considered representative of this setting, however, are influenced primarily by exterior areas and have little influence from areas upgradient from the outcrop of the Inyan Kara Group.

Especially complex interactions between ground water and surface water can occur in streams within the combined loss zone and artesian spring settings. A schematic diagram illustrating these interactions is presented as figure 38, and a brief description of these interactions is provided in the following paragraphs.

Upstream from the outcrop of the Madison Limestone, stream channels in most of the larger **drainage basins** have **perennial** (or nearly perennial) flow, and associated alluvial deposits generally are saturated to the approximate level of the stream (fig. 38A). Farther downstream (fig. 38B), streamflow losses commonly begin to occur where the Madison Limestone outcrop is encountered, which provides recharge to the Madison aquifer but diminishes flow in the stream channel.

Substantial streamflow losses occur along most stream channels in loss zones within outcrops of the Madison Limestone and Minnelusa Formation (Hortness and Driscoll, 1998). Losses also occur within outcrops of the Minnekahta Limestone in many locations; however, these losses generally are smaller and more difficult to quantify. A summary of approximate **loss thresholds**, or maximum sustainable loss rates for individual streams, is presented in table 4. Streamflow losses can occur along Iron Creek and Higgins Gulch; however, loss thresholds are noted as zero because these streams receive net ground-water discharge from the Madison and Minnelusa aquifers. Newton and Jenny (1880) observed losses in

