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Hydrology of the Black Hills Area, South Dakota

By Daniel G. Driscoll, Janet M. Carter, Joyce E. Williamson, *and* Larry D. Putnam

ABSTRACT

The Black Hills Hydrology Study was initiated in 1990 to assess the quantity, quality, and distribution of surface water and ground water in the Black Hills area of South Dakota. This report summarizes the hydrology of the Black Hills area and the results of this long-term study.

The Black Hills area of South Dakota and Wyoming is an important recharge area for several regional, bedrock aquifer systems and various local aquifers; thus, the study focused on describing the hydrologic significance of selected bedrock aquifers. The major aquifers in the Black Hills area are the Deadwood, Madison, Minnelusa, Minnekahta, and Inyan Kara aquifers. The highest priority was placed on the Madison and Minnelusa aquifers, which are used extensively and heavily influence the surface-water resources of the area.

Within this report, the hydrogeologic framework of the area, including climate, geology, ground water, and surface water, is discussed. Hydrologic processes and characteristics for ground water and surface water are presented. For ground water, water-level trends and comparisons and water-quality characteristics are presented. For surface water, streamflow characteristics, responses to precipitation, annual yields and yield efficiencies, and water-quality characteristics are presented. Hydrologic budgets are presented for ground water, surface water, and the combined ground-water/surface-water system. A summary of study findings regarding the complex flow systems within the Madison and Minnelusa aquifers also is presented.

INTRODUCTION

The Black Hills area is an important resource center that provides an economic base for western South Dakota through tourism, agriculture, the timber industry, and mineral resources. In addition, water originating from the area is used for municipal, industrial, agricultural, and recreational purposes throughout much of western South Dakota. The Black Hills area also is an important recharge area for aquifers in the northern Great Plains.

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

The specific objectives of the Black Hills Hydrology Study included:

1. Inventorying and describing precipitation amounts, streamflow rates, ground-water levels of selected aquifer units, and selected water-quality characteristics for the Black Hills area.

2. Developing hydrologic budgets to define relations among precipitation, streamflow, and aquifer response for selected Black Hills watersheds.
3. Describing the significance of the bedrock aquifers in the Black Hills area hydrologic system, with an emphasis on the Madison and Minnelusa aquifers, through determination of:
   a. aquifer properties (depth, thickness, structure, storage coefficient, hydraulic conductivity, etc.);
   b. the hydraulic connection between the aquifers;
   c. the source aquifer(s) of springs;
   d. recharge and discharge rates, and gross volumetric budgets; and
   e. regional flow paths.
4. Developing conceptual models of the hydrogeologic system for the Black Hills area.

Purpose and Scope

The purpose of this report is to summarize the hydrology of the Black Hills area and present major findings pertinent to the objectives of the Black Hills Hydrology Study. The information summarized in this report has been presented in more detail in previous reports prepared as part of the study. Because the Black Hills area of South Dakota and Wyoming is an important recharge area for several regional, bedrock aquifers and various local aquifers, the study concentrated on describing the hydrogeology and hydrologic significance of selected bedrock aquifers. The highest priority was placed on the Madison and Minnelusa aquifers because: (1) these aquifers are heavily used and could be developed further; (2) these aquifers are connected to surface-water resources through streamflow loss zones and large springs; and (3) hydraulic connection between these aquifers is extremely variable. The Deadwood and Minnekahta aquifers had a lower priority because they are used less and have less influence on the hydrologic system. The fractured Precambrian rocks, Inyan Kara Group, and various local aquifers, including minor bedrock aquifers and unconsolidated aquifers, had the lowest priorities because: (1) the Precambrian and local aquifers are not regional aquifers with regional flowpaths; and (2) the Inyan Kara Group is not used as extensively in the Black Hills area as the other priority units.

Hydrologic analyses within this report generally are by water year, which represents the period from October 1 through September 30. Discussions of timeframes refer to water years, rather than calendar years, unless specifically noted otherwise.

Description of Study Area

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

The Black Hills uplift formed as an elongated dome about 60 to 65 million years ago during the Laramide orogeny (Darton and Paige, 1925). The dome trends north-northwest and is about 120 mi long and 60 mi wide. Land-surface altitudes range from 7,242 ft above sea level at Harney Peak to about 3,000 ft in the adjacent plains. Most of the higher altitudes are heavily forested with ponderosa pine, which is the primary product of an active timber industry. White spruce, quaking aspen, paper birch, and other native trees and shrubs are found in cooler, wetter areas (Orr, 1959). The lower altitude areas surrounding the Black Hills primarily are urban, suburban, and agricultural. Numerous deciduous species such as cottonwood, ash, elm, oak, and willow are common along streams in the lower altitudes. Rangeland, hayland, and winter wheat farming are the principal agricultural uses for dryland areas. Alfalfa, corn, and vegetables are produced in bottom lands and in irrigated areas. Various other crops, primarily for cattle fodder, are produced in both dryland areas and in bottom lands.

Beginning in the 1870's, the Black Hills have been explored and mined for many commodities including gold, silver, tin, tungsten, mica, feldspar, bentonite, beryl, lead, zinc, uranium, lithium, sand, gravel, and oil (U.S. Department of Interior, 1967). Mines within the study area have used various techniques including placer mining, underground mining, and open-pit mining.

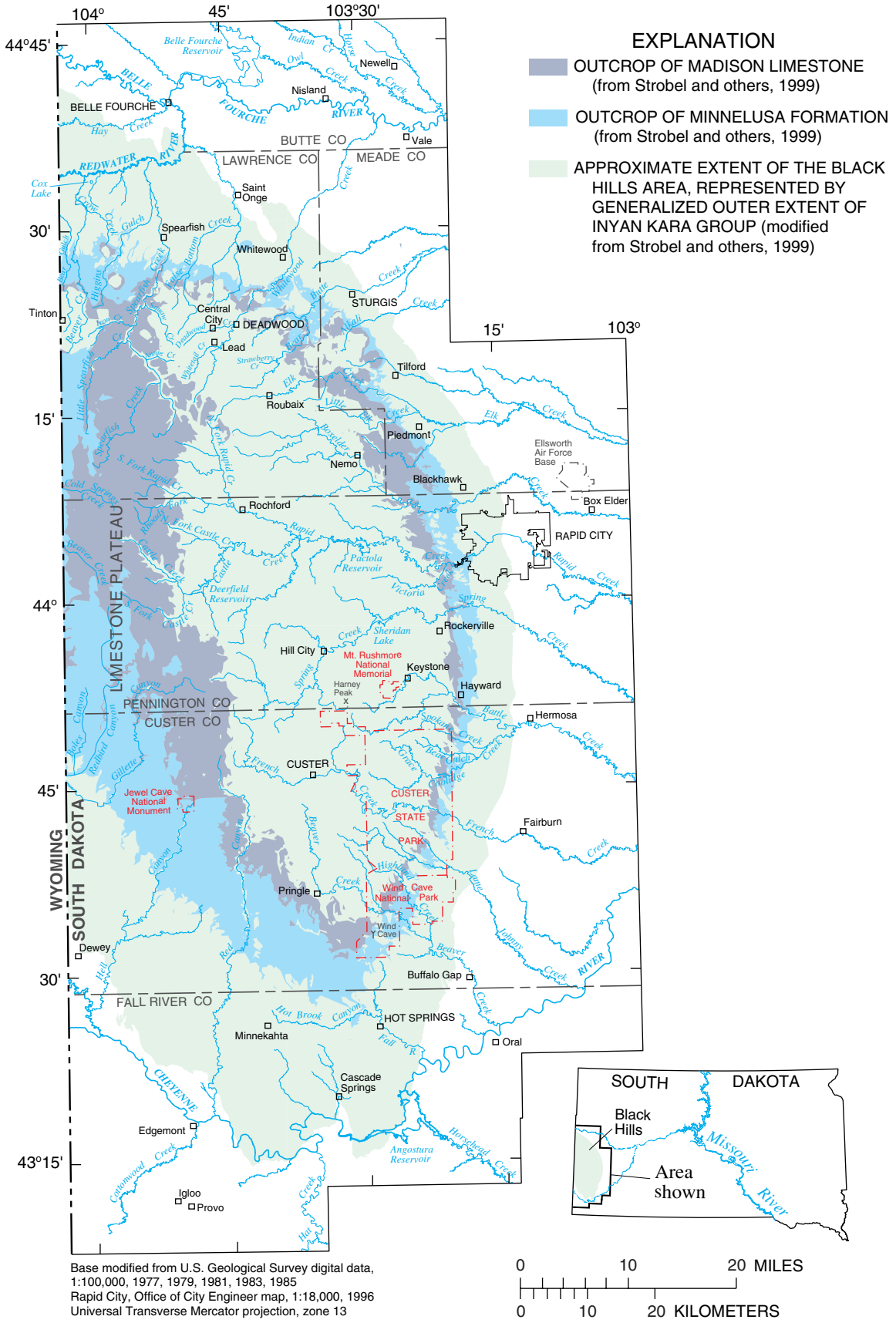


Figure 1. Area of investigation for the Black Hills Hydrology Study.

