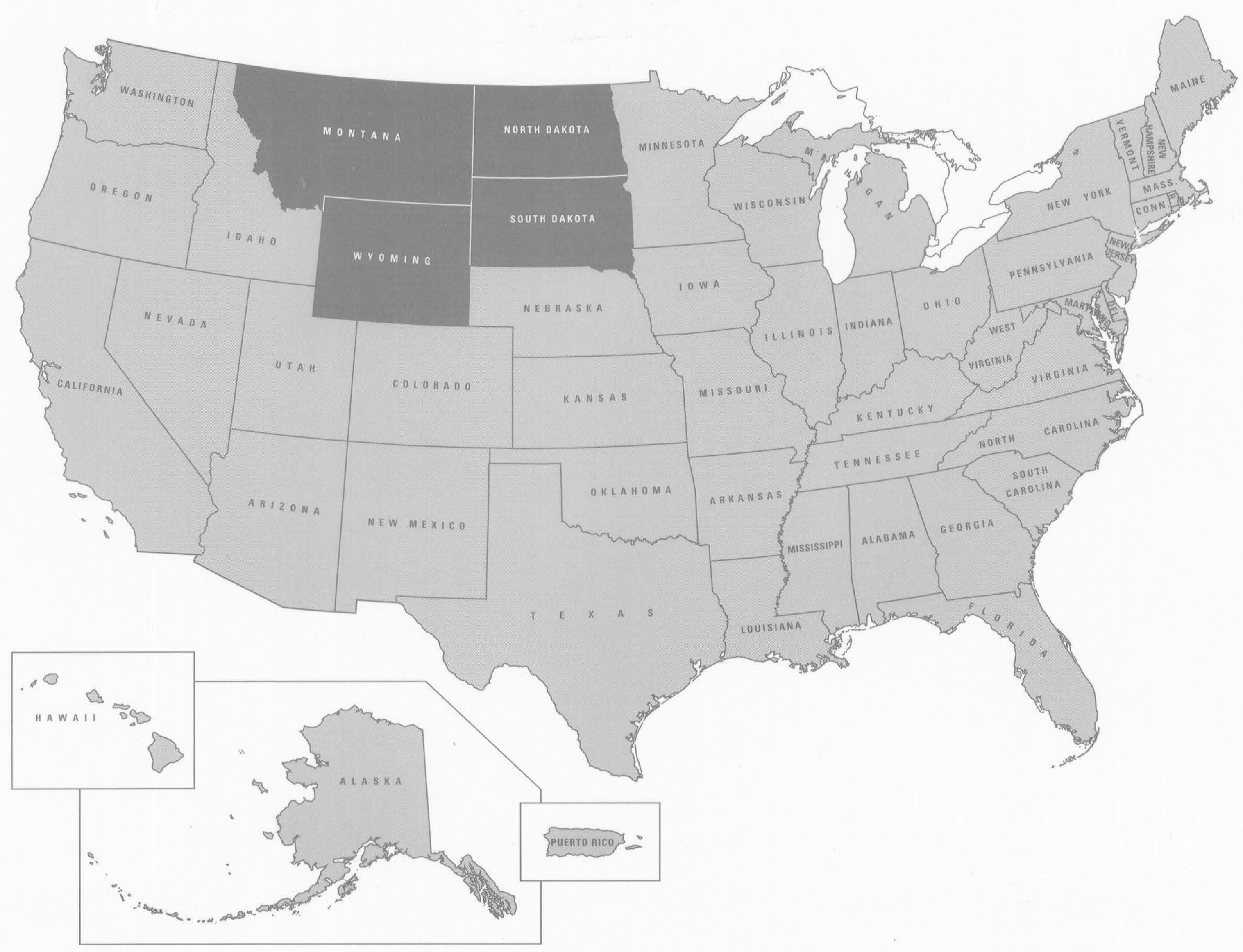
Ground Water Atlas of the United States

Segment 8

Montana
North Dakota
South Dakota
Wyoming



HYDROLOGIC INVESTIGATIONS ATLAS 730–I

U.S. Geological Survey

Reston, Virginia
1996

GROUND WATER ATLAS OF THE UNITED STATES
Hydrologic Investigations Atlas 730–I

FOREWORD

The Ground Water Atlas of the United States presents a comprehensive summary of the Nation's ground-water resources, and is a basic reference for the location, geography, geology, and hydrologic characteristics of the major aquifers in the Nation. The information was collected by the U.S. Geological Survey and other agencies during the course of many years of study. Results of the U.S. Geological Survey's Regional Aquifer-System Analysis Program, a systematic study of the Nation's major aquifers, were used as a major, but not exclusive, source of information for compilation of the Atlas.

The Atlas, which is designed in a graphical format that is supported by descriptive discussions, includes 13 chapters, each representing regional areas that collectively cover the 50 States and Puerto Rico. Each chapter of the Atlas presents and describes hydrogeologic and hydrologic conditions for the major aquifers in each regional area. The scale of the Atlas does not allow portrayal of minor features of the geology or hydrology of each aquifer presented, nor does it include discussion of minor aquifers. Those readers that seek detailed, local information for the aquifers will find extensive lists of references at the end of each chapter.

An introductory chapter presents an overview of ground-water conditions Nationwide and discusses the effects of human activities on water resources, including saltwater encroachment and land subsidence.

Gordon P. Eaton

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, *Director*

CONVERSION FACTORS

For readers who prefer to use the International System (SI) units, rather than the inch-pound terms used in this report, the following conversion factors may be used:

Multiply inch-pound units	*By*	*To obtain metric units*
	Length	
inch (in)	25.4	millimeter (Mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
billion gallons per day (Bgal/d)	3.785	million cubic meters per day (Mm^3/d)
acre-foot	1,233	cubic meter (m^3)
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
acre-foot per year	0.00003909	cubic meter per second (m^3/s)
	Transmissivity	
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
	Temperature	
degree Fahrenheit (°F)	5/9(°F–32)=°C	degree Celsius (°C)

Sea Level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

ATLAS ORGANIZATION

The Ground Water Atlas of the United States is divided into 14 chapters. Chapter A presents introductory material and nationwide summaries; chapters B through M describe all principal aquifers in a multistate segment of the conterminous United States; and chapter N describes all principal aquifers in Alaska, Hawaii, and Puerto Rico.

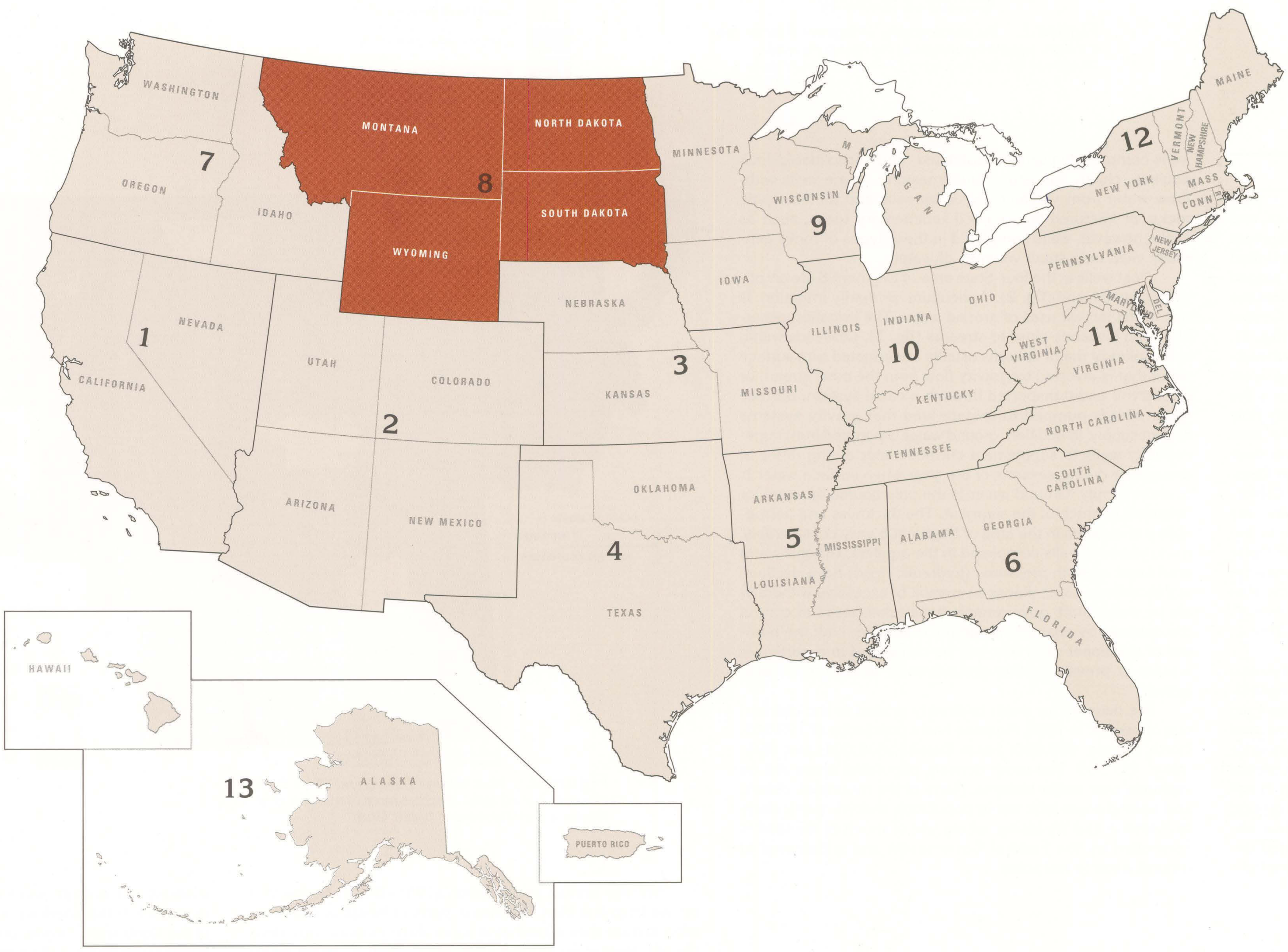
Segment Number	*Chapter content*	*Hydrologic Atlas Chapter*
—	Introductory material and nationwide summaries	730–A
1	California, Nevada	730–B
2	Arizona, Colorado, New Mexico, Utah	730–C
3	Kansas, Missouri, Nebraska	730–D
4	Oklahoma, Texas	730–E
5	Arkansas, Louisiana, Mississippi	730–F
6	Alabama, Florida, Georgia, South Carolina	730–G
7	Idaho, Oregon, Washington	730–H
8	Montana, North Dakota, South Dakota, Wyoming	730–I
9	Iowa, Michigan, Minnesota, Wisconsin	730–J
10	Illinois, Indiana, Kentucky, Ohio, Tennessee	730–K
11	Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia	730–L
12	Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont	730–M
13	Alaska, Hawaii, Puerto Rico	730–N

Ground Water Atlas of the United States

Segment 8

Montana, North Dakota, South Dakota, Wyoming

By R.L. Whitehead



CONTENTS

Cartographic design and production by Loretta J. Ulibarri and Derald L. Dunagan

Regional summary

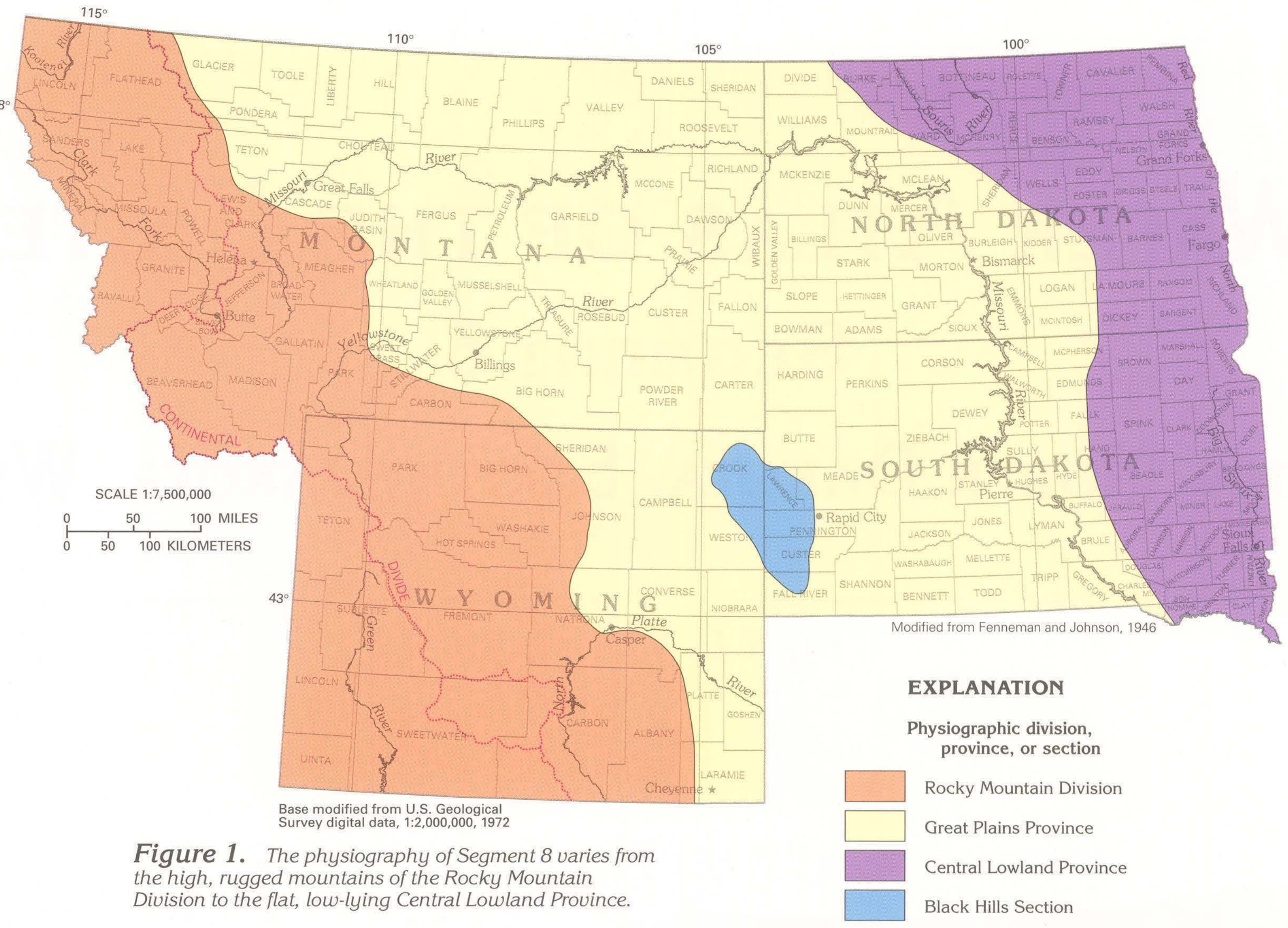


Figure 1. The physiography of Segment 8 varies from the high, rugged mountains of the Rocky Mountain Division to the flat, low-lying Central Lowland Province.