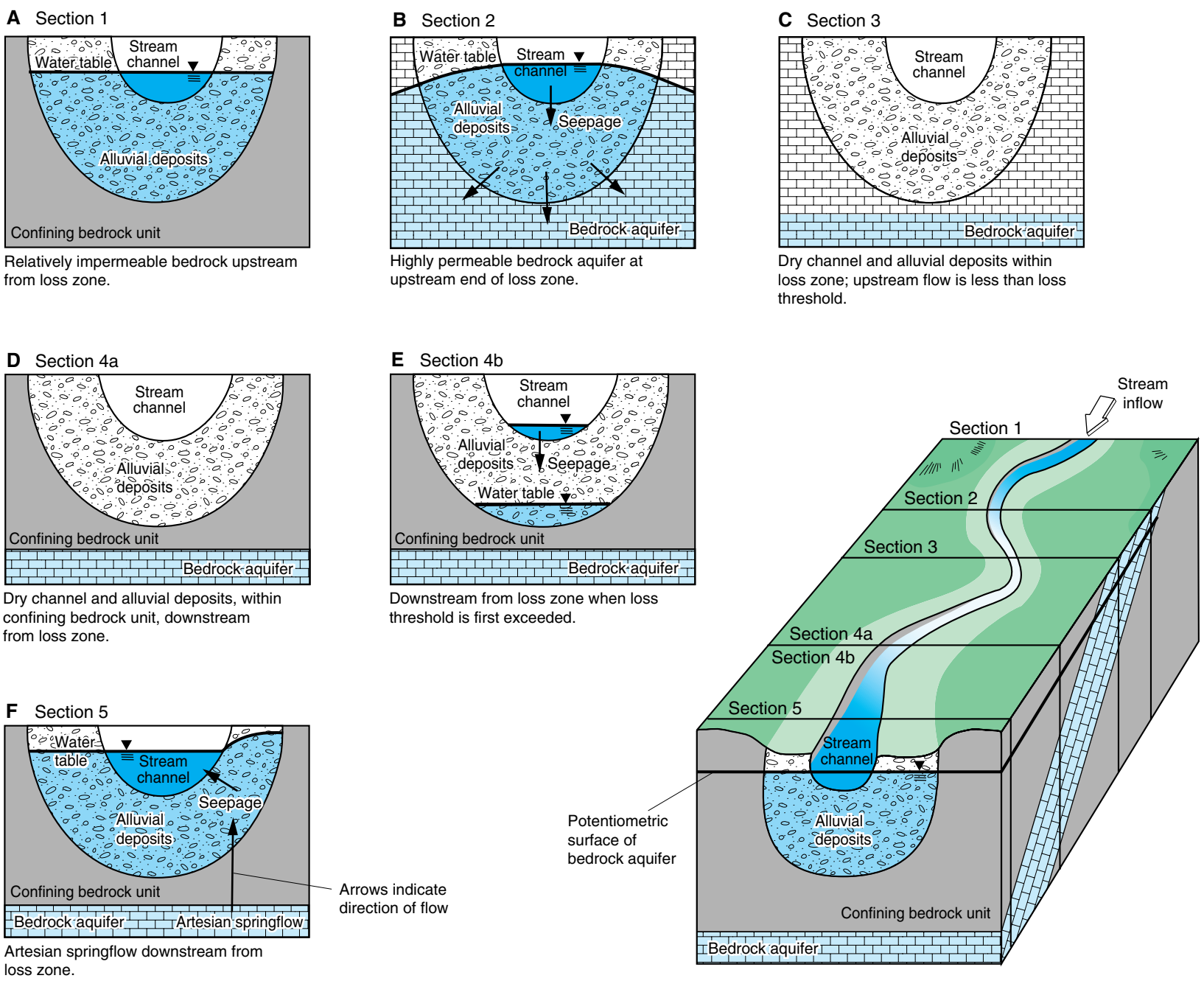


Figure 38. Schematic diagram illustrating interactions between ground water and surface water in the combined loss zone and artesian spring settings. This diagram represents a downstream progression in a generic stream reach from just upstream of a loss zone to just downstream from an artesian spring.

Whitewood Creek; however, loss zones apparently were sealed by fine-grained mine tailings that have been discharged to the stream (Hortness and Driscoll, 1998).

Within and immediately downstream from loss zones, stream channels and associated alluvial deposits generally are not saturated when loss thresholds are not exceeded (figs. 38C and D). Flow may occur downstream from a loss zone when upstream streamflow exceeds the loss threshold; however, additional depletion of streamflow occurs in saturating alluvial deposits (fig. 38E). Artesian springflow that is sufficient to saturate alluvial deposits and sustain streamflow occurs in many stream channels downstream from loss zones (fig. 38F). A series of photographs is presented in figure 39 that shows a downstream progression of channel conditions along Grace Coolidge Creek.

Hortness and Driscoll (1998) concluded that loss thresholds are relatively stable and generally are not affected by flow rates or duration of flow through loss zones. Decreases in apparent loss rates were documented, however, for several streams following extended periods of wet climatic conditions and large recharge. Measurable effects for Boxelder Creek and Elk Creek were attributed to perched springflow originating from large outcrops of the Madison Limestone and Minnelusa Formation that are located adjacent to loss zones.

Table 4. Summary of loss thresholds from Black Hills streams to bedrock aquifers

[From Hortness and Driscoll (1998). ft^3/s, cubic feet per second]

Stream name	Approximate loss threshold (ft^3/s)
Beaver Creek[1]	5
Highland Creek	10
South Fork Lame Johnny Creek	1.4
North Fork Lame Johnny Creek	2.3
French Creek	15
Battle Creek	12
Grace Coolidge Creek	21
Bear Gulch[1]	.4
Spokane Creek	2.2
Spring Creek	28
Rapid Creek	10
Victoria Creek	1.0
Boxelder Creek	50
Elk Creek	19
Little Elk Creek	3.3
Bear Gulch[2]	4
Beaver Creek[2]	9
Iron Creek	0
Spearfish Creek	23
Higgins Gulch	0
False Bottom Creek	15
Whitewood Creek	0
Bear Butte Creek	12

[1]Located in southern Black Hills.
[2]Located in northern Black Hills.

A

Photograph by Janet M. Carter

B

Photograph by Joyce E. Williamson

C

Photograph by Janet M. Carter

Figure 39. Downstream progression of channel conditions along Grace Coolidge Creek. Photograph A shows disappearance of flow within the streamflow-loss zone. Photograph B shows the dry channel within the outcrop of the Madison Limestone. Photograph C shows an artesian spring located adjacent to an outcrop of the Minnekahta Limestone, which is a typical location for artesian springs.