Acknowledgments

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

HYDROGEOLOGIC FRAMEWORK

The Black Hills are located within the Great Plains physiographic province in western South Dakota and eastern Wyoming (fig. 2). 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, and both streamflow and aquifer recharge are influenced by climatic conditions. Overviews of the climate, geology, ground water, and surface water are provided in the following sections.

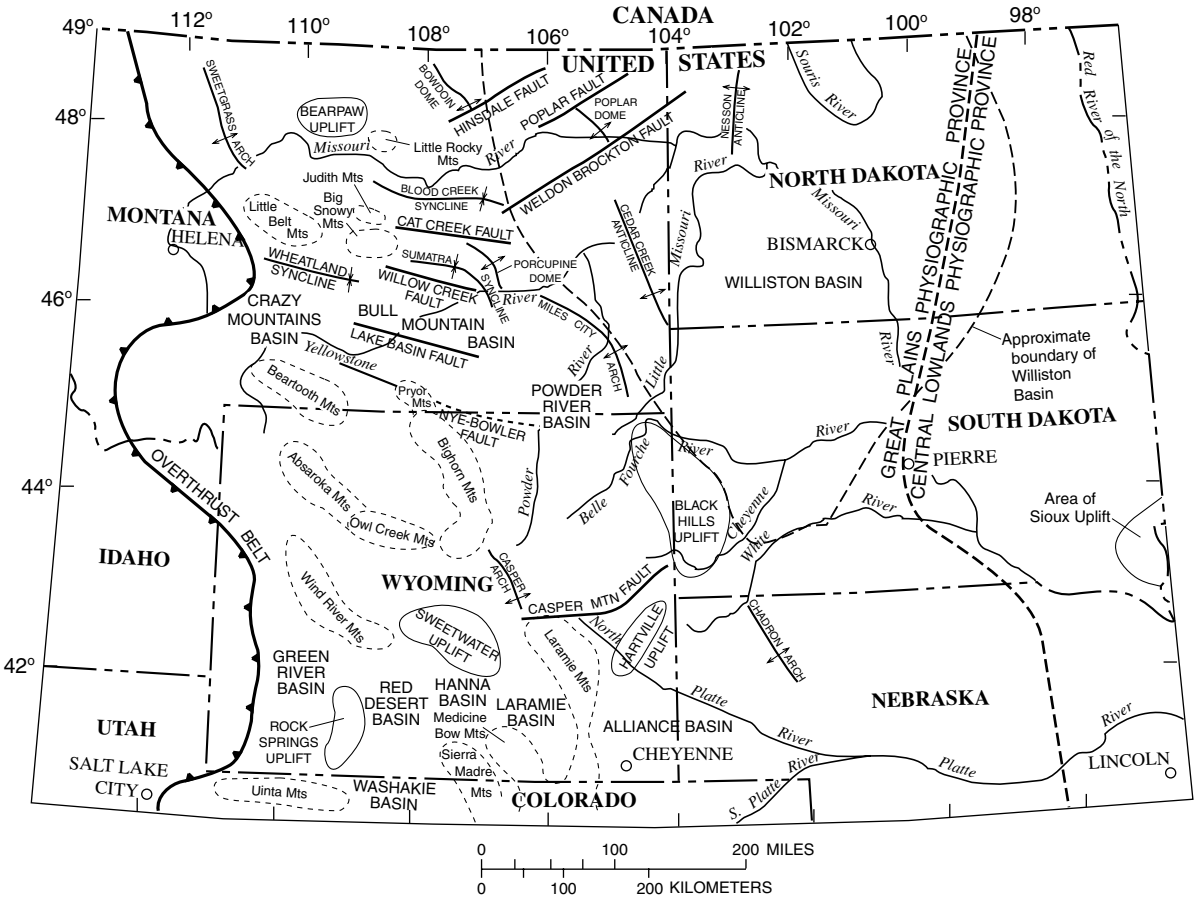


Figure 2. Present-day structural and physiographic features in the northern Great Plains area (modified from Peterson, 1981, and Busby and others, 1995).

Climatic Framework

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

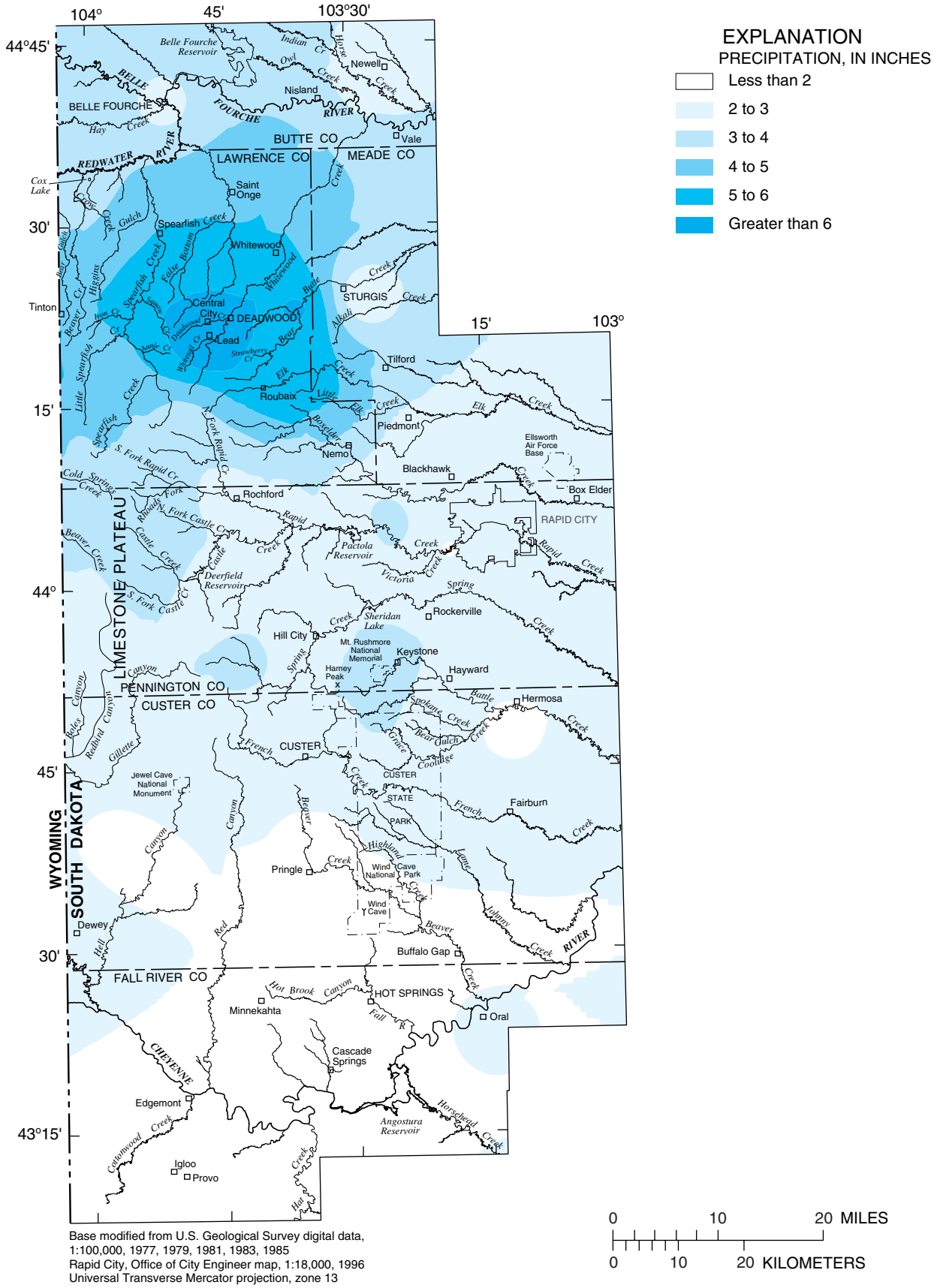
Precipitation data sets used for this study generally were taken from Driscoll, Hamade, and Kenner (2000), who summarized available precipitation data (1931-98) for the Black Hills area. These investigators compiled monthly precipitation records for 52 long-term precipitation gages operated by National Oceanic and Atmospheric Administration (1998) and 42 short-term precipitation gages operated by the USGS. These data sets are available on the World Wide Web at http://sd.water.usgs.gov/projects/bhhs/precip/home.htm. A geographic information system (GIS) was used by Driscoll, Hamade, and Kenner (2000) to generate spatial distributions of monthly precipitation data for 1,000-by-1,000-meter grid cells for the study area; an example is shown in figure 3. Monthly distributions were composited to produce annual distributions for counties within the study area and for drainage areas of selected streamflow-gaging stations; these data sets were presented by Driscoll and Carter (2001). The precipitation distributions were used extensively for various applications including evaluating responses of ground-water levels and streamflow to precipitation, estimating precipitation recharge for bedrock aquifers, and developing long-term hydrologic budgets.