INTRODUCTION

The States of Montana, North Dakota, South Dakota, and Wyoming compose the 392,764-square-mile area of Segment 8, which is in the north-central part of the continental United States. The area varies topographically from the high rugged mountain ranges of the Rocky Mountains in western Montana and Wyoming to the gently undulating surface of the Central Lowland in eastern North Dakota and South Dakota (**fig. 1**). The Black Hills in southwestern South Dakota and northeastern Wyoming interrupt the uniformity of the intervening Great Plains. Segment 8 spans the Continental Divide, which is the drainage divide that separates streams that generally flow westward from those that generally flow eastward. The area of Segment 8 is drained by the following major rivers or river systems: the Green River drains southward to join the Colorado River, which ultimately discharges to the Gulf of California; the Clark Fork and the Kootenai Rivers drain generally westward by way of the Columbia River to discharge to the Pacific Ocean; the Missouri River system and the North Platte River drain eastward and southeastward to the Mississippi River, which discharges to the Gulf of Mexico; and the Red River of the North and the Souris River drain northward through Lake Winnipeg to ultimately discharge to Hudson Bay in Canada.

These rivers and their tributaries are an important source of water for public-supply, domestic and commercial, agricultural, and industrial uses. Much of the surface water has long been appropriated for agricultural use, primarily irrigation, and for compliance with downstream water pacts. Reservoirs store some of the surface water for flood control, irrigation, power generation, and recreational purposes. Surface water is not always available when and where it is needed, and ground water is the only other source of supply. Ground water is obtained primarily from wells completed in unconsolidated-deposit aquifers that consist mostly of sand and gravel, and from wells completed in semiconsolidated- and consolidated-rock aquifers, chiefly sandstone and limestone. Some wells withdraw water from volcanic rocks, igneous and metamorphic rocks, or fractured fine-grained sedimentary rocks, such as shale; however, wells completed in these types of rocks generally yield only small volumes of water.

Most wells in the four-State area of Segment 8 are on privately owned land (**fig. 2**). Agriculture, primarily irrigation, is one of the largest uses of ground water. The irrigation generally is on lowlands close to streams (**fig. 3**). Lowlands within a few miles of major streams usually are irrigated with surface water that is diverted by gravity flow from the main stream or a reservoir and transported through a canal system. Surface water also is pumped to irrigate land that gravity systems cannot supply. In addition, ground water is pumped from large-capacity wells to supplement surface water during times of drought or during seasons of the year when surface water is in short supply. Ground water is the only source of water for irrigation in much of the segment. The thickness and permeability of aquifers in the area of Segment 8 vary considerably, as do yields of wells completed in the aquifers. Ground-water levels and artesian pressures (hydraulic head) have declined significantly in some places as a result of excessive withdrawals by wells. State governments have taken steps to control the declines by enacting programs that either limit the number of additional wells that can be completed in a particular aquifer or prevent further ground-water development altogether.

The demand for water is directly related to the distribution of people. In 1990, Montana had a population of 799,065; North Dakota, 638,800; South Dakota, 696,004; and Wyoming, 453,588. The more densely populated areas are on lowlands near major streams. Many of the mountain, desert, and upland areas lack major population centers, particularly in Montana and Wyoming, where use of much of the land is controlled by the Federal Government and withdrawal of ground water is restricted.

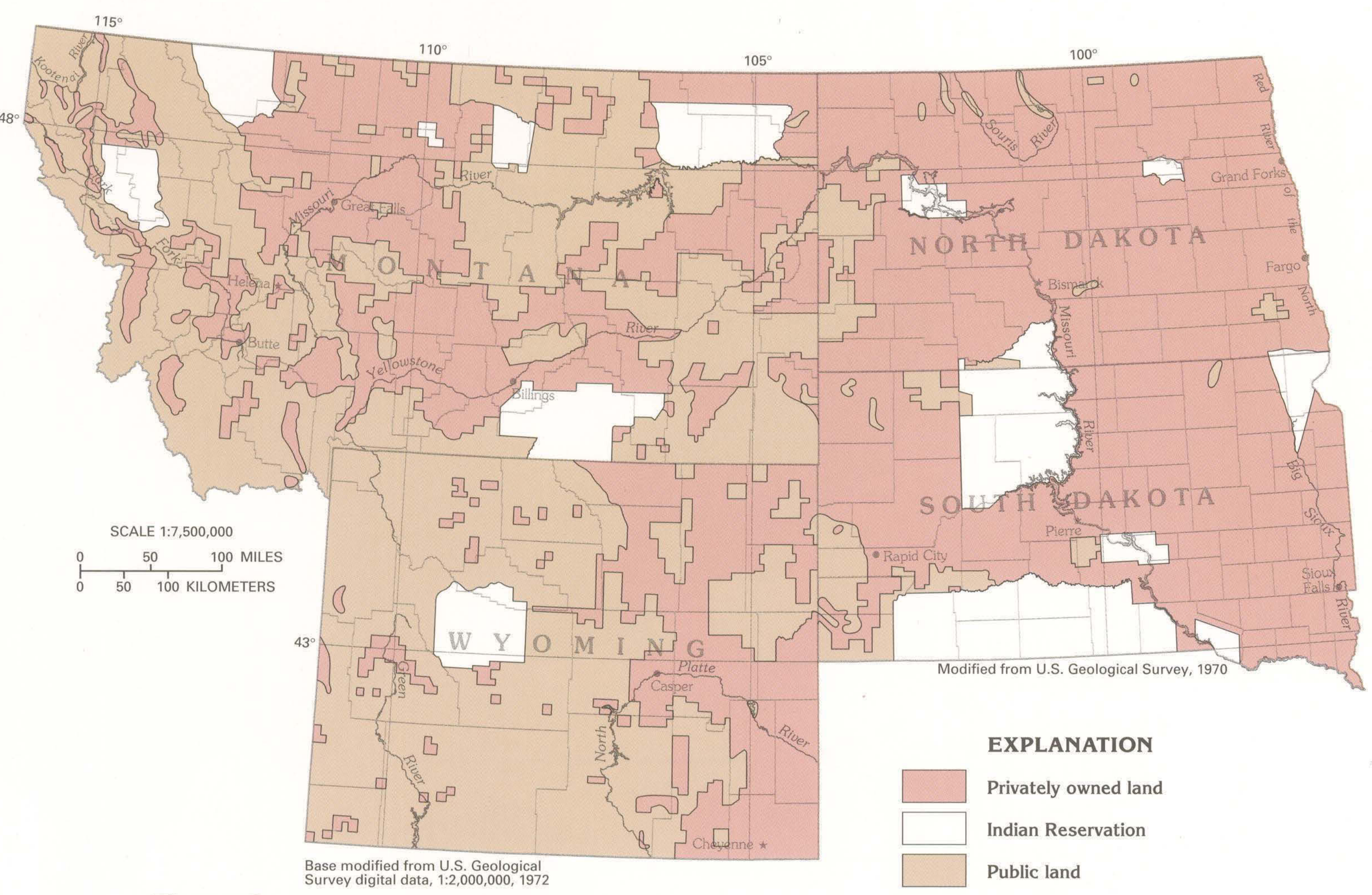


Figure 2. Most of North Dakota and South Dakota is privately owned land, whereas more than one-half of Montana and Wyoming is public land.

Average annual precipitation (1951–80) in Segment 8 ranges from less than 8 inches in parts of Montana and Wyoming to more than 40 inches in some of the mountainous areas (**fig. 4**). Most storms move eastward through Segment 8 and are particularly common during the winter months. Moisture that evaporates from the Pacific Ocean is absorbed by eastward-moving air. As the moisture-laden air masses move eastward, they rise and cool as they encounter mountain ranges and lose some of their moisture to condensation. Consequently, the western sides of mountain ranges receive the most precipitation, much of it as snow during the winter months. In contrast, the eastern sides of some of the higher mountain ranges are in rain shadows and receive little precipitation. East of the Continental Divide, precipitation that falls during many summer storms results from northward-moving, moisture-laden air masses from the Gulf of Mexico. These air masses move northward when the polar front recedes; accordingly, a major part of the annual precipitation falls on the plains during the growing season. Average annual precipitation minus the total of average annual runoff plus evapotranspiration (the combination of evaporation and transpiration by plants) is the amount of water potentially available for recharge to the aquifers.

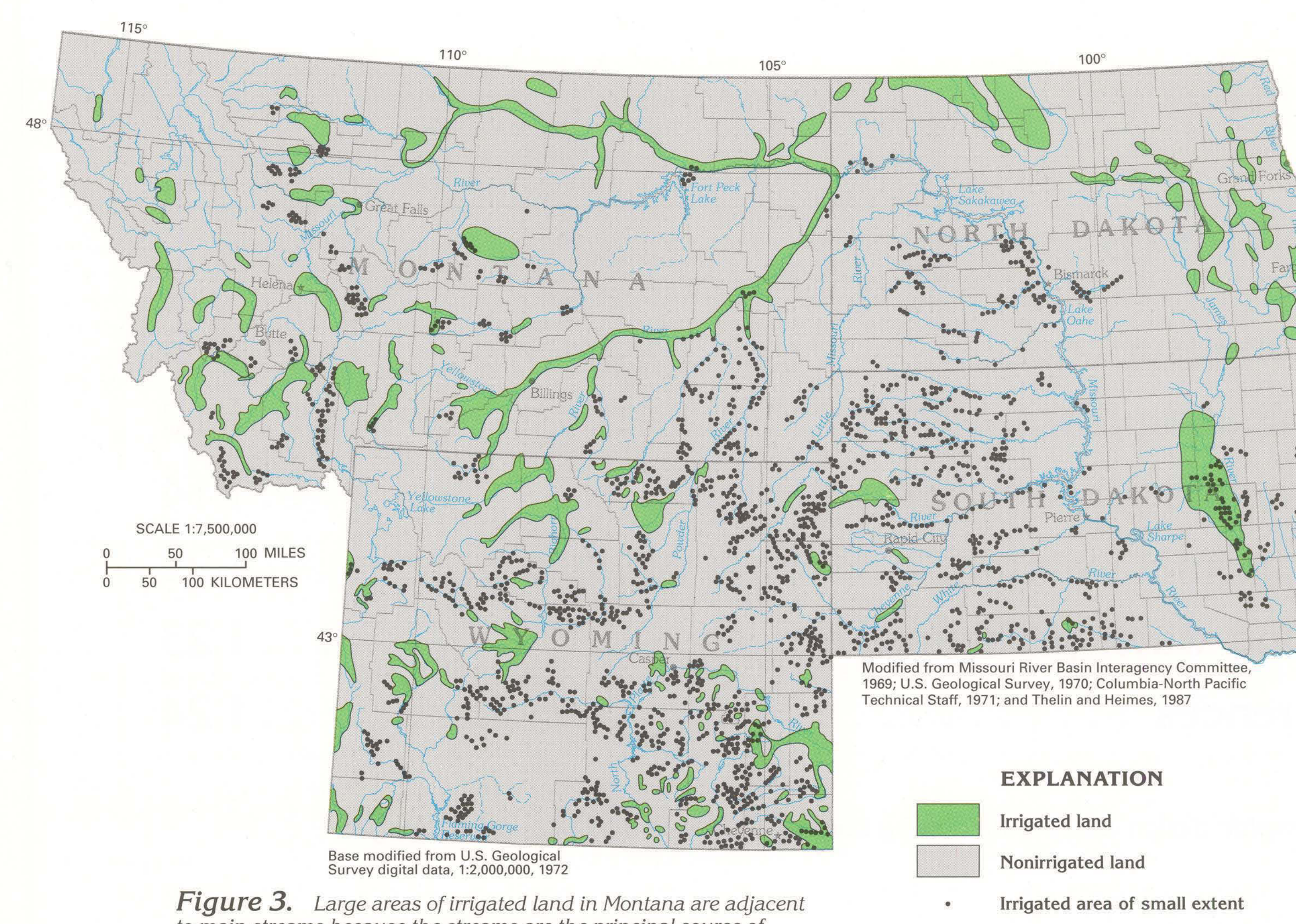


Figure 3. Large areas of irrigated land in Montana are adjacent to main streams because the streams are the principal source of the irrigation water. In Wyoming, North Dakota, and South Dakota, however, ground water is used extensively for irrigation in areas of small extent.