Within streamflow loss zones, stream channels and associated alluvial deposits generally are dry unless loss thresholds (maximum sustainable loss rates) are exceeded. Unique loss thresholds exist for individual streams, with measured loss thresholds ranging from negligible (no measurable losses) to as much as 50 cubic feet per second for Boxelder Creek.

Streamflow loss thresholds are relatively stable, with little change over time. Increased springflow within loss zones resulting from prolonged wet conditions can temporarily reduce apparent loss rates. Introduction of fine-grained sediment has altered loss rates in several streams.

Changes in loss thresholds resulting from changes in channel conditions have been documented for Whitewood Creek (previously discussed), Spring Creek, and Grace Coolidge Creek (Hortness and Driscoll, 1998). The loss threshold in Spring Creek reportedly was temporarily decreased (Powell, 1940) by placing bentonite in known loss areas. The loss threshold for Grace Coolidge Creek also was temporarily reduced by massive amounts of fine-grained sediments resulting from the Galena Fire (fig. 40), a large forest fire that burned about one-half of the drainage area in 1988 (Whitesides, 1989). It is likely that temporary reduction of loss thresholds may occur in other burned areas following forest fires.

The combined influence of loss zones and artesian springs are important factors affecting streamflow characteristics around the periphery of the Black Hills. Only two streams in the study area maintain perennial flow through loss zones. One is Whitewood Creek (previously discussed), in which the loss zone apparently has been sealed by mine tailings. The other is Rapid Creek, in which flow is regulated by two upstream reservoirs. The natural flow of Rapid Creek generally would be sufficient to exceed the relatively small loss threshold of 10 **cubic feet per second**. Spearfish Creek also would maintain perennial flow under most conditions; however, flow is diverted around the loss zone for hydroelectric power generation.

Many streams in the study area have perennial (or nearly perennial) flow downstream from artesian springs. Locations of major artesian springs are included in figure 34. The largest artesian spring discharge areas are located near the northern and southern axes of the Black Hills. In the southern Black Hills, Cascade Springs (fig. 41) and springs along Fall River, Beaver Creek, and Stockade Beaver Creek (located in Wyoming) are especially large and consistent. Springs along Grace Coolidge Creek and Battle Creek have more variable flow characteristics and may approach zero flow during extremely infrequent periods of prolonged drought conditions.

Photograph by Deitrich H. Whitesides

Figure 40. Ash bars and large deltas, such as these in tributaries to Grace Coolidge Creek, formed as the result of heavy erosion following the Galena Fire in 1988. The loss threshold of Grace Coolidge Creek was temporarily reduced by massive amounts of fine-grained sediments resulting from the fire. The background photograph shows the regrowth in the burned area more than 10 years after the fire that consumed 16,788 acres.

Photograph by Mark T. Anderson

Photograph by Joyce E. Williamson

Along Rapid Creek, the combined flow of Cleghorn and Jackson Springs is large and steady (Anderson and others, 1999); however, the flow of City Springs is much smaller and subject to prolonged periods of zero flow (Driscoll and Carter, 2001). Large but highly variable springs occur along Elk Creek, with springflow ranging from zero to as much as 20 cubic feet per second (Driscoll and Carter, 2001). Transient and relatively small springs also exist along Spring Creek and Bear Butte Creek; however, these springs probably do not originate as artesian springflow from the Madison and Minnelusa aquifers.

In the northern Black Hills, a number of artesian springs contribute to consistently large **base flow** of the Redwater River, in which flow typically originates from a series of springs along Sand Creek (fig. 42) in Wyoming. Additional flow is contributed by Cox Lake and springs along Crow Creek, which comprise the largest artesian spring discharge area in the Black Hills area. Other springs (Old Spearfish Hatchery and Higgins Gulch) are located just west of Spearfish.

Photograph by Andrew J. Long

Figure 41. Cascade Springs, like many artesian springs in the Black Hills, provides a consistent source of flow to streams. Cascade Springs flows about 20 cubic feet per second and originates primarily from the Madison aquifer.