Spatial precipitation patterns in the Black Hills area are highly influenced by orography, as shown by an isohyetal map (fig. 4) for 1950-98, which is the period commonly used for hydrologic budgets presented in this report. Areas of relatively low precipitation occur in the low altitudes around the periphery of the Black Hills. Most areas with altitudes exceeding 6,000 ft 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 (1950-98) 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 from the northwest, and the southern Black Hills influenced primarily by drier air currents from the south-southeast. As a result, annual precipitation averages about 16 to 17 inches for most of Fall River County (fig. 4) and 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 1931-98 are presented in figure 5. For the study area, the long-term average of 18.61 inches is slightly larger than the median (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.

The largest precipitation amounts typically occur during May and June, and the smallest amounts typically occur during November through February (fig. 6). The most variable month is May, during which precipitation has ranged 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. 7).

Long-term (1931-98) trends in precipitation (fig. 8) are an important consideration for hydrologic analysis for the Black Hills area. Figure 8A 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. Figure 8B shows that the associated departures (from the average) have ranged from a deficit (-) of 8.39 inches to a surplus (+) of 8.78 inches, respectively. The cumulative trends are readily apparent from figure 8C, 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.



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

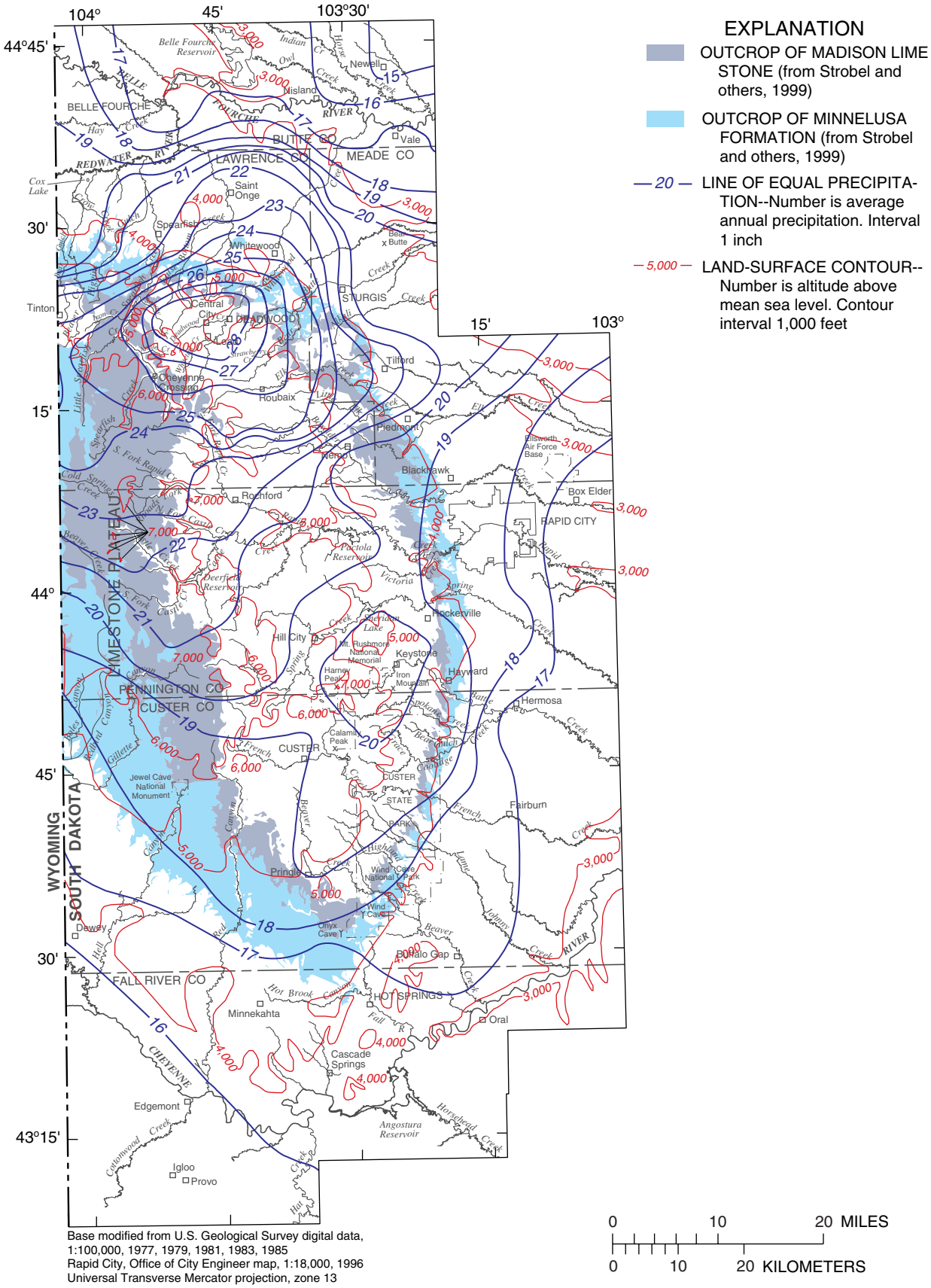


Figure 4. Isohyetal map showing distribution of average annual precipitation for Black Hills area, water years 1950-98 (from Carter, Driscoll, and Hamade, 2001).