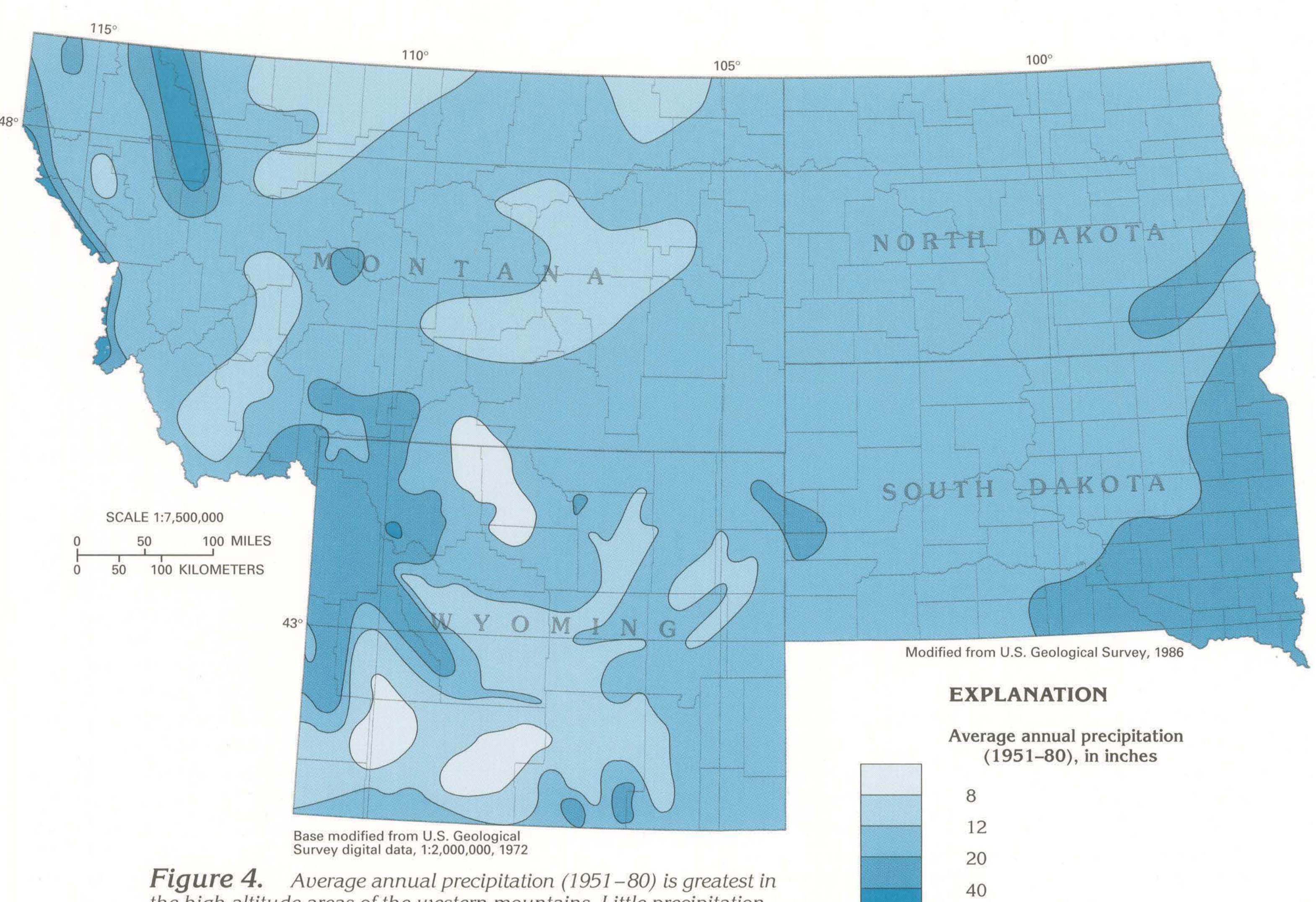


Figure 4. Average annual precipitation (1951–80) is greatest in the high-altitude areas of the western mountains. Little precipitation falls on the central part of the area, but the eastern parts of North Dakota and South Dakota receive moderate amounts of precipitation.

Average annual runoff (1951–80) in the area of Segment 8 varies greatly, and the distribution of runoff (**fig. 5**) generally parallels that of precipitation. In arid and semiarid areas of the segment, most precipitation replenishes soil moisture, evaporates, or is transpired by vegetation, and only a small part of the precipitation is left to maintain streamflow or recharge aquifers. In wetter areas of the segment, much of the precipitation runs off the land surface directly to perennial streams. Because a smaller percentage of precipitation in wet areas usually is lost to evapotranspiration than in dry areas, more water is, therefore, available to recharge aquifers where more precipitation falls. Precipitation that falls as snow generally does not become runoff until spring thaws begin. Runoff is affected in some areas by reservoirs that have been constructed on major streams to mitigate flooding and to store water for irrigation, electrical power generation, and recreation. Water stored in reservoirs during times when runoff is great is subsequently released during drier periods to maintain downstream flow.

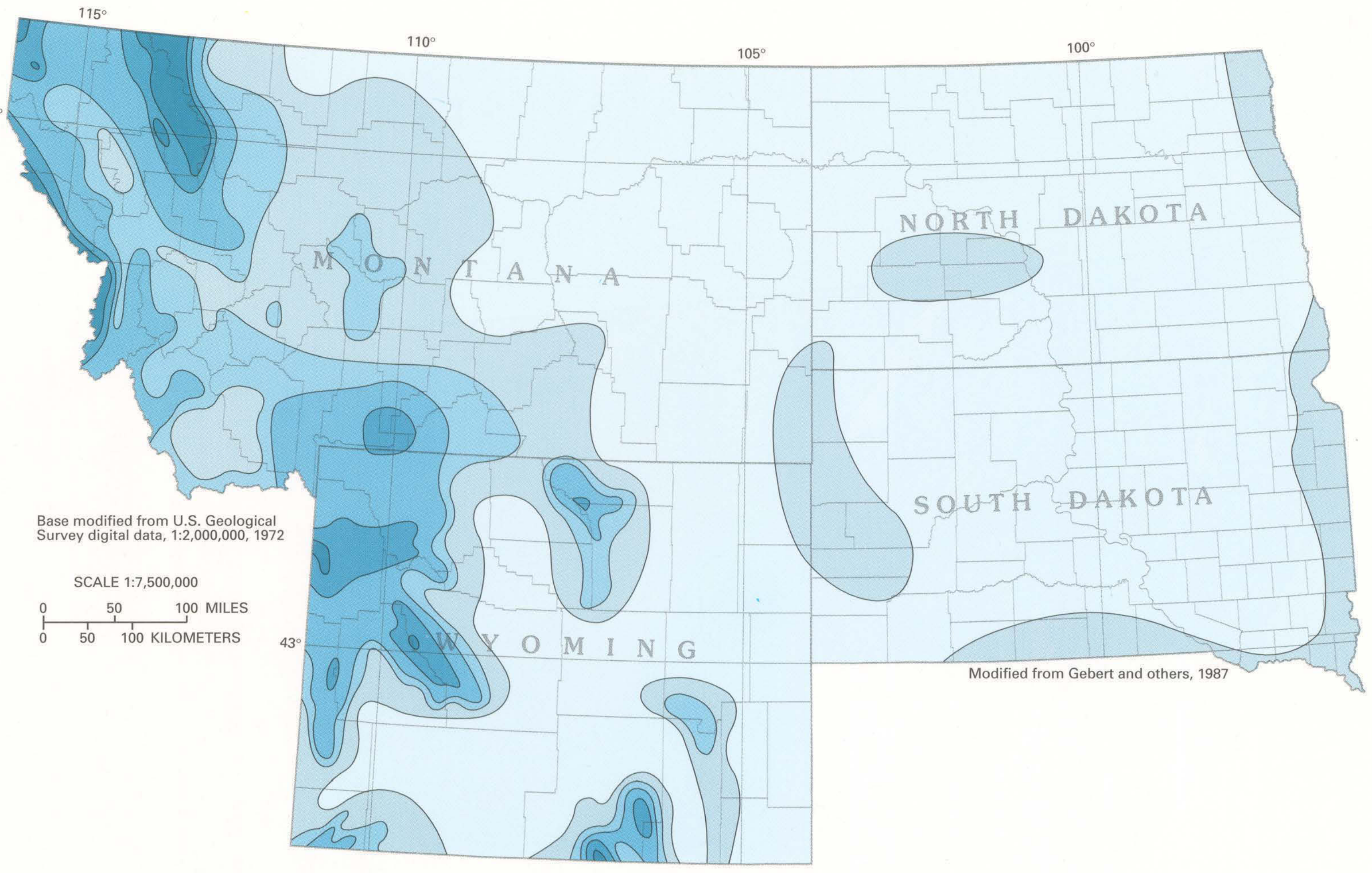


Figure 5. *Average annual runoff (1951–80) is greatest from the western mountains. Runoff generally is small throughout the Northern Great Plains and in the interior basins between some mountain ranges.*

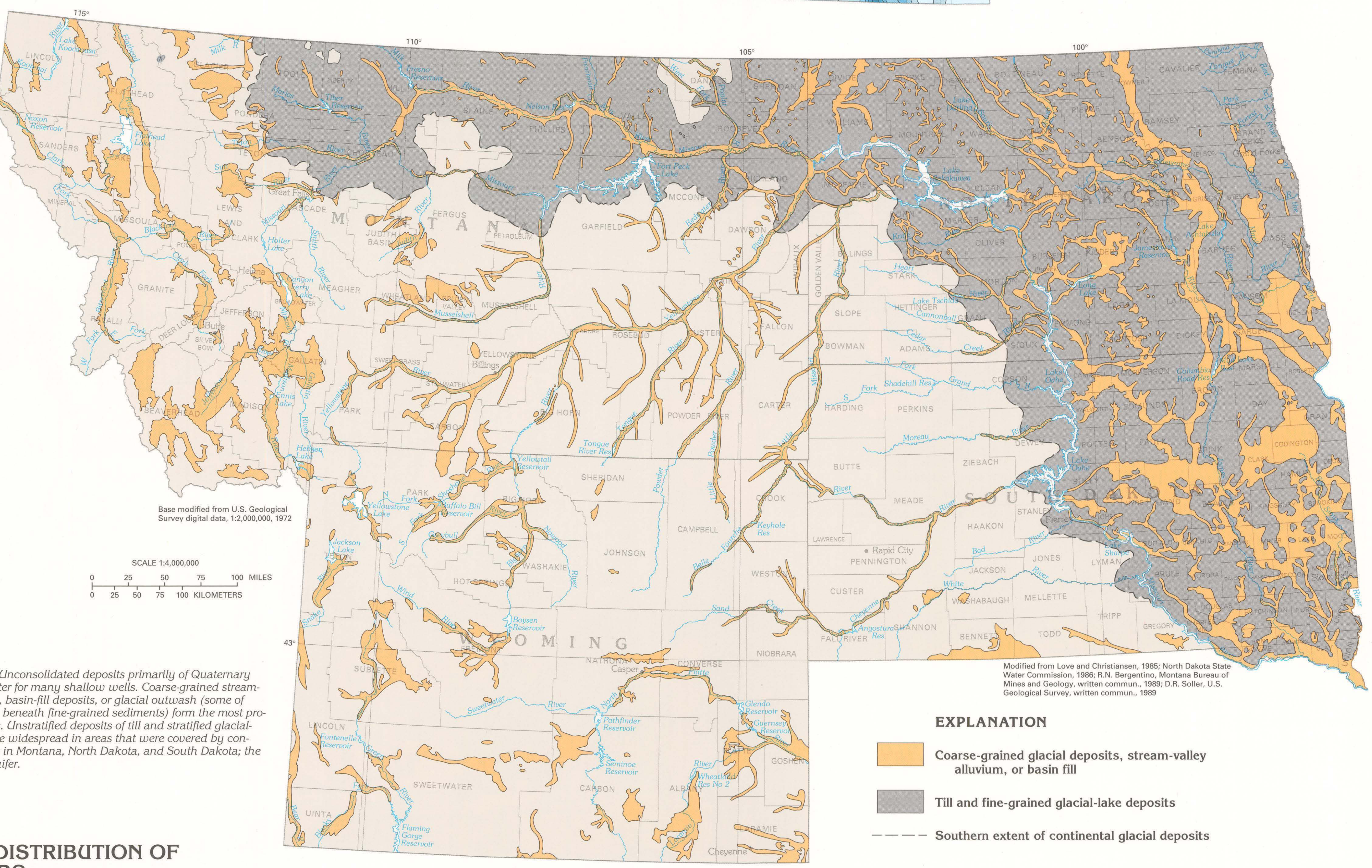


Figure 6. *Unconsolidated deposits primarily of Quaternary age provide water for many shallow wells. Coarse-grained stream-valley alluvium, basin-fill deposits, or glacial outwash (some of which is buried beneath fine-grained sediments) form the most productive aquifers. Unstratified deposits of till and stratified glacial-lake deposits are widespread in areas that were covered by continental glaciers in Montana, North Dakota, and South Dakota; the till is not an aquifer.*

AREAL DISTRIBUTION OF AQUIFERS

The numerous aquifers in Segment 8 vary greatly in composition. Some of the aquifers consist of unconsolidated sand and gravel; other aquifers consist of semiconsolidated or consolidated sedimentary rocks that are almost flat lying in some places and are folded and faulted in other places; still other aquifers consist of hard, crystalline, igneous and metamorphic rocks that are impermeable except where they are fractured. The different aquifers are grouped into seven categories of principal aquifers in this report, depending on the hydrologic and geologic characteristics of the rocks that compose the aquifers. The extent of the aquifers in unconsolidated deposits primarily of Quaternary age is shown in **figure 6**. The extent of the remaining six categories of aquifers that are at or near the land surface and that consist primarily of semiconsolidated to consolidated rocks is mapped in **figure 7**. In the areas where no principal aquifer is mapped, local aquifers may yield small amounts of water to wells.