The largest artesian spring discharge areas are located near the northern and southern axes of the Black Hills uplift. The single largest spring discharge area includes Cox Lake and springs along Crow Creek.

Figure 42. Artesian springflow in Wyoming along Sand Creek (upper photograph) accounts for as much as 20 cubic feet per second of the total springflow contributed to the Redwater River (lower photograph). Cumulative artesian springflow contributing to the Redwater River commonly approaches 100 cubic feet per second.

Photographs by Joyce E. Williamson

Whitewood Creek and Rapid Creek are the only two streams in the study area with perennial flow through loss zones.

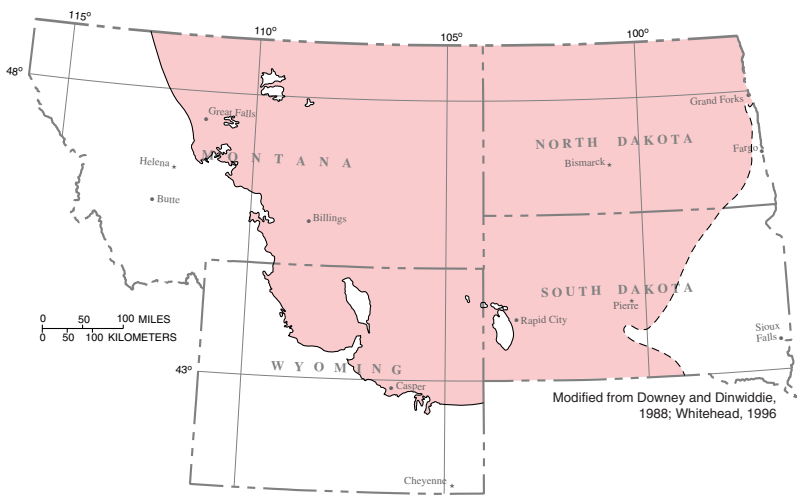
Photograph courtesy of Bureau of Reclamation

Figure 43. Streamflow conditions in the Black Hills are influenced by reservoirs, such as Pactola Reservoir. Pactola Reservoir is formed by an earthfill dam completed in 1956. Pactola Reservoir is used to regulate flow in Rapid Creek to provide flood control and water for municipal and irrigation uses. Total storage of Pactola Reservoir is 99,000 acre-feet, of which 43,000 acre-feet is exclusive flood control storage.

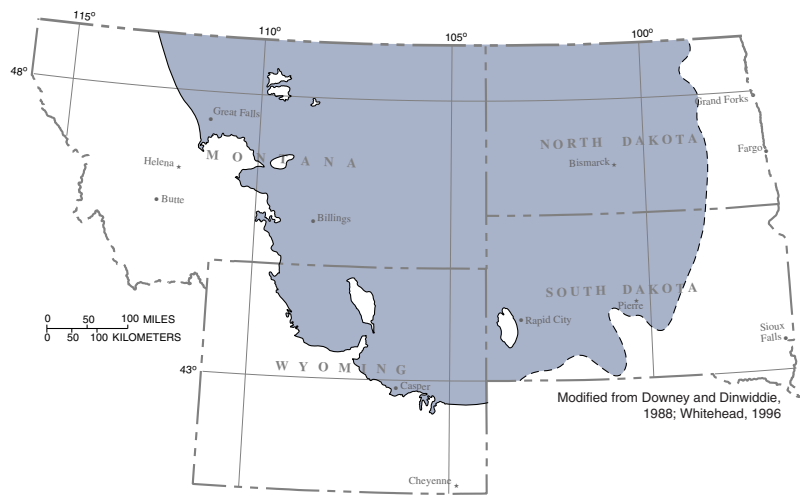
The Deadwood, Madison, Minnelusa, and Inyan Kara aquifers are major regional aquifers that underlie parts of Montana, North Dakota, South Dakota, Wyoming, and Canada.