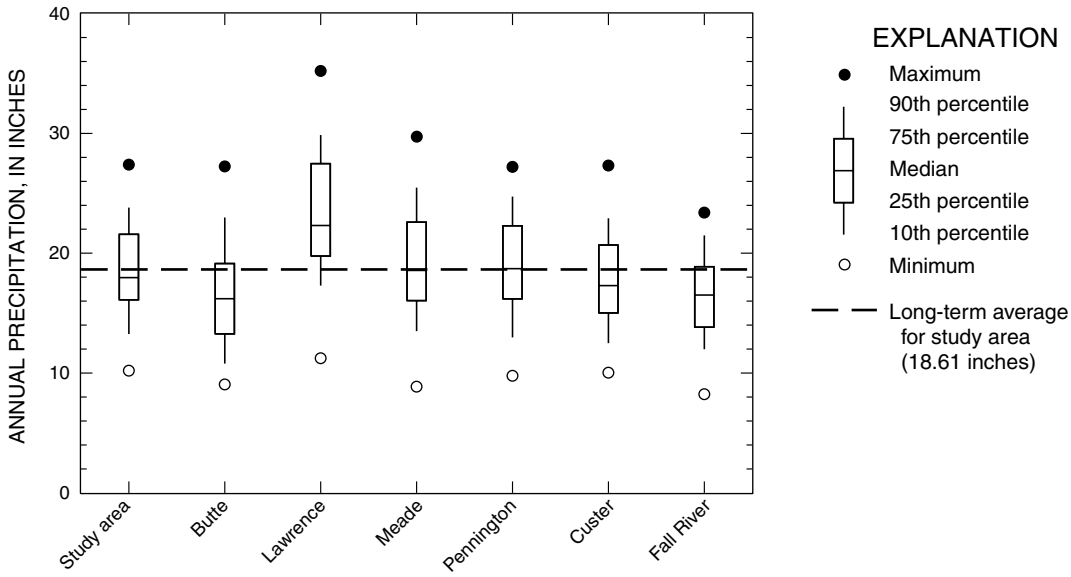


Figure 5. Distribution of annual precipitation for the study area and counties within the study area, water years 1931-98 (modified from Driscoll and Carter, 2001).

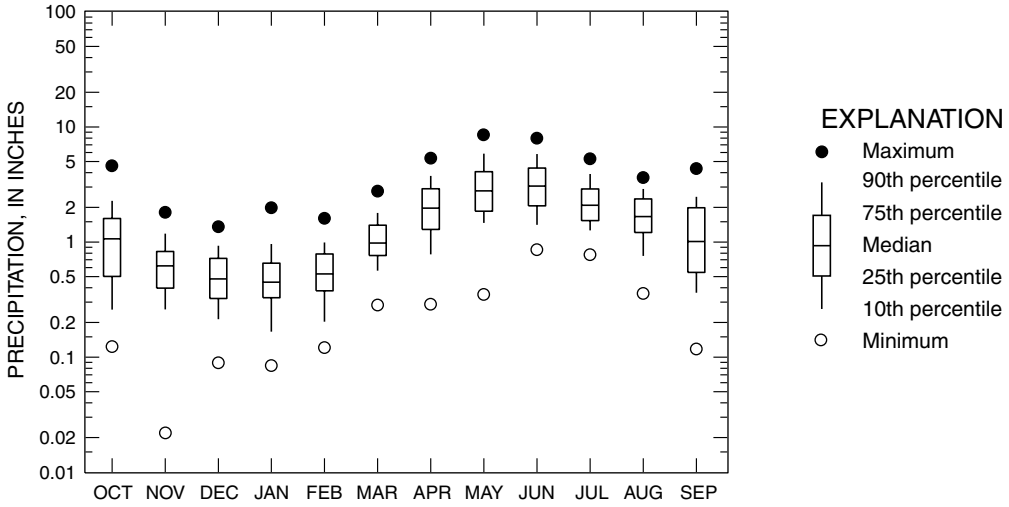


Figure 6. Distribution of monthly precipitation for the study area, water years 1931-98 (from Driscoll, Hamade, and Kenner, 2000).

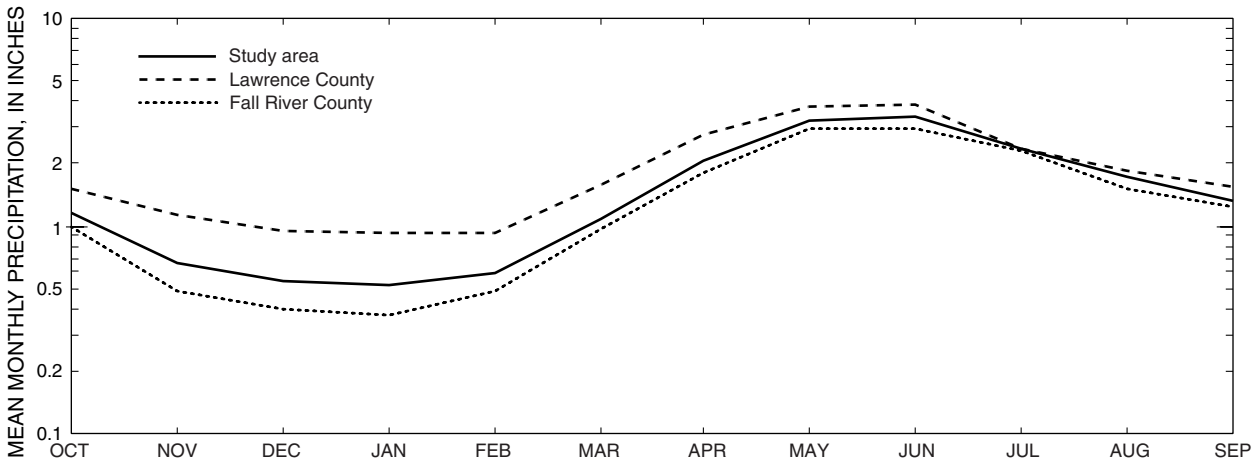


Figure 7. Mean monthly precipitation for study area and selected counties, water years 1931-98 (from Driscoll and Carter, 2001).