Aquifers that consist of unconsolidated deposits are in all four States of Segment 8 (**fig. 6**). The unconsolidated-deposit aquifers consist of sand and gravel of primarily Quaternary age, deposited by glaciers and streams. The glacial deposits are mostly in the northern and eastern parts of the segment and formed during multiple advances of continental ice sheets from the north and northeast during the Pleistocene Epoch. As the huge sheets of ice advanced, rock and soil particles were planed from the land surface and transported in the ice or pushed in front of it. Some of these materials were redistributed by meltwater during ice retreats. Where they consist of stratified sand and gravel, meltwater deposits form productive aquifers. In contrast, clay and silt that were deposited in glacial lakes and poorly sorted, unstratified deposits of clay, silt, sand, gravel, and boulders (called till) have minimal permeability. Many of the aquifers mapped in the eastern parts of North Dakota and South Dakota are buried beneath till or glacial-lake deposits. In parts of western Montana and Wyoming, mountain or alpine glaciers locally deposited sand and gravel that constitute the aquifers; most of these deposits are of small extent and are not differentiated in this report from alluvium deposited by streams. Unconsolidated sand and gravel, which were deposited as stream-valley alluvium, are in and adjacent to the channels of most of the larger streams in the segment (**fig. 6**). Intermontane basins in western Montana and Wyoming have been partially filled by clay, silt, sand, and gravel deposited as coalescing alluvial fans by streams that enter the basins from the surrounding mountains. These alluvial deposits are collectively called basin fill and form productive aquifers where they consist primarily of sand and gravel. In many of the intermontane basins, particularly in Montana, the basin-fill deposits mapped in **figure 6** are hydraulically connected to underlying upper Tertiary aquifers (**compare figs. 6 and 7**). The unconsolidated-deposit aquifers are important sources of water because they generally are located in flat lowlands where most of the rural and urban population of the segment also is located.

Aquifers in semiconsolidated and consolidated rocks have been divided into six categories in the four States of Segment 8, as shown in **figure 7**. Some of the aquifers in semiconsolidated and consolidated rocks underlie the glacial and alluvial deposits that compose the unconsolidated-rock aquifers, and the two types of aquifers can be in direct hydraulic connection. The consolidated-rock aquifers are differentiated primarily by rock type (that is, whether they mostly consist of igneous, metamorphic, or sedimentary rocks) and secondarily by the age of the rocks.

Aquifers in volcanic and associated sedimentary rocks are in a small area in northwestern Wyoming and southwestern Montana. These aquifers consist of basaltic and rhyolitic flows, beds of volcanic ash and tuff, and beds of semiconsolidated to consolidated sedimentary rocks that contain volcanic material. The complexly interbedded rocks and deposits that compose these aquifers are of Quaternary age.

Upper Tertiary aquifers are important sources of water in western Montana, southern South Dakota, and southeastern Wyoming; they also supply water locally in central and western Wyoming. These aquifers consist mostly of unconsolidated to semiconsolidated deposits of sand and gravel, commonly interbedded with silt and clay. In Montana, the aquifers locally contain thin beds of volcanic ash and basalt. Most of the rocks that compose the upper Tertiary aquifers are of Pliocene or Miocene age. The upper Tertiary aquifers in Montana and in western and central Wyoming mostly are ancient alluvial deposits that occupy structural basins which are surrounded by mountains. The alluvium was derived from the mountains and transported into the valleys by streams. Upper Tertiary aquifers in southern South Dakota and southeastern Wyoming likewise consist mostly of ancient alluvium deposited by streams, but the alluvium is in the form of wide sheets because the streams that transported it anastomosed across a wide, gentle plain.

Lower Tertiary aquifers extend throughout large areas in all four States of Segment 8 (**fig. 7**) and consist of semiconsolidated to consolidated sedimentary rocks of Oligocene through Paleocene age. Sandstone composes most of the water-yielding beds of these aquifers, but locally, coal beds that are exposed at the land surface have been ignited naturally and the burned coal has formed highly permeable clinker beds that compose high-yielding local aquifers. The sandstone and coal are interbedded with fine-grained rocks, such as shale and siltstone, and locally contain beds of limestone. The fine-grained rocks mostly form confining units but can yield small volumes of water where they are fractured or deeply weathered.

Upper Cretaceous aquifers mostly are deeply buried but are exposed locally at the land surface as a narrow to wide band that borders the lower Tertiary aquifers. The upper Cretaceous aquifers consist of consolidated sandstone and are underlain by a thick sequence of shale that forms a confining unit which separates them from aquifers in older rocks. Locally, where the shale is fractured or deeply weathered, it can yield sufficient water for domestic supplies, but is not considered to be an aquifer in this report.

Lower Cretaceous aquifers consist of consolidated sandstone and are either exposed at the land surface or buried only to shallow depths in three general areas (**fig. 7**). One area is a broad, irregular band that extends northwestward from central Wyoming through west-central Montana almost to the Canadian border. The second area in northeastern Wyoming and southwestern South Dakota is oval and surrounds older rocks on the flanks of the Black Hills Uplift. The third area is a narrow, discontinuous band parallel to the eastern State line of North and South Dakota where the lower Cretaceous aquifers subcrop beneath glacial deposits. Locally, where sandstones of Jurassic age yield water, they are included as part of the lower Cretaceous aquifers in this report.

Paleozoic aquifers are exposed at the land surface in small, irregular, discontinuous areas in Montana, South Dakota, and Wyoming and subcrop beneath glacial deposits in northeastern North Dakota. These aquifers generally crop out on the flanks of uplifts or where they have been folded upward into anticlines and were subsequently exposed by erosion. Paleozoic aquifers consist of sandstone, dolomite, and limestone; the limestone formations are the most productive aquifers. The Madison Limestone and equivalent rocks of Mississippian age constitute a high-yielding aquifer in upper Paleozoic rocks. Shale, evaporite beds, and salt of Devonian and Silurian age form an effective confining unit that separates the Mississippian aquifers from lower Paleozoic sandstone and limestone aquifers in formations of Ordovician and Cambrian age. Upper and lower Paleozoic aquifers are not differentiated in **figure 7** because of the scale of the map.

Rocks throughout large areas of western Montana and northwestern Wyoming generally yield little water to wells. The extremely variable lithology of these rocks includes volcanic rocks, several kinds of igneous and metamorphic rocks, and consolidated sedimentary rocks, some of which are as old as Precambrian. The permeability of these rocks varies greatly because their composition and degree of fracturing varies widely. These rocks are mostly in sparsely populated mountainous areas and the small amounts of water they yield is used primarily for domestic supplies and stock watering. Thus, they are not considered to be major aquifers in this report, even though they may be important local sources of supply. Likewise, local aquifers in Cretaceous and Paleozoic rocks of the thrust belt of westernmost Wyoming are not differentiated because of the scale of the map and are not considered to be major aquifers.

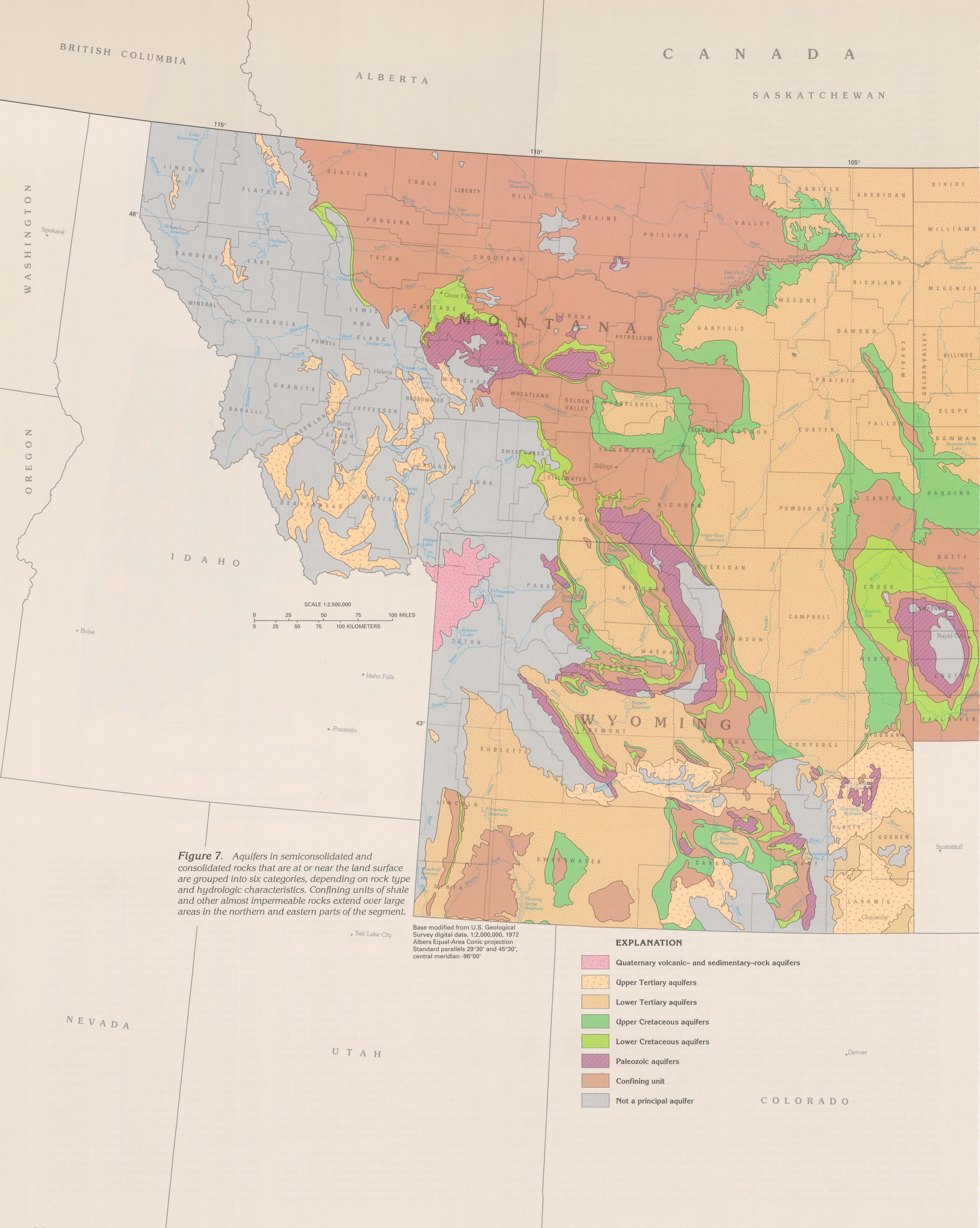
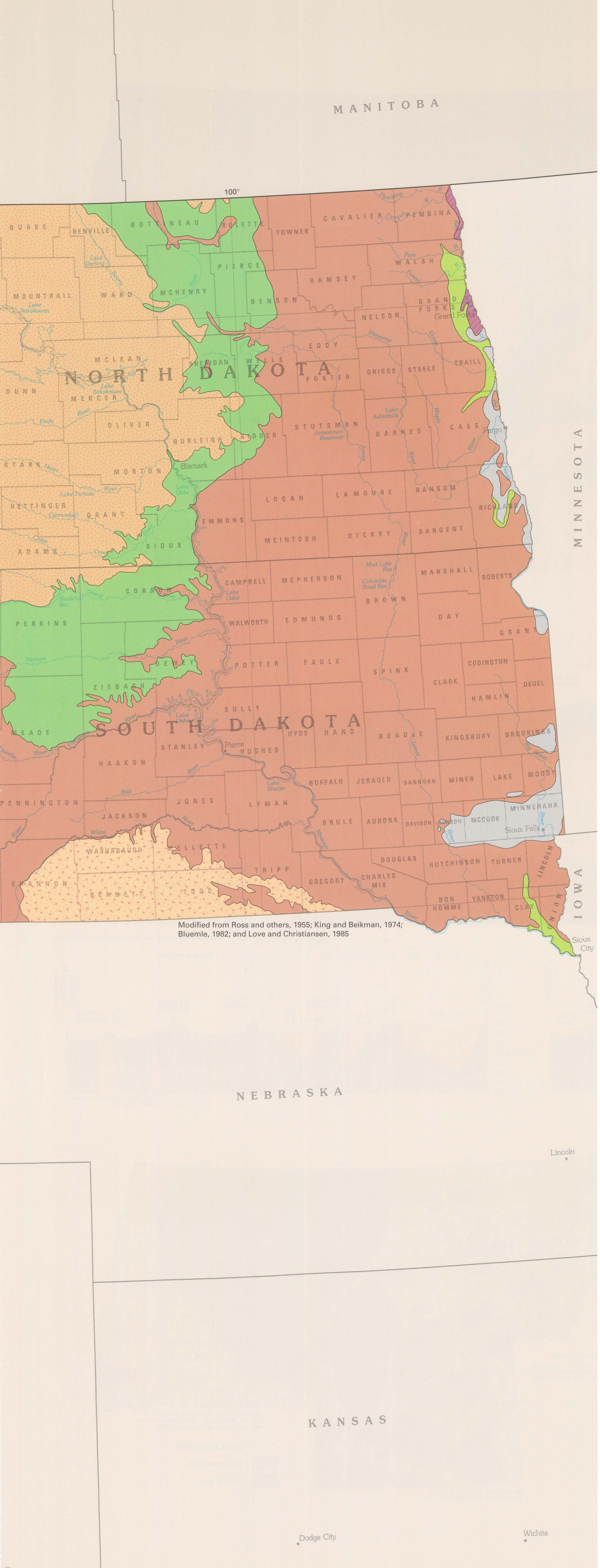