Streamflow conditions in many areas also are influenced by water-management activities and water use. The largest consumptive use of surface water within the study area is for irrigation supply (Amundson, 1998). The largest withdrawals are associated with irrigation projects along Rapid Creek and the Cheyenne and Belle Fourche Rivers, where Bureau of Reclamation storage reservoirs provide reliable water supplies. Angostura Reservoir supplies the Angostura Unit; Deerfield Reservoir and Pactola Reservoir (fig. 43) supply the Rapid Valley Project; and Keyhole (located in northeastern Wyoming) and Belle Fourche Reservoirs supply the Belle Fourche Project (Bureau of Reclamation, 1998). Details about these reservoirs, along with storage records through water year 1993, were reported by Miller and Driscoll (1998). Large irrigation withdrawals also are made from Beaver Creek near Buffalo Gap and from Spearfish Creek and the Redwater River in the northern Black Hills, where streamflow is sufficiently reliable to provide consistent supplies. Smaller irrigation withdrawals are made from many other area streams. Approximately 86,000 acres within the study area are irrigated annually (Bureau of Reclamation, 1998).

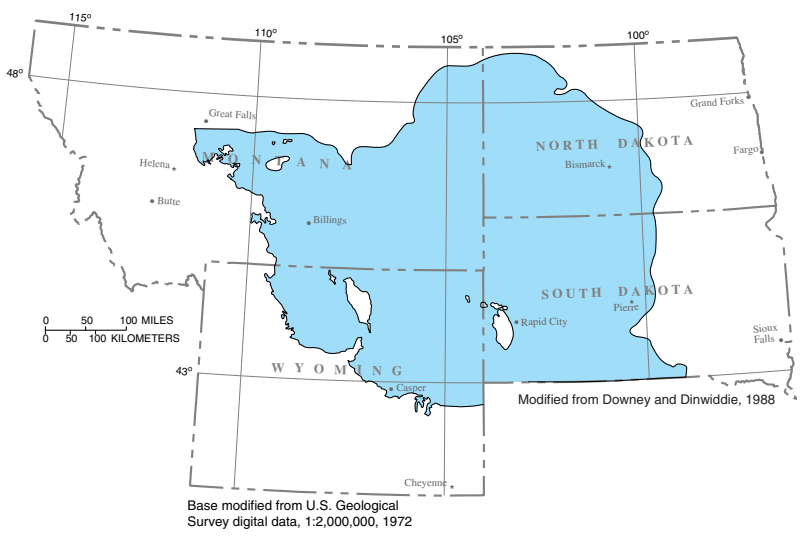
Streamflow in many area streams is influenced by a variety of other generally nonconsumptive diversions and regulation mechanisms (such as smaller reservoirs). Diversions from Rapid, Elk, and Spearfish Creeks have historically provided water for mining operations (Homestake Mining Company) and municipal supplies (Central City, Deadwood, and Lead) in the Whitewood Creek Basin (Miller and Driscoll, 1998). Homestake Mining Company also diverts water from Spearfish Creek for two hydroelectric powerplants; these flows are returned to Spearfish Creek below the loss zone. Substantial withdrawals for municipal supplies also are made from Rapid Creek.



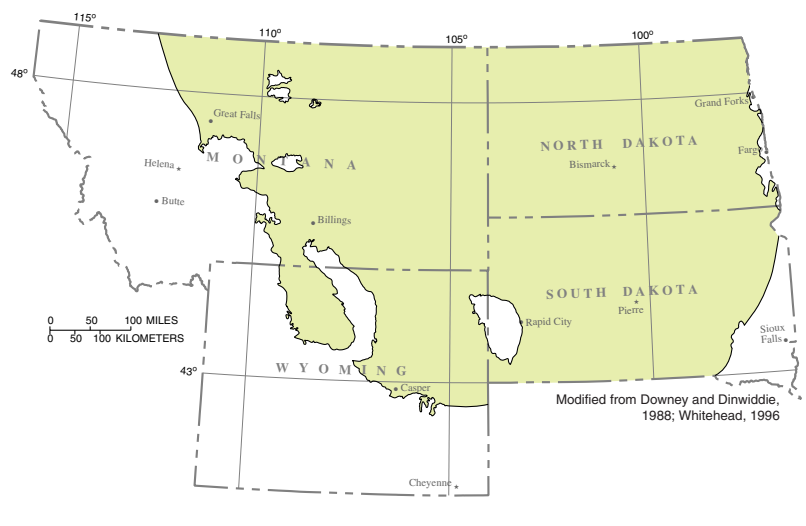
Cambrian and Ordovician rocks
(contains Deadwood aquifer)