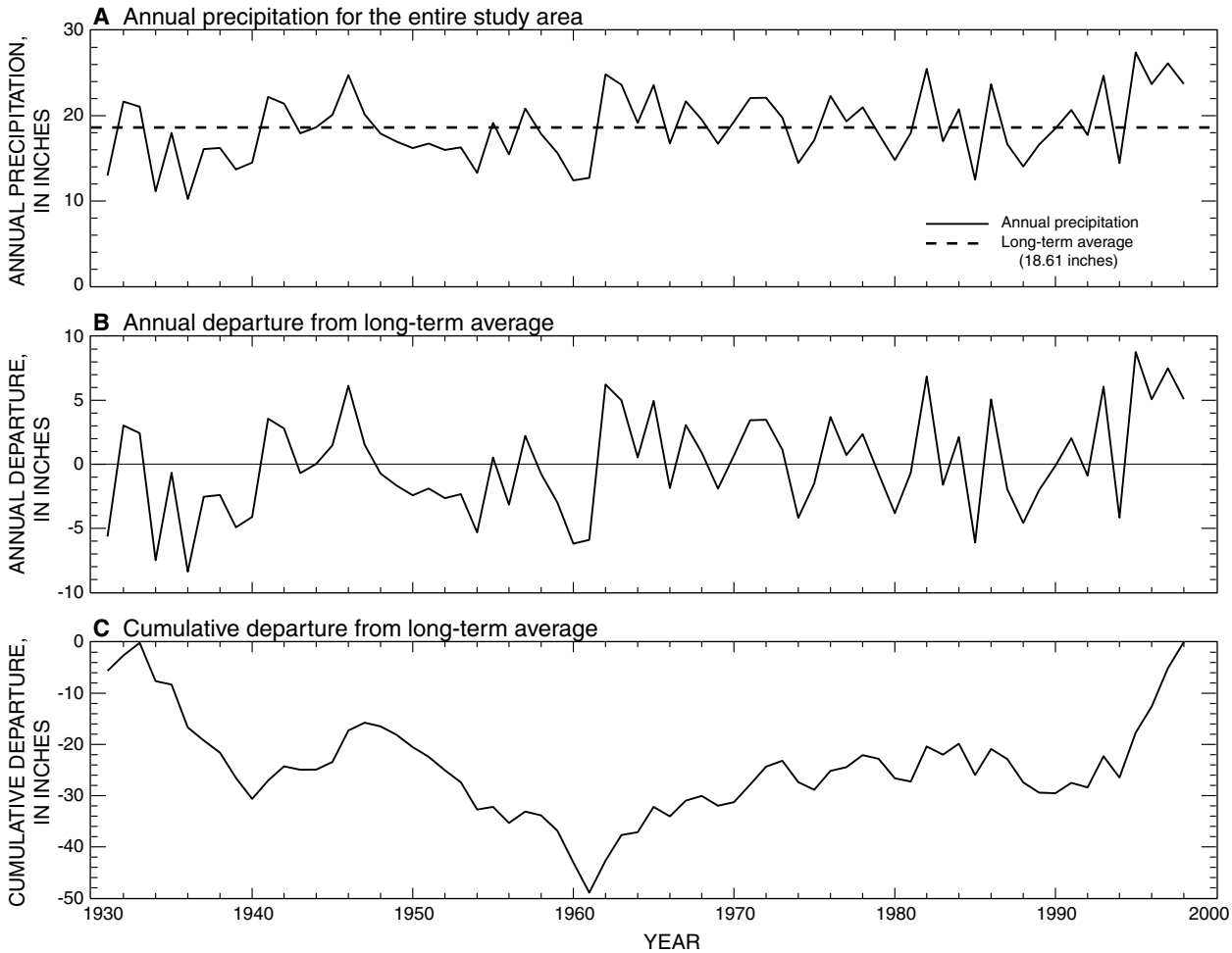


Figure 8. Long-term trends in precipitation for the Black Hills area, water years 1931-98 (from Driscoll, Hamade, and Kenner, 2000).

The long-term precipitation trends are especially important because of potential for bias in analysis and interpretation of available hydrologic data sets, which are much more abundant for the recent wet years. Water-level records are available for 71 observation wells in the Black Hills area for 1998, compared with five wells for 1965 (Driscoll, Bradford, and Moran, 2000). Miller and Driscoll (1998) reported streamflow records for 65 gages for 1993, compared with 30 gages for 1960. Thus, the potential for bias is an important consideration in analysis of hydrologic data sets for the Black Hills area.

Average annual potential evaporation generally exceeds average annual precipitation throughout 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).

Geologic Framework

The stratigraphic and structural features in the Black Hills area are complex. Many of the geologic formations, such as the Deadwood Formation, Madison Limestone, Minnelusa Formation, Minnekahta Limestone, and Inyan Kara Group, in the Black Hills (fig. 9) are regionally extensive. Several formations thin or pinch out in southern and eastern South Dakota. To better understand the stratigraphic and structural settings in the Black Hills, an overview of the regional geologic setting is provided first and is followed by an overview of the local geologic setting.

Regional Geologic Setting

Parts of Montana, North Dakota, South Dakota, and Wyoming are included in the Northern Great Plains area. The present-day structural features (fig. 2) of the Northern Great Plains are directly related to the geologic history of the Cordilleran platform, which is a part of the stable interior of the North American Continent (Downey, 1986). The present-day structure probably was controlled by the pre-existing structural grain in the Precambrian basement and modified during the Laramide orogeny (Downey, 1984).

During Paleozoic time, the area generally was broad, flat, and covered by shallow, warm seas (Downey, 1984). Numerous disconformities during Paleozoic time indicate intermittent transgressions and regressions when seas advanced from west to east in response to tectonic activity of the Antler orogeny to the west (Sandberg and Poole, 1977). Deposits generally were beach, shallow marine, carbonate, sabkha, and evaporite units (Redden and Lisenbee, 1996).

During Cretaceous time, the area was covered by a north-south trending sea, which extended from the Gulf of Mexico to the Arctic Ocean (Downey, 1986). During Late Cretaceous time, the sea was at its widest extent, but marine deposition was interrupted by frequent east-west regressions (Anna, 1986).

Paleostructure

The Northern Great Plains area was part of the Cordilleran platform throughout most of Paleozoic time. The Williston Basin, which covers parts of North Dakota, South Dakota, southern Saskatchewan, southwestern Manitoba, and eastern Montana (fig. 10), began to take shape during Ordovician time (Carlson and Anderson, 1965). Other major Jurassic and Cretaceous (pre-Laramide) paleostructural elements (fig. 10) include the Powder River Basin, the Central Montana trough and uplift, the Cedar Creek anticline, and the Alberta shelf (Anna, 1986).

The Laramide orogeny, which affected the eastern Rocky Mountains of the United States, began during late Cretaceous time and continued in the Eocene period (Redden and Lisenbee, 1996). The Laramide orogeny was characterized by large-scale warping, deep erosion of uplifts, and deposition of orogenic sediments into basins (Tweto, 1975). Most, if not all, pre-Laramide structural features (fig. 10) were reactivated and became more prominent during the Laramide orogeny (Anna, 1986). During the Laramide orogeny, the Bighorn and Laramie Mountains, the Black Hills, and the Central Montana uplift formed, and the Williston and Powder River Basins (fig. 2) were downwarped into essentially their present configuration (Anna, 1986).

ERATHEM	SYSTEM	ABBREVIATION FOR STRATIGRAPHIC INTERVAL	STRATIGRAPHIC UNIT	THICKNESS IN FEET	DESCRIPTION
CENOZOIC	QUATERNARY & TERTIARY (?)	QTac	UNDIFFERENTIATED ALLUVIUM AND COLLUVIUM	0-50	Sand, gravel, boulder, and clay.
		Tw	WHITE RIVER GROUP	0-300	Light colored clays with sandstone channel fillings and local limestone lenses.
	TERTIARY	Tui	INTRUSIVE IGNEOUS ROCKS	--	Includes rhyolite, latite, trachyte, and phonolite.
MESOZOIC	CRETACEOUS	Kps	PIERRE SHALE	1,200-2,700	Principal horizon of limestone lenses giving teepee buttes. Dark-gray shale containing scattered concretions. Widely scattered limestone masses, giving small teepee buttes. Black fissile shale with concretions.
			NIOBRARA FORMATION	[1]80-300	Impure chalk and calcareous shale.
			CARLILE SHALE — Turner Sandy Member Wall Creek Member	[1]350-750	Light-gray shale with numerous large concretions and sandy layers. Dark-gray shale
			GREENHORN FORMATION	225-380	Impure slabby limestone. Weathers buff. Dark-gray calcareous shale, with thin Orman Lake limestone at base.
			GRANEROS GROUP — BELLE FOURCHE SHALE	150-850	Gray shale with scattered limestone concretions. Clay spur bentonite at base.
			GRANEROS GROUP — MOWRY SHALE	125-230	Light-gray siliceous shale. Fish scales and thin layers of bentonite.
			GRANEROS GROUP — MUDDY SANDSTONE / NEWCASTLE SANDSTONE	0-150	Brown to light-yellow and white sandstone.
			GRANEROS GROUP — SKULL CREEK SHALE	150-270	Dark-gray to black siliceous shale.
		Kik	INYAN KARA GROUP — FALL RIVER FORMATION	10-200	Massive to thin-bedded, brown to reddish-brown sandstone.
			INYAN KARA GROUP — LAKOTA FM — Fuson Shale Minnewaste Limestone Chilson Member	10-190 0-25 25-485	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 — Redwater Member Lak Member Hulett Member Stockade Beaver Mem. Canyon Spr Member	250-450	Greenish-gray shale, thin limestone lenses. Glauconitic sandstone; red sandstone near middle.
			GYPSUM SPRING FORMATION	0-45	Red siltstone, gypsum, and limestone.
	TRIASSIC	TRPs	SPEARFISH FORMATION — Goose Egg Equivalent	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.
		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.
	PENNSYLVANIAN				
	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 buff to purple sandstone. Greenish glauconitic shale flaggy dolomite and flat-pebble limestone conglomerate. Sandstone, with conglomerate locally at the base.
PRECAMBRIAN		p€u	UNDIFFERENTIATED 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 9. Stratigraphic section for the Black Hills.