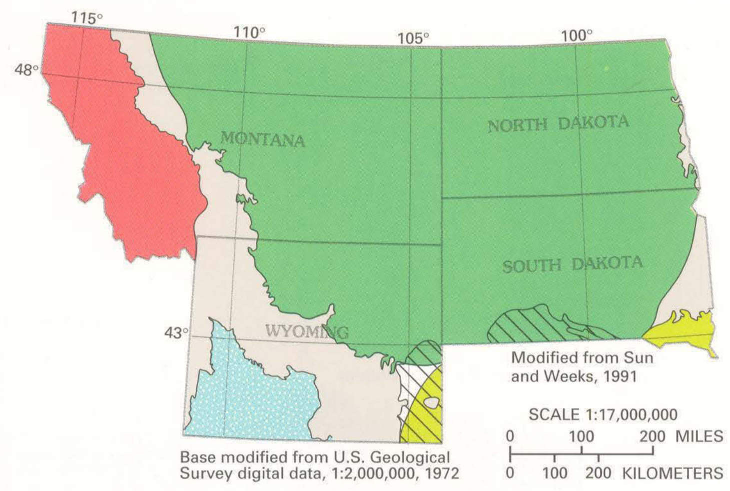
Figure 7. Aquifers in semiconsolidated and consolidated rocks that are at or near the land surface are grouped into six categories, depending on rock type and hydrologic characteristics. Confining units of shale and other almost impermeable rocks extend over large areas in the northern and eastern parts of the segment.

AREAL DISTRIBUTION OF AQUIFERS—Continued



Modified from Ross and others, 1955; King and Beikman, 1974; Bluemle, 1982; and Love and Christiansen, 1985

Some of the aquifers in Segment 8 have been grouped together and studied as regional aquifers or regional aquifer systems. An aquifer system is a grouping of two or more aquifers that commonly consist of the same kind of rock, and can be of two types. The first type consists of vertically stacked aquifers that are hydraulically connected; that is, the groundwater flow systems in the aquifers function in a similar manner, and a change in conditions in one of the aquifers affects the other aquifer(s). The second type is a set of aquifers that are not physically connected, but share many common hydrologic and geologic characteristics and thus can best be described and studied together. Both types of aquifer systems are in Segment 8, and their extent is shown in **figure 8**. Quaternary unconsolidated-deposit aquifers and upper Tertiary aquifers partly fill intermontane basins in western Montana and, although not hydraulically connected, the basins share common geologic and hydrologic characteristics. These basin-fill aquifers collectively compose the Northern Rocky Mountains Intermontane Basins aquifer system. Upper and lower Tertiary aquifers are in direct hydraulic connection in eastern Wyoming and southern South Dakota where they form part of the High Plains aquifer system, which is only in a small part of Segment 8. In southwestern Wyoming, upper and lower Tertiary aquifers, upper and lower Cretaceous aquifers, and Paleozoic aquifers are part of the Upper Colorado River Basin aquifer system. Although the Northern Great Plains aquifer system (**fig. 9**) contains many of the same aquifers as the Upper Colorado River Basin aquifer system, the two aquifer systems are not hydraulically connected. Deeply buried lower Cretaceous aquifers in small areas in southeastern South Dakota and Wyoming are part of the Central Midwest aquifer system, which is continuous with part of the Northern Great Plains aquifer system to the north. Except for the basin-fill aquifers of the Northern Rocky Mountains Intermontane Basins aquifer system, the regional aquifers and aquifer systems listed above consist of layered rocks that compose stacked aquifers.



EXPLANATION

Regional aquifer system that has been studied in detail as of 1996

- High Plains aquifer system
- Northern Great Plains aquifer system
- Upper Colorado River Basin aquifer system
- Central Midwest aquifer system

Regional aquifer system that has not been studied in detail as of 1996

- Northern Rocky Mountains Intermontane Basins aquifer system

Figure 8. *Regional aquifer systems extend throughout most of Segment 8. The High Plains aquifer system overlies parts of the Northern Great Plains and the Central Midwest aquifer systems, but is separated from them by a confining unit.*

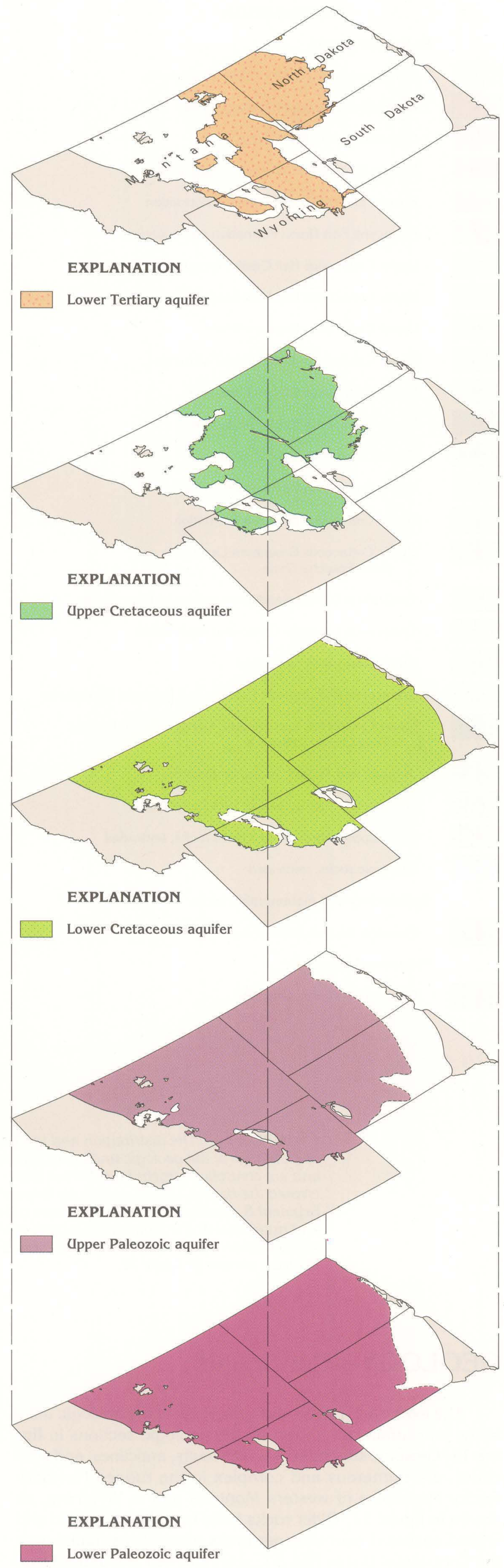


Figure 9. *The Northern Great Plains aquifer system contains overlapping aquifers in lower Tertiary, upper Cretaceous, lower Cretaceous, upper Paleozoic and lower Paleozoic rocks.*

GEOLOGY

The geologic and hydrogeologic nomenclature used in this report differs from State to State because of independent geologic interpretations and varied distribution and lithology of rock units. A fairly consistent set of nomenclature, however, can be derived from the most commonly used rock names. Therefore, the nomenclature used in this report is basically a synthesis of that of the U.S. Geological Survey, the Montana Bureau of Mines and Geology, the North Dakota Geological Survey, the South Dakota Geological Survey, and the Geological Survey of Wyoming. Individual sources for nomenclature are listed with each correlation chart prepared for this report.

Unconsolidated to consolidated rocks in Montana, North Dakota, South Dakota, and Wyoming range in age from Precambrian to Quaternary (**fig. 10**). Rocks that are of different ages or compositions from these mapped in the figure might be present locally, especially in mountainous areas that have complex geologic structures, but cannot be shown because of the map scale. Unconsolidated deposits of possibly Pliocene to Holocene age are present throughout large parts of Segment 8 and coincide with the unconsolidated-deposit aquifers mapped in **figure 6**; accordingly, these deposits are not shown in figure 10. Because rock type largely determines the water-yielding characteristics of the aquifers, the principal aquifer map shown in **figure 7** resembles a simplified version of the geologic map shown in **figure 10**.

Precambrian rocks are exposed mostly in western Montana and in Wyoming, but smaller areas of these rocks are in central Montana, eastern and western South Dakota, and eastern North Dakota (**fig. 10**). Sedimentary rocks of Precambrian age (the Belt Supergroup) crop out over a wide area in western Montana. In Wyoming and southwestern Montana, Precambrian rocks mostly are plutonic igneous rocks but also include several types of metamorphic rocks. The Precambrian rocks exposed in central Montana and western South Dakota primarily are metamorphic rocks. Granitic Precambrian rocks subcrop beneath glacial deposits in easternmost North Dakota, and the Sioux quartzite of Precambrian age directly underlies glacial deposits over a wide area in southeastern South Dakota.

Paleozoic sedimentary rocks, which underlie most of Segment 8, are exposed at the land surface mostly in mountainous areas where they flank uplifts or anticlines, or have been displaced upward along faults. The Paleozoic sedimentary rocks consist mostly of shale, siltstone, sandstone, and carbonate rocks, as well as some salt and evaporite beds, and are deeply buried where they are downwarped in large structural basins.

Mesozoic (chiefly Cretaceous) sedimentary rocks are exposed over wide areas in Montana and Wyoming, and subcrop beneath glacial deposits in large parts of eastern North Dakota and South Dakota. These rocks consist mostly of shale, siltstone, and sandstone but contain some beds of conglomerate, anhydrite, chalk, carbonate rocks, and bentonite (clay that formed from the chemical decomposition of volcanic ash). Like the Paleozoic sedimentary rocks that underlie them, the Mesozoic sedimentary rocks are downwarped in large structural basins in parts of the segment.

Paleocene and Eocene sedimentary rocks are exposed at the land surface chiefly in a wide, irregular band that extends from southwestern Wyoming to northwestern North Dakota (**fig. 10**). These rocks consist of sandstone, siltstone, and claystone, with some beds of coal and lignite. Large areas of Tertiary intrusive and volcanic rocks are present in northwestern Wyoming and western Montana.

Oligocene and undifferentiated upper Tertiary sedimentary rocks are in scattered areas in southern South Dakota and central and southeastern Wyoming. These rocks consist mostly of semiconsolidated to unconsolidated deposits of clay and sand, with some gravel.

Tertiary and Quaternary valley-fill deposits that consist of unconsolidated gravel, sand, silt, and clay are in western Montana and Wyoming, and Quaternary silicic volcanic rocks are in small areas in northwestern Wyoming and southwestern Montana. These rocks are mostly rhyolite, tuff, and ash-flow deposits and extend throughout most of Yellowstone National Park.

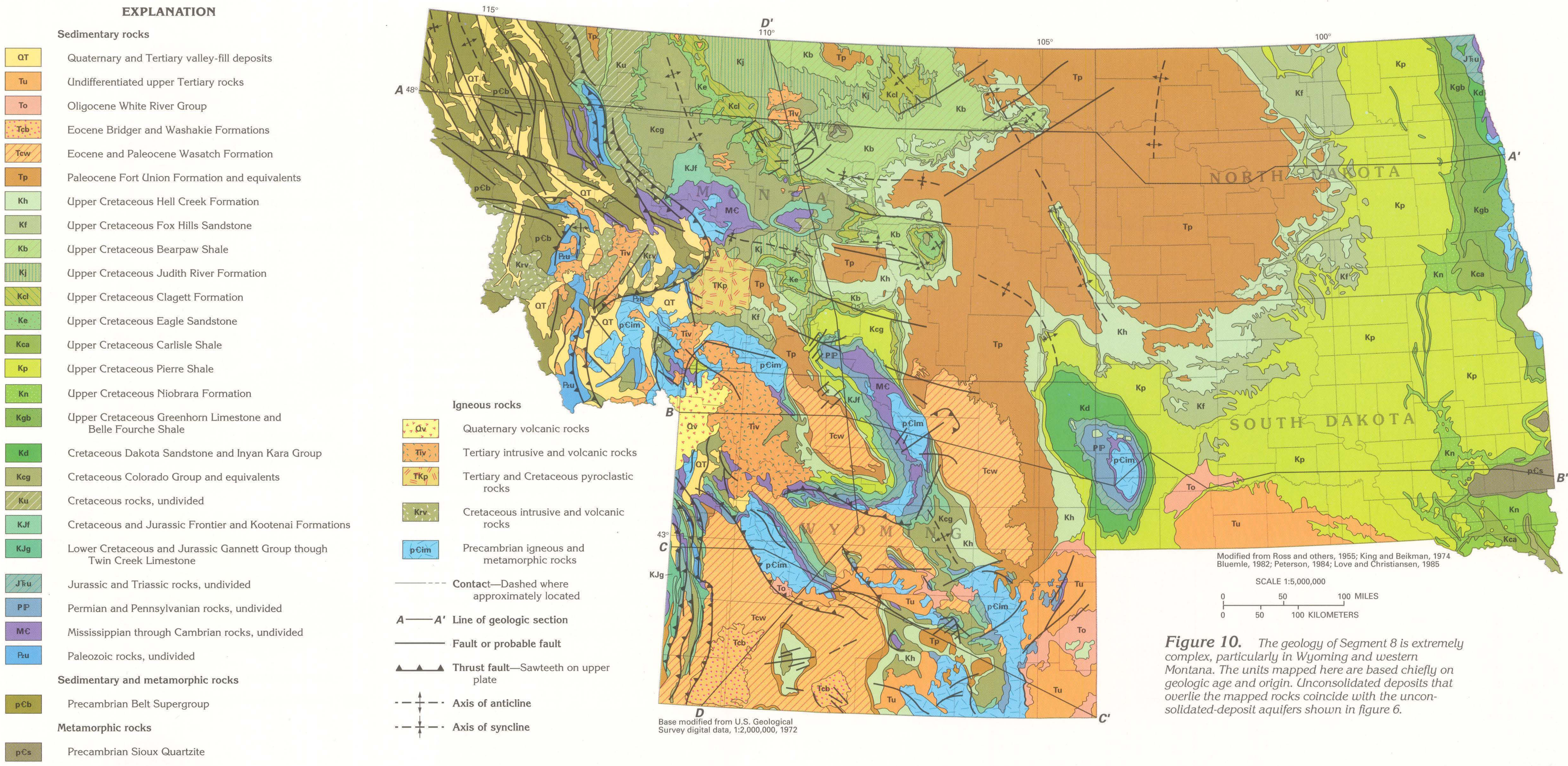


Figure 10. The geology of Segment 8 is extremely complex, particularly in Wyoming and western Montana. The units mapped here are based chiefly on geologic age and origin. Unconsolidated deposits that overlie the mapped rocks coincide with the unconsolidated-deposit aquifers shown in figure 6.