Mississippian rocks
(contains Madison aquifer)



Pennsylvanian rocks
(contains Minnelusa aquifer)



Cretaceous rocks
(contains Inyan Kara aquifer)

Figure 44. Approximate extent of rocks containing regional aquifers in the Northern Great Plains area.

Regional Ground-Water Framework

Four of the major bedrock aquifers in the Black Hills area (Deadwood, Madison, Minnelusa, and Inyan Kara aquifers) are regionally extensive and are discussed in this section of the report in the context of both regional and local hydrologic settings. A fifth major aquifer (Minnekahta) generally is used only locally, as are aquifers in the igneous and metamorphic rocks within the crystalline core area. The major aquifers underlie parts of Montana, North Dakota, South Dakota, Wyoming, and Canada. The parts of the regional aquifers in Canada are not described or shown in this report.

Precambrian rocks form the basement underlying the aquifers. The extents of the geologic units that contain the four regional aquifers are shown in figure 44. Regionally, the Deadwood aquifer is contained in Cambrian and Ordovician rocks, the Madison aquifer is contained within Mississippian rocks, the Minnelusa aquifer is contained within Pennsylvanian rocks, and the Inyan Kara aquifer is contained within Cretaceous rocks. Several of these units thin or pinch out in southern and eastern South Dakota.

The Deadwood, Madison, and Minnelusa aquifers are within Paleozoic rock units (fig. 45). These aquifers are recharged in outcrop areas around major uplifts such as the Black Hills. Flow generally is from the recharge areas to the northeast, with regional flow largely being diverted around the Black Hills area. Discharge from the Deadwood aquifer is to adjacent aquifers, to lakes and springs in eastern North Dakota, and to springs and seeps where the aquifer crops out in Canada (Downey, 1984). The Madison and Minnelusa aquifers discharge by upward leakage to other aquifers, including the Inyan Kara aquifer in central South Dakota, and by easterly flow to underlying aquifers (Downey, 1984).

Although the Deadwood, Madison, and Minnelusa aquifers are regionally extensive, the water in these aquifers is not usable everywhere for consumption or other purposes. In general, these aquifers contain **fresh water** (dissolved solids **concentration** less than 1,000 mg/L (milligrams per liter)) only in and near recharge areas, which are indicated by the light-blue areas shown in figure 45. For the most part, these aquifers are deeply buried, contain high amounts of salt, and are important oil and gas reservoirs in deep parts of the Williston Basin (Whitehead, 1996). A **brine** is a body of water that is highly mineralized and has a **dissolved solids** concentration greater than that of sea water, which is 35,000 mg/L. A large body of brine water with dissolved solids concentrations exceeding 100,000 mg/L occurs in the Williston Basin (fig. 45). In some parts of the Williston Basin, dissolved solids concentrations exceed 300,000 mg/L (Whitehead, 1996), which is greater than that of the Great Salt Lake in Utah or the Dead Sea.

Generally, water in the Inyan Kara aquifer is confined by several thick shale layers except in aquifer outcrop areas around uplifts like the Black Hills or others farther west. Water generally moves northeasterly from recharge areas to discharge areas in eastern North Dakota and South Dakota (Whitehead, 1996). Like the other regional aquifers, the Inyan Kara aquifer contains little fresh water except near recharge areas. Much of the water is highly mineralized, especially in the Williston Basin (Whitehead, 1996).

Although the major aquifers are regionally extensive, much of the water is highly mineralized. In parts of the Williston Basin, these aquifers contain water that is more mineralized than the Great Salt Lake or the Dead Sea.