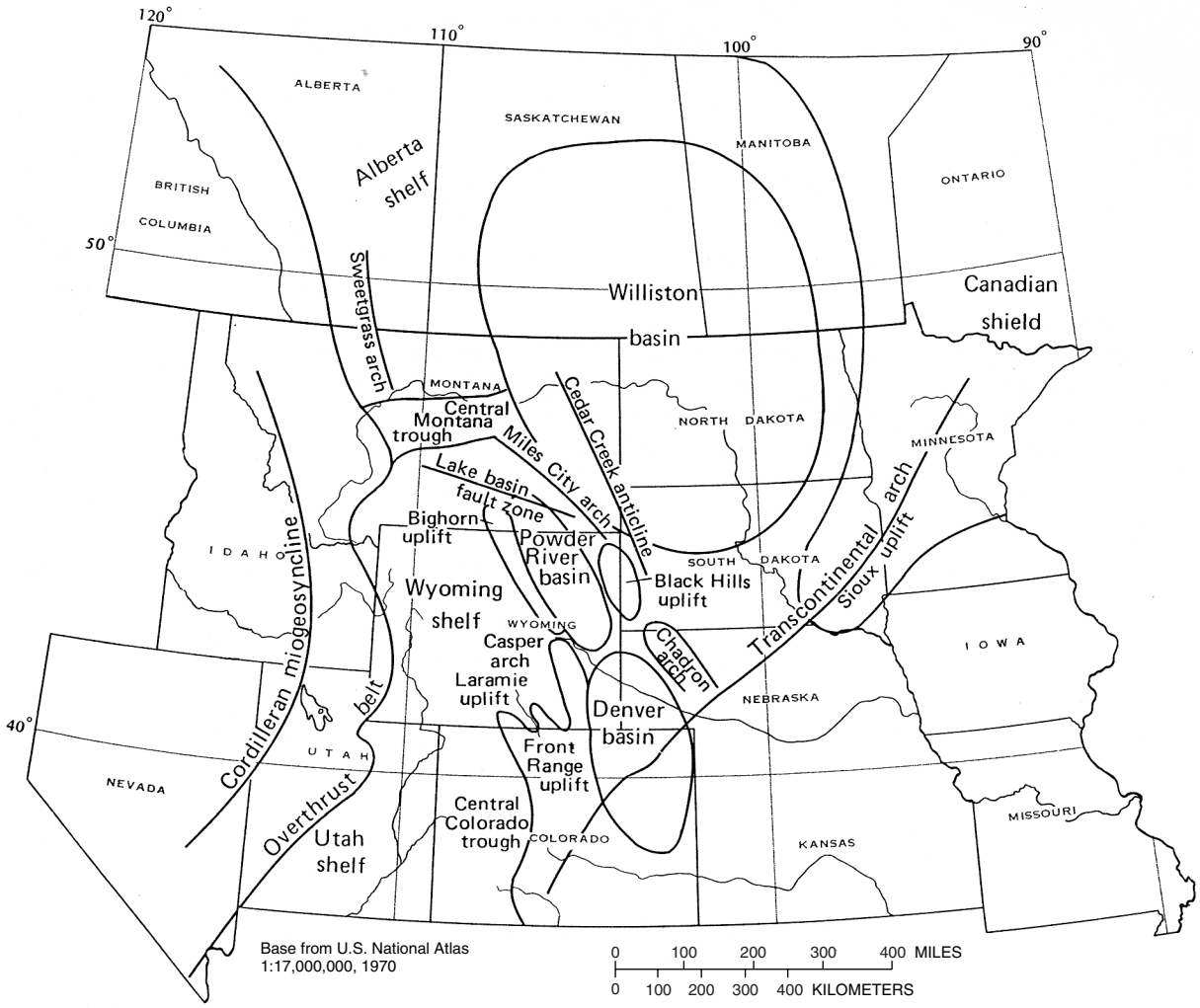


Figure 10. Regional paleostructure during Jurassic and Cretaceous time in the western interior of the United States (modified from Anna, 1986).

Stratigraphy

Precambrian rocks form the basement in the northern Great Plains area. Precambrian rocks are exposed in the central core of many of the mountain ranges, but lie greater than 15,000 ft below land surface at the center of the Williston Basin (Downey and Dinwiddie, 1988).

Rocks of Cambrian and Ordovician age consist of sandstone, shale, limestone, and dolomite and represent the shoreward facies of a transgressive sea (Peterson, 1981). The extent of the Cambrian and Ordovician rocks in the northern Great Plains area is shown in figure 11. The principal geologic units of Cambrian and Ordovician age are the Deadwood Formation, Emerson Formation, Winnipeg Formation, Red River Formation (Whitewood Formation), and Stony Mountain Formation (fig. 12). Rocks of Cambrian and Ordovician age extend into Canada where they are exposed along the Precambrian shield (Downey, 1986). Erosion during Devonian time truncated the Ordovician geologic units in South Dakota and Wyoming to the south of a line extending between the central Black Hills and southern Bighorn Mountains (Peterson, 1981). Rocks of Silurian age are not present in the Black Hills area.

The extent of Mississippian rocks in the northern Great Plains area is shown in figure 11. These rocks overlying the Bakken Formation (where present) are termed the Madison Limestone, or Madison Group where divided (fig. 12). The Madison Limestone consists of a sequence of marine carbonates and evaporites deposited mainly in a warm, shallow-water environment (Downey, 1986). Development of karst (solution) features in the Madison Limestone was common because the carbonate rocks are relatively soluble in water (Downey, 1986). Complex and interconnected solution features developed in the Madison Limestone during tropical conditions when it was exposed at or near land surface (Busby and others, 1995). Large and extensive cave systems have formed in the outcrop areas of the Madison Limestone in the Bighorn Mountains and in the Black Hills.

Rocks of Pennsylvanian age consist primarily of marine sandstone, shale, siltstone, and carbonate. The Pennsylvanian rocks are divided into many different geologic units (fig. 12). Rocks of Pennsylvanian-age have been truncated by pre-Jurassic erosion progressively northward across central Montana; these rocks thin to zero thickness near the axis of the central Montana trough (Downey, 1986; figs. 10 and 11).

A sequence of red shale, siltstone, and evaporite deposits belonging to the upper part of the Goose Egg and Spearfish Formations of Triassic age overlie the Minnelusa Formation (Downey and Dinwiddie, 1988). Jurassic rocks, which include the Nesson, Piper, Rierdon, and Sundance Formations and their equivalents (fig. 12) are predominantly carbonate, shale, and calcareous shale (Anna, 1986).

Deposits during Cretaceous time primarily were sandstones, shales, and minor carbonates (Redden and Lisenbee, 1996). A number of formation names have been applied to the various Cretaceous units in the northern Great Plains area; however, in several instances, these formation names are used only in one State or subregion (fig. 13). Lower Cretaceous rocks (fig. 13) range in thickness from zero in eastern North Dakota and South Dakota to more than 1,400 ft in west-central Wyoming (Anna, 1986). The extent of the Lower Cretaceous sandstones, which include the Inyan Kara Group, Muddy Sandstone, and Newcastle or Dakota Sandstone, is shown in figure 11. The sedimentary pattern of Upper Cretaceous rocks (fig. 13) is associated with four main transgressions and regressions of shallow seas.

Tertiary units (fig. 13) generally were deposited in a continental environment (Downey, 1986). Deposits of Quaternary age in the northern Great Plains area consist of alluvium, glacial materials, and other surficial deposits. Alluvial deposits fill major drainages in the area. Glacial deposits are located only in the eastern parts of North Dakota and South Dakota and in the northernmost part of Montana (Downey, 1986).

Local Geologic Setting

The Black Hills uplift is a northwest-trending, asymmetric, elongate dome, or doubly plunging anticline. Uplift began about 62 million years ago during the Laramide orogeny and probably continued in the Eocene period (Redden and Lisenbee, 1996). Large anticlines occur on the northern and southern flanks of the Black Hills and plunge away from the uplift into the surrounding plains. Numerous smaller folds, faults, domes, and monoclines also occur in the Black Hills (fig. 14). Igneous intrusions were emplaced on the northern flanks of the uplift during the Tertiary Period.