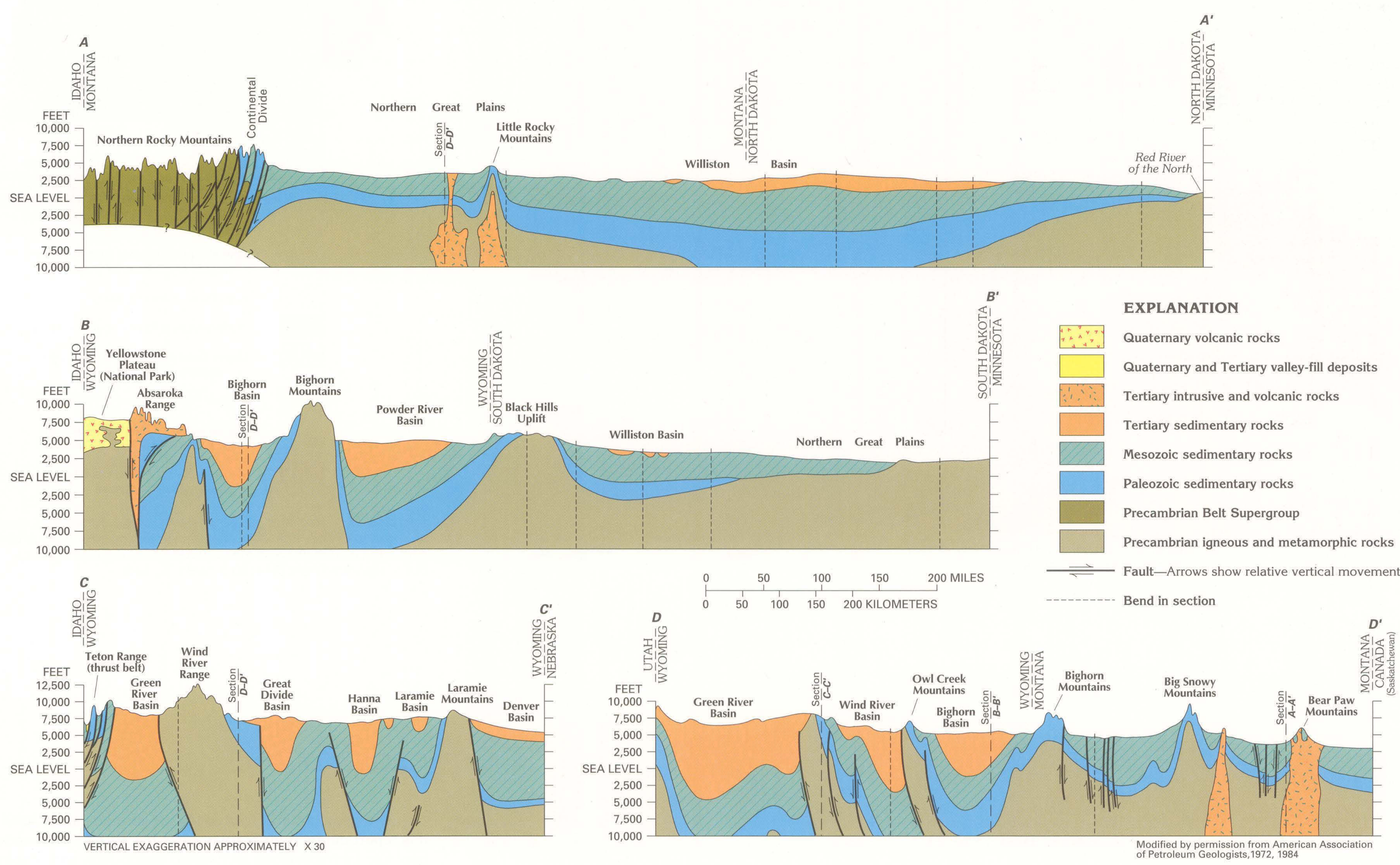


Figure 11. The distribution and thickness of groupings of the geologic units vary greatly and are controlled largely by tectonics that created the basins, uplifts, and faults throughout Segment 8. Geologic structures are more complex and numerous in the mountainous parts of the segment than elsewhere. The lines of the sections are shown in figure 10.

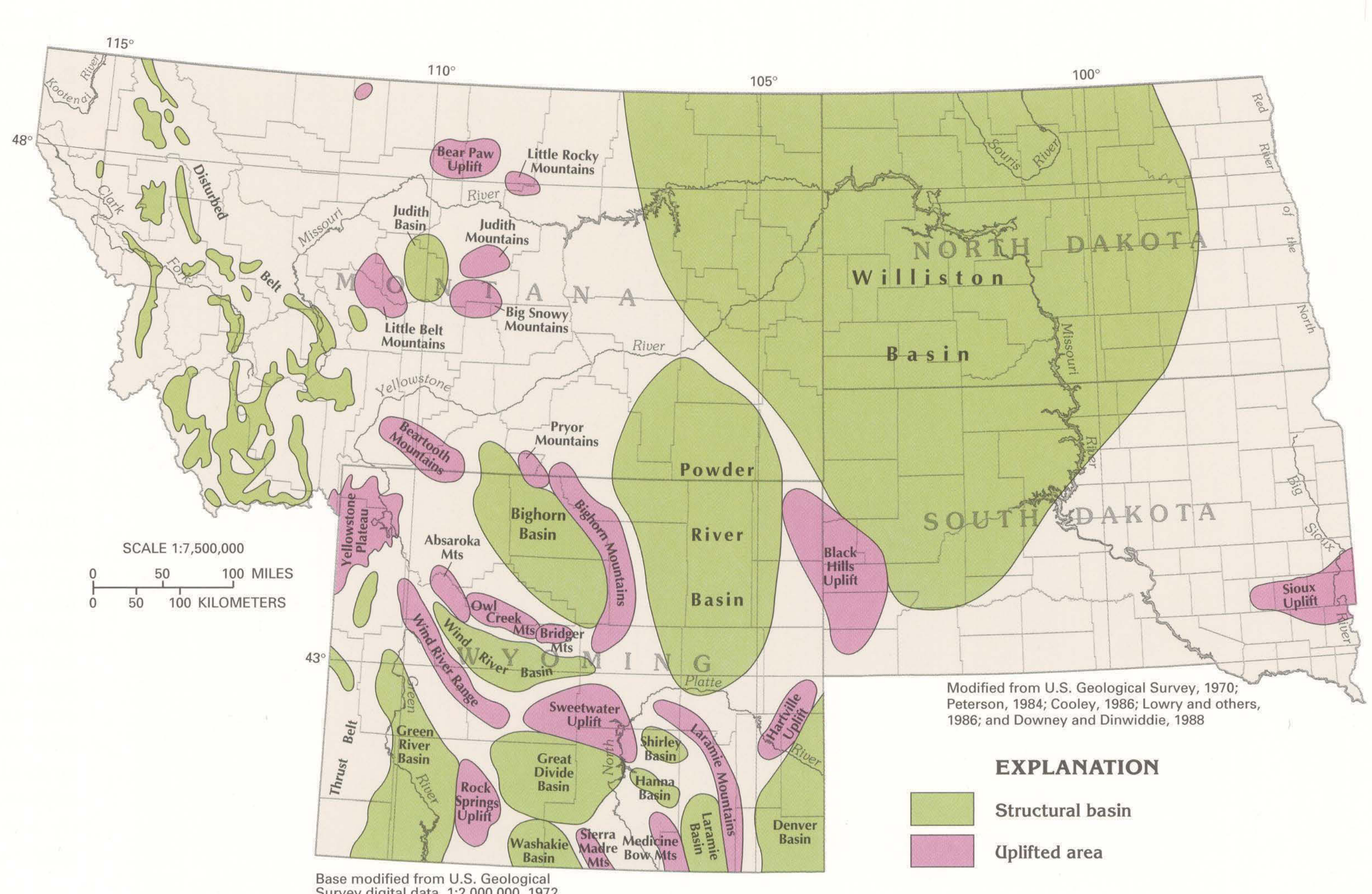
GEOLOGY—Continued

The extent and relations of groupings of the geologic units in the subsurface are shown by the geologic sections in **figure 11**. Geologic structures, such as faults, anticlines, and synclines, are numerous and complex in the rugged Northern Rocky Mountains of western Montana and in Wyoming, as shown in **figure 11**. Older rocks have been lifted upward and shifted eastward over younger rocks along thrust faults near the Continental Divide (**fig. 11**, section *A–A′*) and in the Teton Range (**fig. 11**, section *C–C′*). Thick sequences of Paleozoic and younger sedimentary rocks have been downfolded into deep basins, such as the Bighorn and Powder River Basins (**fig. 11**, section *B–B′*), and the numerous basins in southern Wyoming shown in **figure 11**, sections *C–C′* and *D–D′*. Some of the basins are bounded by faults, and the combined thickness of rocks is greater than 15,000 feet in many of the basins. Where these sedimentary rocks have been upfolded into anticlines that separate the basins, the rocks have been partly or completely removed by erosion, and older, mostly crystalline rocks are exposed along the axes of the uplifts or anticlines. In Yellowstone National Park (**fig. 11**, section *B–B′*), Quaternary volcanic rocks overlie the crystalline rocks.

Eastward from central Montana and eastern Wyoming, the dominant geologic structures are broad, gentle downwarps, some of which are hundreds of miles wide. The Williston Basin, which is shown in **figure 11**, sections *A–A′* and *B–B′*, is the largest such structure in Segment 8 and is filled with sedimentary rocks that range in age from Cambrian to Oligocene. The combined thickness of the sedimentary rocks in the Williston Basin is greater than 16,000 feet near the center of the basin, but these rocks thin slightly westward (**fig. 11**, section *A–A′*) and greatly eastward until they are absent in eastern North Dakota and South Dakota (**fig. 11**, section *B–B′*) where underlying crystalline rocks are near the land surface and are covered only by glacial deposits. Uplifts, such as the Black Hills Uplift in western South Dakota (**fig. 11**, section *B–B′*), are places where the Paleozoic and younger sedimentary rocks have been eroded away and crystalline rocks are exposed.

Tectonic forces that acted on the four States produced large areas of subsidence and uplift. Many of the areas of subsidence are large structural basins, but some basins, such as those in the Northern Rocky Mountains, are considerably smaller (**fig. 12**). Large basins, such as the Bighorn, the Hanna, and the Williston, are more than 16,000 feet deep in their central parts; some of the smaller intermontane basins are less than 3,000 feet deep. The amount of uplift in the segment likewise varies considerably. Some areas of the Middle and the Northern Rocky Mountains have peaks that exceed 12,000 feet in altitude. In contrast, the Judith Mountains and the Black Hills Uplift are much lower and reach altitudes of only about 6,000 and 7,000 feet, respectively.

Figure 12. Segment 8 contains many large geologic structural features. Uplifted areas are topographically high, whereas structural basins, some of which are very deep and contain thick rock sequences, are topographically lower.



GROUND-WATER OCCURRENCE AND MOVEMENT

The following primary factors determine the occurrence and movement of water in the aquifers of Segment 8:

- The amount and type of porosity in the deposits and rocks that compose the aquifers
- The degree of interconnection of the pore spaces (permeability)
- Topography of the region
- The availability of recharge
- Geologic structure

Most of the deposits and rocks in the segment, including the shale beds that compose confining units and the dense crystalline rocks that are not principal aquifers, will yield small volumes of water to wells. Only those deposits and rocks that have substantial permeability, however, are considered to be principal aquifers in this report.