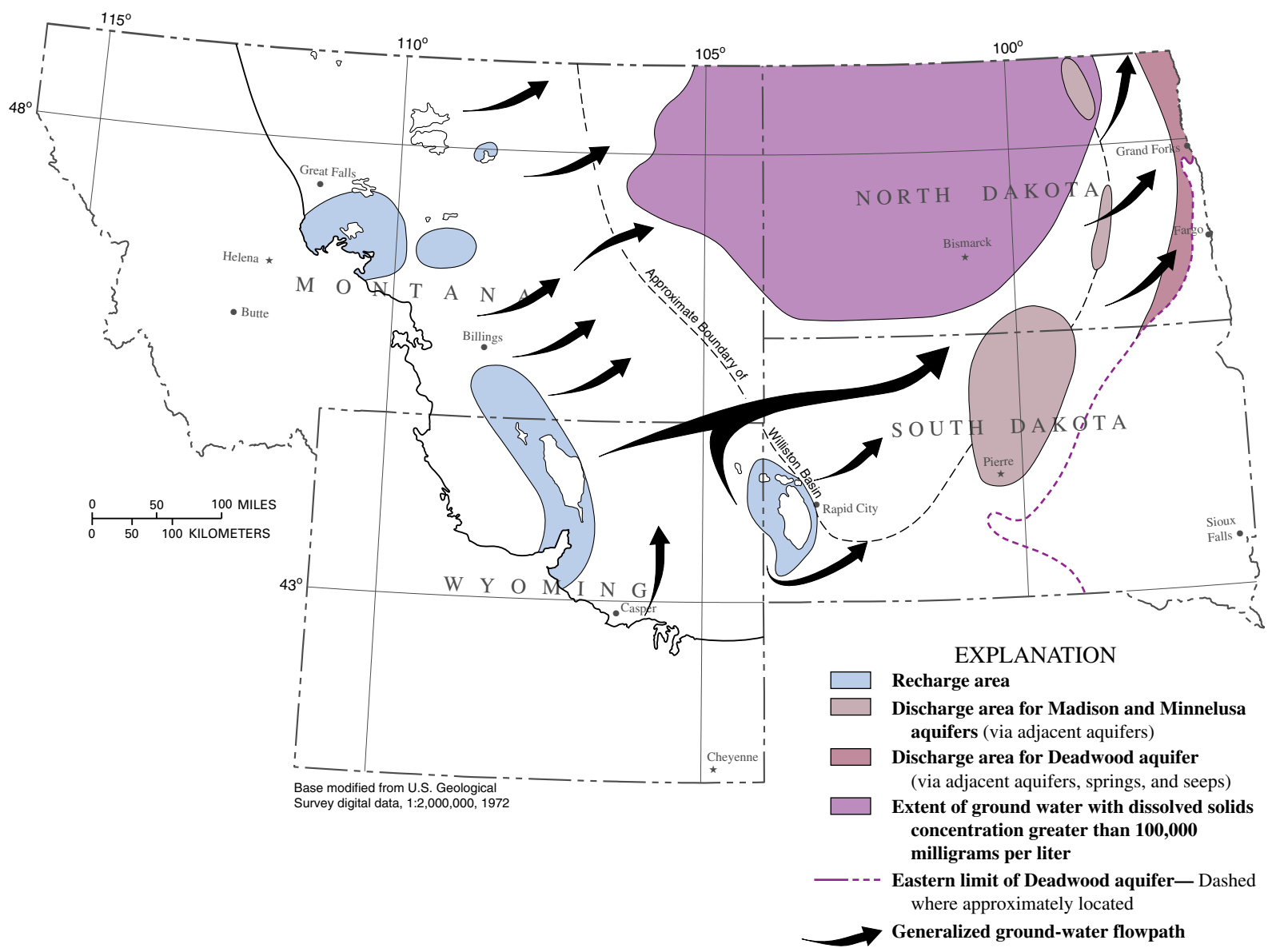


Figure 45. General direction of ground-water flow in regional aquifers within Paleozoic rock units (modified from Downey and Dinwiddie, 1988; Whitehead, 1996).