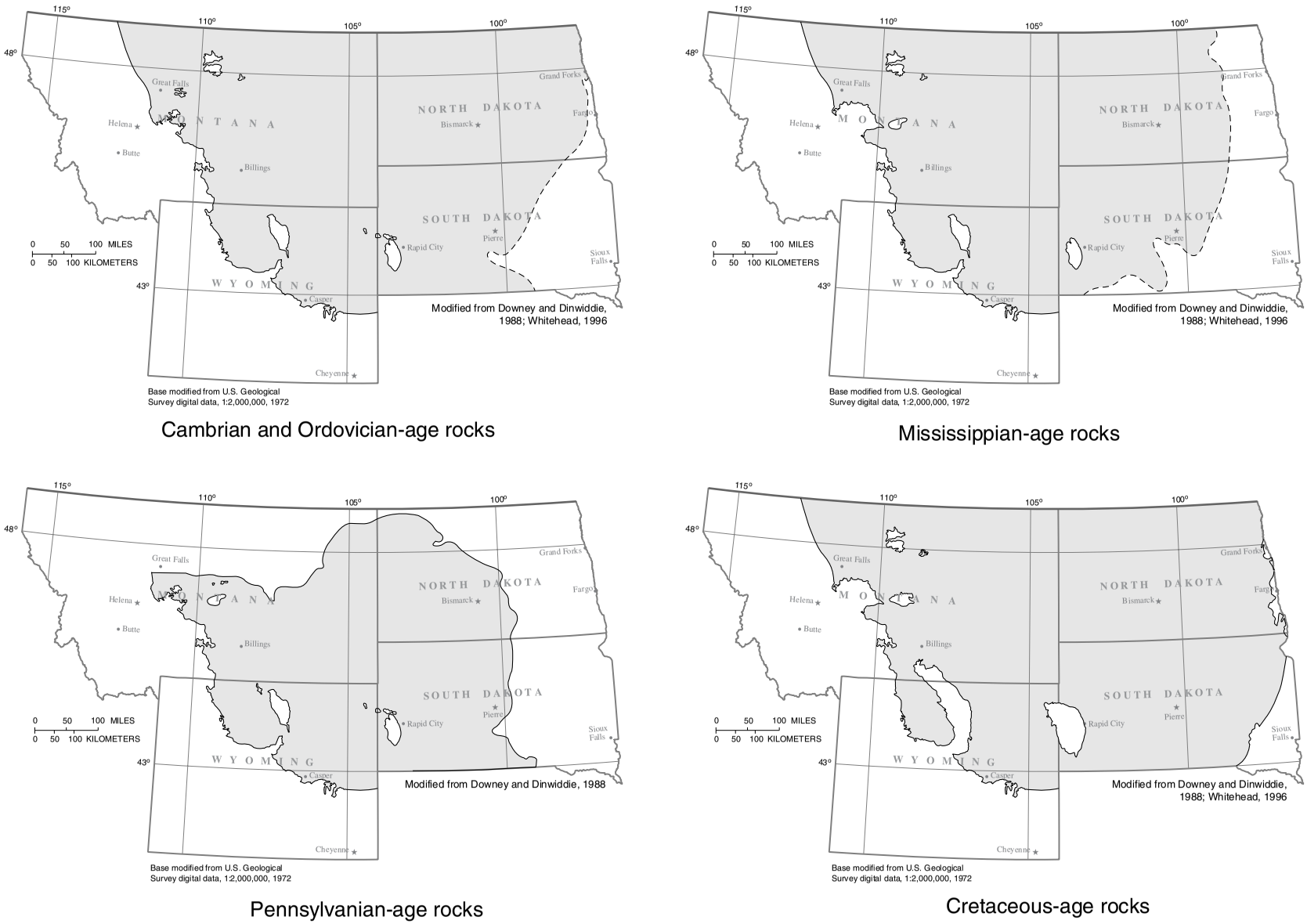


Figure 11. Approximate extent of rocks in the northern Great Plains area for selected geologic periods.