The permeability of an aquifer is directly related to the amount and type of porosity of the aquifer material. The most common porosity type in the aquifers of Segment 8 is primary, or intergranular porosity (open spaces between individual grains or rock particles). This is the porosity type in the unconsolidated-deposit aquifers, the unconsolidated to semiconsolidated sand and gravel of the alluvial deposits in the upper Tertiary aquifers, and the consolidated sandstone beds in the lower Tertiary, upper and lower Cretaceous, and Paleozoic aquifers. Beds of fragmented volcanic material, such as ash, tuff, and cinders, also have primary porosity. Vesicles in volcanic rocks and openings formed by cracking of the upper and lower surfaces of basalt flows during cooling also are types of primary porosity. Pore spaces generally are well connected in all rocks with primary porosity in the segment.

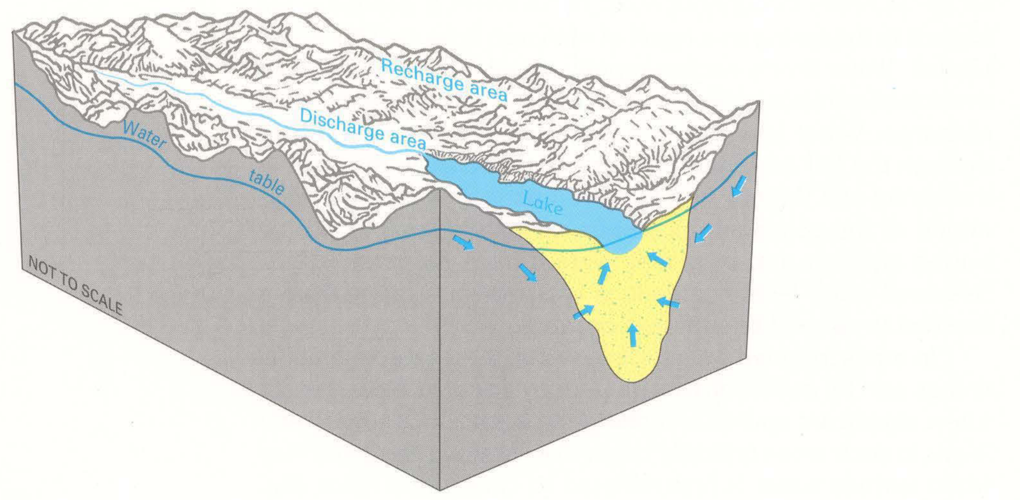
Secondary porosity forms after a rock is consolidated or after a flow of volcanic material cools. Secondary porosity in volcanic rocks consists of joints and fractures that formed as shrinkage cracks in the central parts of basalt and rhyolite flows when the flows cooled; basalt and rhyolite are rock types in the Quaternary volcanic- and sedimentary-rock aquifers. However, most of the secondary porosity in the aquifers of Segment 8 consists of joints and fractures that are the result of tectonic activity. All consolidated rocks in the segment are fractured, but the fractures generally are not well connected. Fractures are the principal types of openings in the aquifers in crystalline rocks. Secondary porosity has developed in some of the limestone and dolomite beds in the Paleozoic aquifers as a result of partial dissolution of the carbonate rocks by circulating ground water that commonly is slightly acidic. Solution openings are most common where the carbonate rocks are exposed at land surface or are buried only to shallow depths and large springs issue from some of the solution openings. Some solution openings also are present, however, where the carbonate rocks are deeply buried or where anhydrite or gypsum beds have been partially dissolved.

Geologic structures, such as faults and folds, can affect the movement of ground water on a local to regional scale. Some fault zones, especially those filled with intensely fractured rock, are conduits for the movement and storage of water. Where permeable fault zones extend to great depths, ground water can circulate downward and become heated to greater-than-normal temperatures by geothermal heat sources. Fault zones that are filled with clay or finely ground rock (called fault gouge) are almost impermeable and can form barriers to ground-water flow. Thrust faults, along which older rocks are displaced laterally over younger rocks, can result either in aquifers of different ages being juxtaposed or aquifers being covered with older, less permeable rocks. Aquifer recharge areas coincide with the crests or axes of anticlines where permeable rocks have been folded upward and are exposed at the land surface or with the flanks of anticlines or monoclines where these structures have been eroded. Water generally moves from these recharge areas toward troughs that represent the axes of synclines. The aquifers commonly contain highly mineralized water in the synclines where they have been downwarped to great depths.

Water in all the aquifers moves in response to gravity from recharge areas down the hydraulic gradient to discharge areas. Much of the recharge is from precipitation that falls directly on the aquifers where they are at or near the land surface in topographically high areas, but some of the recharge is by leakage through the beds of streams that cross the aquifers. The water percolates downward, enters the aquifers, and subsequently moves toward discharge areas at lower altitudes. Some buried aquifers receive recharge by downward leakage from overlying aquifers. This situation is common in areas where unconsolidated-deposit aquifers overlie bedrock aquifers in the central and eastern parts of the four-State segment. Locally, water can move upward from deeply buried aquifers along zones of fractured rock to recharge shallower aquifers. Certain aquifers are recharged in some places by lateral flow from adjacent aquifers. Lateral recharge is particularly important in the basin-fill aquifers of western Montana and Wyoming (**fig. 13**). Local aquifers in bedrock receive recharge directly from precipitation; some of the water then moves laterally into the unconsolidated-deposit aquifers that partially fill basins in the bedrock. The water moves through the unconsolidated-deposit aquifers and discharges to surface-water bodies, such as lakes or streams, near the basin centers. Water in the local bedrock aquifers and the unconsolidated-deposit aquifers shown in **figure 13** is under unconfined, or water-table, conditions.

All the aquifers of Segment 8 discharge mostly by movement of water to lakes and streams, by leakage to shallower aquifers, and to springs. Some water discharges by evapotranspiration (the sum of transpiration by plants and evaporation) and withdrawals from wells.

Figure 13. Local aquifers in bedrock have sufficient permeability so that water moves laterally through them to recharge unconsolidated-deposit aquifers in an adjacent basin. Ultimately, the water discharges from the unconsolidated-deposit aquifers to lakes or streams.



EXPLANATION

- Unconsolidated-deposit aquifer
- Local aquifer in bedrock
- Direction of ground-water movement

Many of the aquifers in Segment 8 consist of sedimentary rocks, such as sandstone and limestone, that alternate with confining units of fine-grained sediments, such as shale. Tectonic forces uplifted these originally flat-lying sedimentary layers in places and arched them upward over crystalline rocks that are the centers of anticlines or uplifts (**fig. 14**). Erosion subsequently removed the sedimentary rocks from the central parts of the upfolded rocks and exposed the permeable sediments along the flanks of mountainous areas, such as the Black Hills Uplift of western South Dakota. Precipitation that falls on the flanks of the mountains provides some direct recharge to the sandstone and limestone aquifers; some water leaks downward through the beds of streams that flow across the aquifers; and some water leaks upward or downward through confining units from vertically adjacent aquifers, thus providing additional recharge. The water moves down the dip of the aquifers, discharges as upward leakage through confining units to shallower aquifers (**fig. 14**), and might eventually reach the surface or be discharged to a deeply entrenched major stream that acts as a regional drain. Circulation is sluggish in the deeply buried parts of the aquifers; accordingly, many aquifers contain slightly saline to very saline water at depth. Except where the aquifers crop out, water in the sandstone and limestone aquifers shown in **figure 14** is under confined, or artesian, conditions. The water levels in wells completed in the confined parts of these aquifers accordingly will rise above the tops of the aquifers. If the hydraulic head in one of the aquifers is large enough, then water can rise above the land surface, and a well completed in the aquifer will flow. In places in Segment 8, the hydraulic head in some of the aquifers is as much as 1,000 feet above the land surface.

An example of the way in which geologic structures, such as folds and faults, affect the movement of ground water is shown in **figure 15**. Water generally enters the sandstone and limestone aquifers in topographically high recharge areas, although some water can move through the shale confining units where the shale is fractured. In folded and faulted rocks, the water generally follows a tortuous route from recharge areas to discharge areas—it first moves parallel to the folded bedding planes of the aquifers and then moves along or across fault planes to enter other aquifers on the opposite side of the fault. Some of the water discharges upward to overlying aquifers, and some issues as springflow where folded, permeable beds are exposed at the land surface (**fig. 15**). Not all faults are conduits for ground-water flow. Fault zones that are filled with clay or that have become sealed with silica or other minerals as a result of fault movement are practically impermeable, whereas those filled with rock fragments can be extremely permeable. Some faults permit water to circulate to great depths where it can become heated by geothermal heat sources. The permeability of the more consolidated, dense, and unweathered rocks generally is more likely to be increased by faulting.

The aquifers in Segment 8 yield variable amounts of water. Unconsolidated deposits and consolidated sedimentary rocks are the most productive aquifers, whereas crystalline rocks generally are the least permeable rocks. Well yields adequate to supply domestic and livestock-watering needs (generally less than 20 gallons per minute) can be obtained from most of the aquifers. The largest yields in the segment are from wells completed in carbonate rocks of the Paleozoic aquifers; some wells completed in these aquifers yield as much as 14,000 gallons per minute.

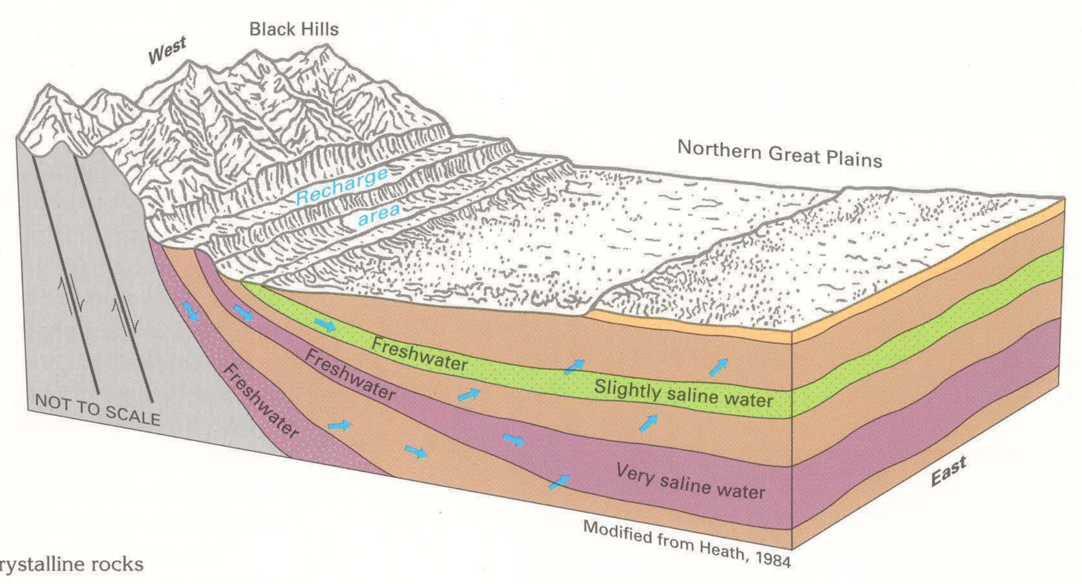
WATER-LEVEL FLUCTUATIONS

Regardless of whether the water in an aquifer or aquifer system is under unconfined or confined conditions, water levels in wells completed in the aquifer or aquifer system reflect the balance between ground-water recharge and discharge. When recharge exceeds discharge, water levels rise; when discharge exceeds recharge, water levels decline. Recharge and discharge tend to balance under long-term natural conditions; such a balance is called a steady-state condition. Climatic changes, fluctuations of weather, or ground-water development can change the steady-state condition so that water levels either rise or fall. Local ground-water development might affect only a single well or a few nearby wells and might not show a regional effect in an areally extensive aquifer.

Ground-water levels can fluctuate when natural recharge or discharge is affected by human activities. When natural recharge is decreased, ground-water levels decline; when natural recharge is increased or when natural discharge is decreased, ground-water levels rise. Changes in irrigation practices, such as the use of sprinklers to replace furrow and flood irrigation, reduce the volume of water available to recharge aquifers by seepage from irrigated fields. If the source of irrigation water changes from imported surface water to local ground water, then water from an outside source is no longer available for recharge as irrigation return flow, and ground-water levels will decline. Sealing and lining earthen canals or reservoirs can reduce the volume of water lost by seepage during transmission and storage, and, thereby, can reduce recharge to aquifers. Where urban shopping centers, residential subdivisions, and industrial development replace irrigated farmland, recharge is reduced because the paving associated with these types of development reduces the area of soil into which precipitation can infiltrate. Dewatering during mining activities can cause a large decline in water levels. The construction of a reservoir or a rise in the water level of an existing lake or reservoir can cause the water level in nearby aquifers to rise.

Ground water is becoming more and more important as a source of water for public supply, domestic and commercial uses, and industrial and agricultural (primarily irrigation) needs in the four-State area of Segment 8. Generally, increased ground-water withdrawals cause water levels to decline except where increased recharge is possible.