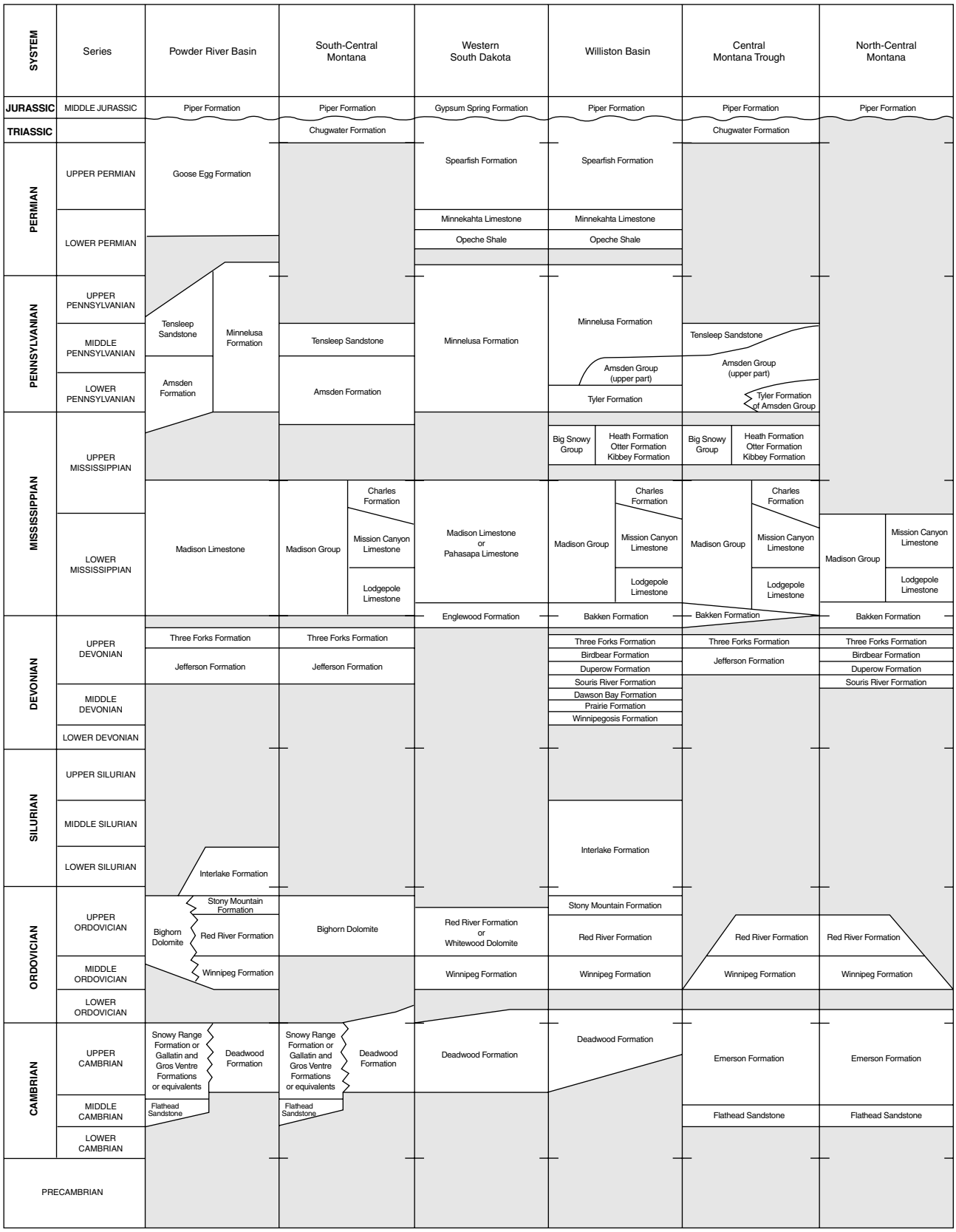
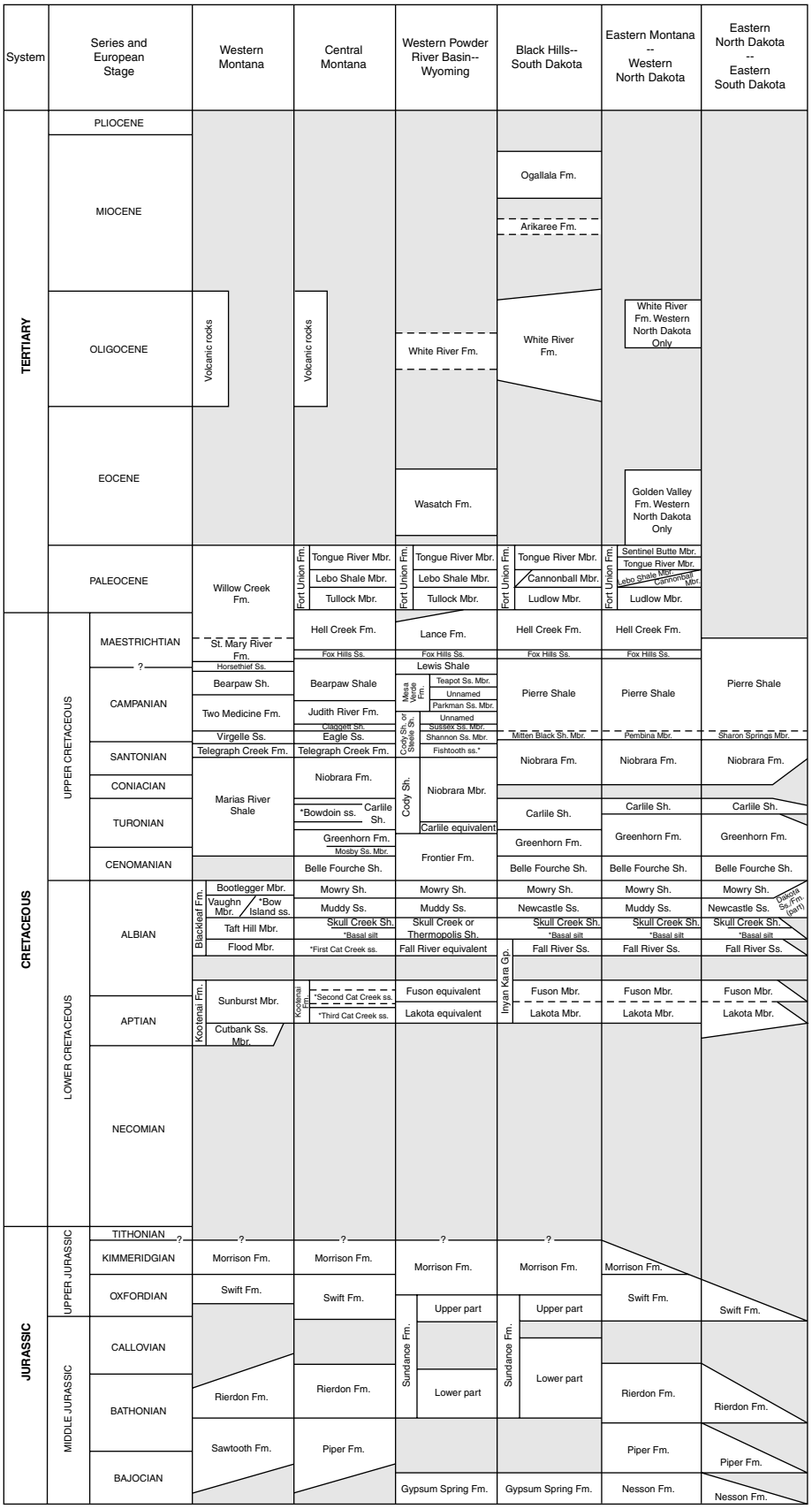
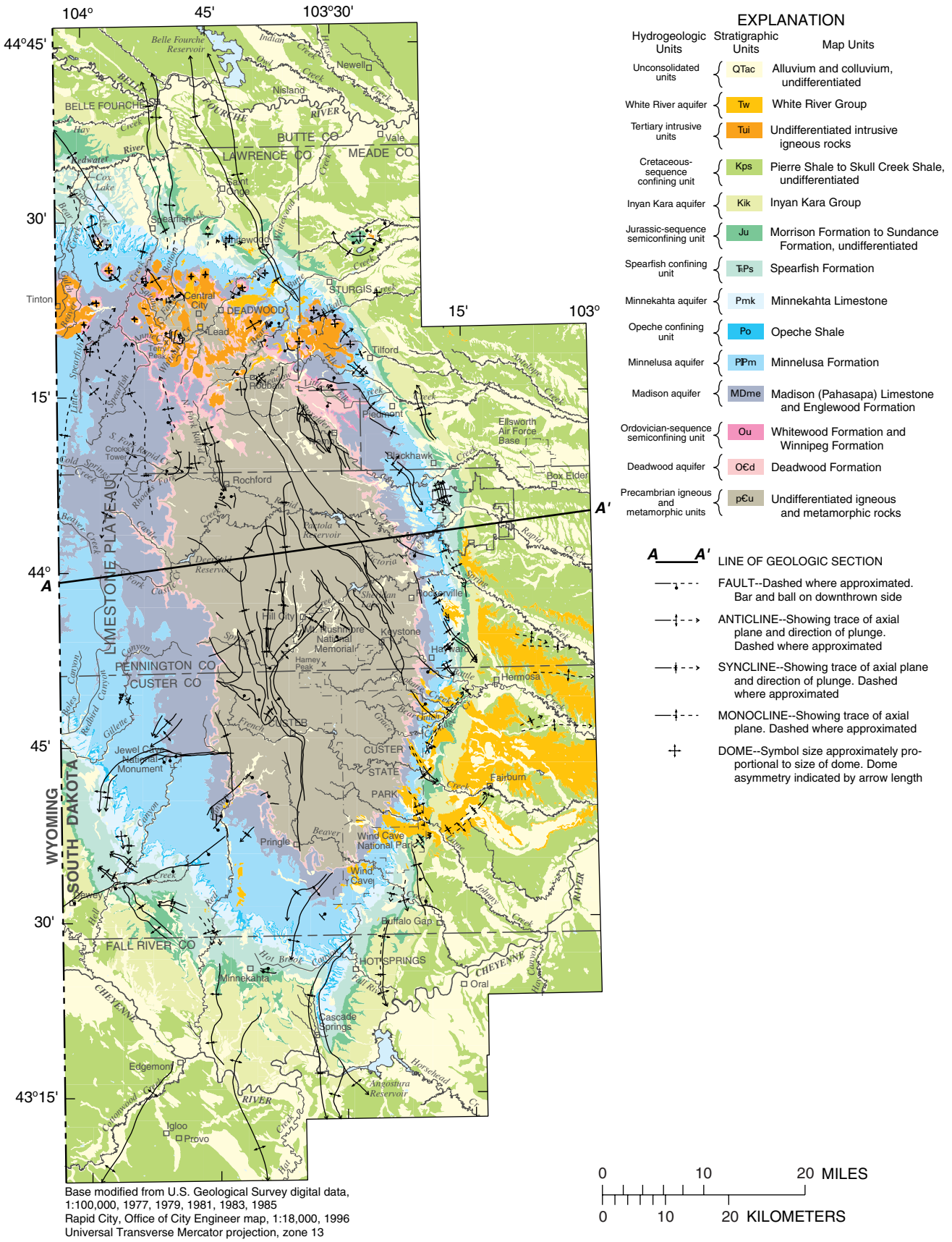


Figure 12. Generalized correlation chart for Paleozoic-age rocks in Montana, North Dakota, South Dakota, and Wyoming (modified from Downey, 1986).



* Of informal or subsurface usage

Figure 13. Generalized correlation chart for Mesozoic- and Cenozoic-age rocks in Montana, North Dakota, South Dakota, and Wyoming (modified from Downey, 1986).



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