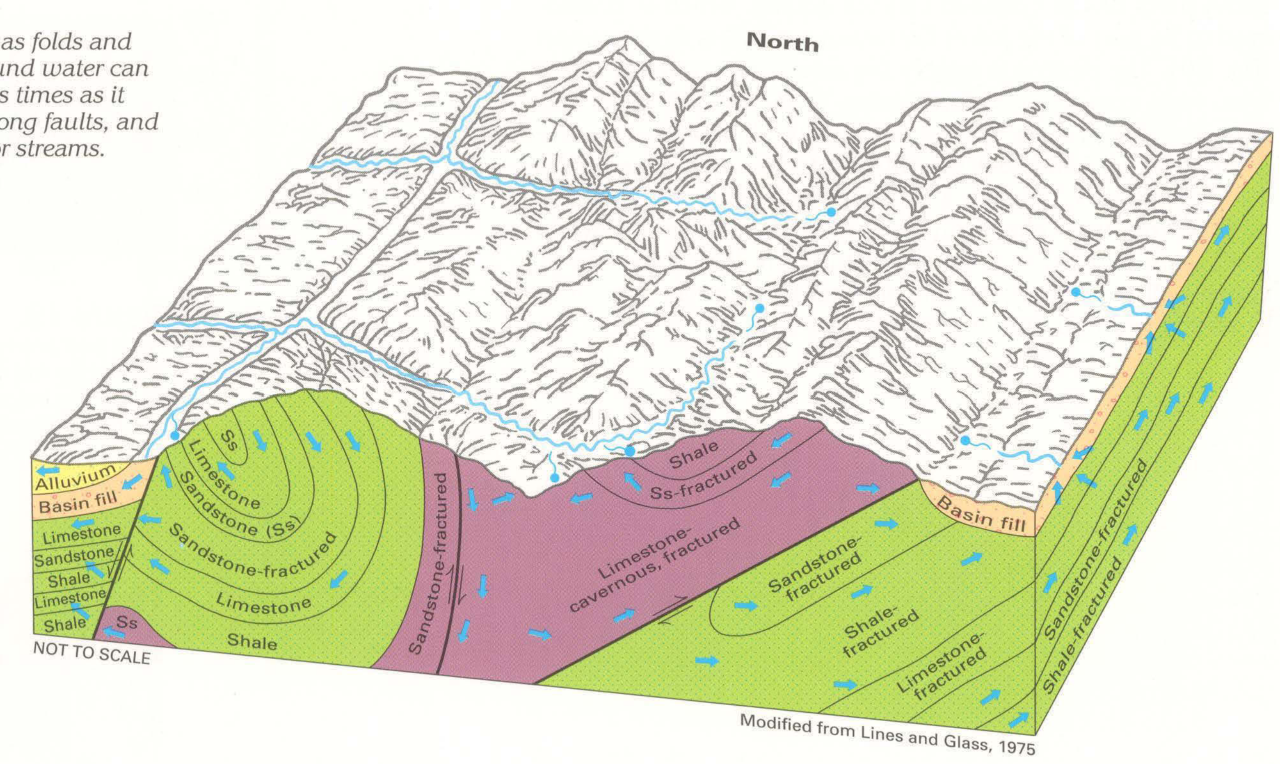
Figure 14. Permeable rocks that were originally flat lying have been uplifted, arched or folded, and eroded in places. Water enters these aquifers as recharge where the aquifers crop out, moves downward through the aquifers, and discharges to overlying aquifers or to the land surface.



EXPLANATION

- Glacial deposits
- Cretaceous sandstone aquifer
- Paleozoic limestone aquifer
- Paleozoic sandstone aquifer
- Not a principal aquifer—Chiefly crystalline rocks
- Shale confining unit
- Direction of ground-water movement
- Fault—Arrows show relative vertical movement

Figure 15. Geologic structures, such as folds and faults, affect ground-water movement. Ground water can change its direction of movement numerous times as it follows bedding planes, moves across or along faults, and discharges to shallower aquifers, springs, or streams.



EXPLANATION

- Unconsolidated-deposit aquifers
- Upper Tertiary aquifers
- Lower Cretaceous aquifers
- Paleozoic aquifers
- Direction of ground-water movement
- Fault—Arrows show relative vertical movement
- Spring

Short-Term Fluctuations

Under natural conditions, ground-water levels in or near recharge areas throughout most of Segment 8 generally are highest in the spring as a result of recharge from snowmelt and rainfall. Water levels decline rapidly during the summer when evapotranspiration rates are highest and discharge exceeds recharge. Water levels continue to decline at a slower rate through the fall and winter months until recharge resumes in the spring and thereby completes an annual cycle. The magnitude of the seasonal fluctuation usually is least in deeply buried aquifers and in places distant from recharge areas. Seasonal water-level fluctuations in Segment 8 range from a few feet to several tens of feet or more.

In areas irrigated with surface water, losses through canal linings and by downward seepage from irrigated fields constitute a significant source of recharge to aquifers. Ground-water levels in such areas typically begin to rise during April and May when surface water is first released to canals and fields (**fig. 16**), reach a maximum in midsummer, start to decline at the end of the irrigation season, and continue to decline to an annual minimum just before the start of the next growing season.

Water-level changes in unconsolidated-deposit aquifers that are in direct hydraulic connection with streams coincide with changes in the water level of the streams. When the water in a stream, such as the Big Sioux River in Brookings County, S. Dak., is at a high level, the river discharges water to the adjacent aquifer (**fig. 17**). Conversely, when water in the river is lower than the water level in the adjacent aquifer, the aquifer discharges to the river. The movement of water from the aquifer to the river is indicated by springs and seeps along the river channel. Ground-water discharge sustains minimum streamflow (base flow) during periods of less-than-normal precipitation and times when water from the river is diverted upstream.

Ground-water levels commonly fluctuate in response to nearby withdrawals. During periods of large withdrawals, water levels in an aquifer decline. If recharge to the aquifer is sufficient, however, then water levels usually recover to the prepumping level when withdrawals cease. For example, large withdrawals from a municipal well field in the High Plains aquifer system at Cheyenne, Wyo., have a rapid effect on the water level in a well completed in the same aquifer less than 1 mile away (**fig. 18**). Withdrawals usually are largest during the summer months. During periods of normal precipitation, such as 1971 through 1976, large withdrawals cease in late summer or fall. Ground-water levels quickly recover but may show a slight seasonal decline until recharge increases in the spring. Withdrawals were large throughout 1977 and 1978, which was a period of less-than-normal precipitation. Ground-water levels, therefore, were low throughout this 2-year period and had not fully recovered by the end of 1979, even though precipitation had increased and less water was withdrawn from the aquifer. This example shows that human activities can have a great effect on ground-water levels.

Long-Term Fluctuations

Long-term trends in ground-water levels generally are caused by the following factors:

- Long-term cycles of greater-than-normal or less-than-normal precipitation
- Long-term withdrawals of ground water in excess of natural recharge
- Changes in irrigation practices
- Changes caused by other human activities

Natural long-term trends of ground-water levels mimic long-term precipitation trends, as shown in **figure 19**. For example, cumulative departures from average annual precipitation in Sanborn County, S. Dak., show a slight decline from 1957 through 1983. Water levels in a well completed in an unconsolidated-deposit aquifer in Sanborn County show a similar slight decline for the same period, which indicates little effect from human activities. By contrast, in adjacent Beadle County, increased withdrawals of ground water for irrigation, which began in 1975, caused a sudden change in the trend of ground-water levels in the same aquifer. Water levels declined much more rapidly after irrigation began.

Water levels have declined steadily in South Dakota in some parts of the confined Dakota aquifer, which is considered to be part of the lower Cretaceous aquifers in this report (**fig. 20**). The decline is largely the result of uncontrolled flow from wells completed in the aquifer. Water levels in an observation well in Aurora County show a trend of steady decline from 1961 to 1966, but the rate of decline decreased from 1967 to mid-1972 when many owners of flowing wells restricted flow from the wells. From mid-1972 to 1979, new flowing wells were constructed within a 10-mile radius of the observation well. As a result, the rate of water-level decline increased to slightly more than the pre-1967 rate.

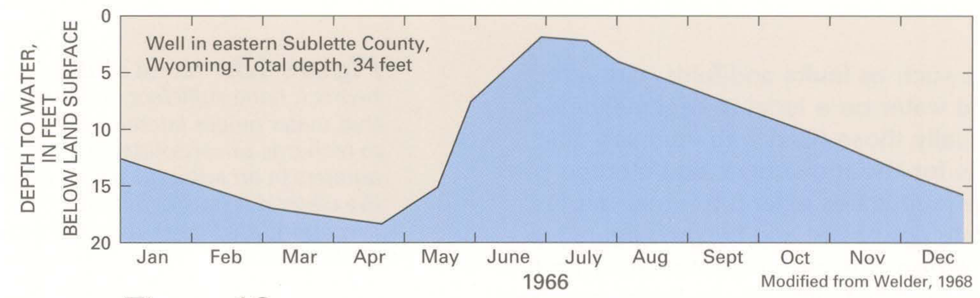


Figure 16. *Water levels in shallow aquifers rise in response to recharge from surface-water irrigation and decline at the end of the irrigation season. Water levels in such areas are highest during the midsummer growing season.*

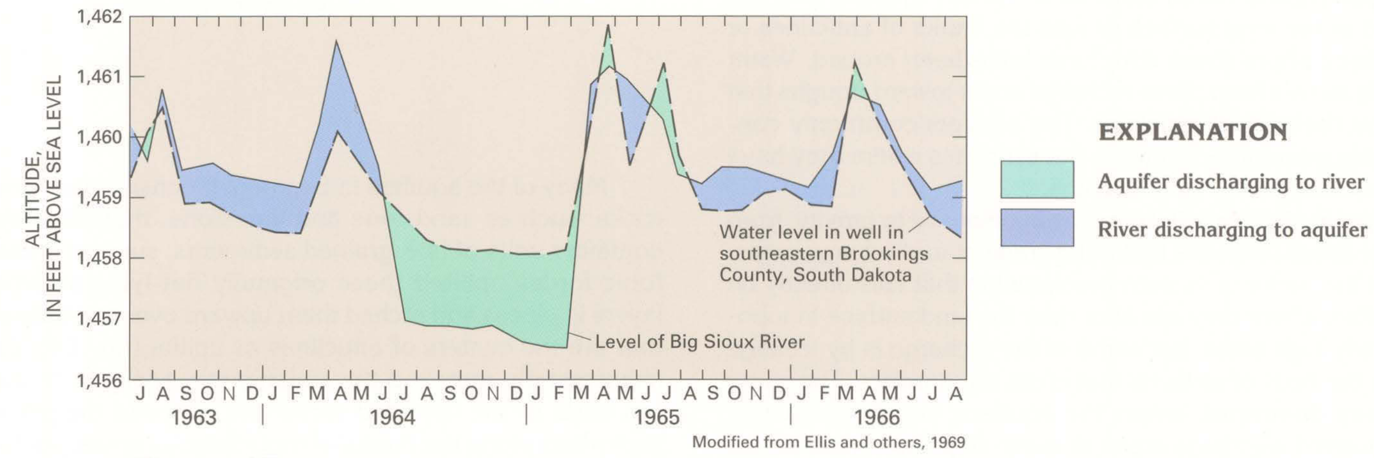


Figure 17. *Change in the water level of a river can reverse the exchange of water between the river and an adjacent aquifer. As the river level rises, river water is discharged to the aquifer, and the water level in the aquifer rises. When the river level is low, water from the aquifer is discharged to the river and maintains the base flow of the river.*

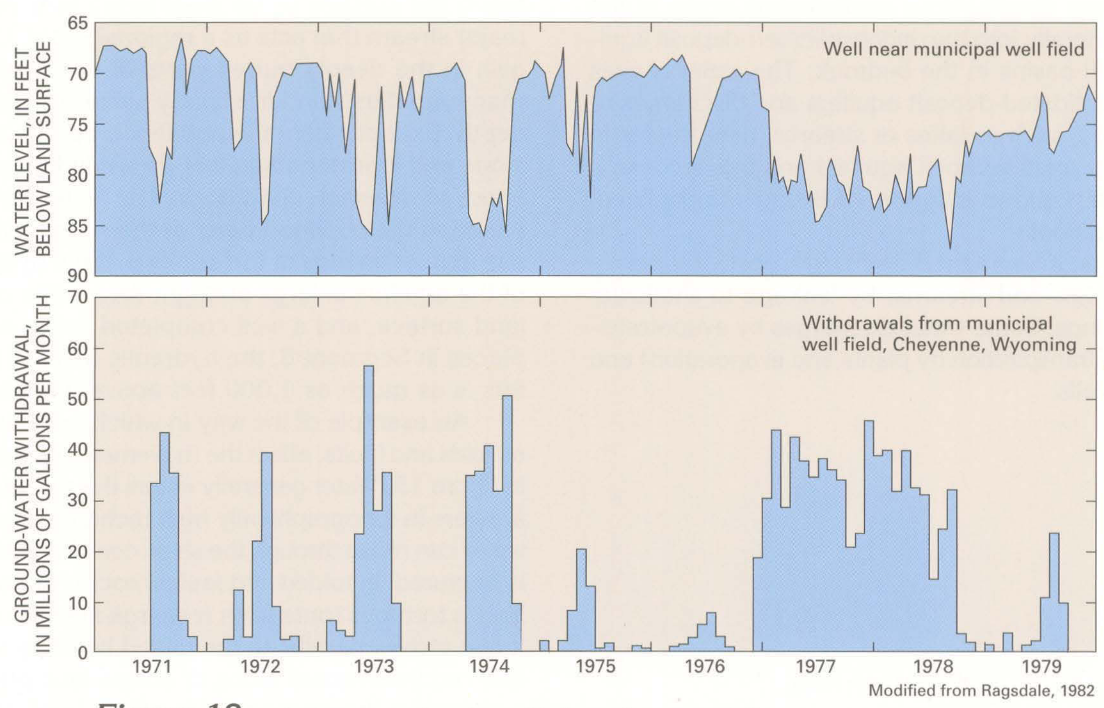


Figure 18. *Large ground-water withdrawals can rapidly affect water levels in a nearby well. When large withdrawals by municipal wells begin, ground-water levels decline. The decline persists until withdrawals cease, whereupon water levels quickly recover.*

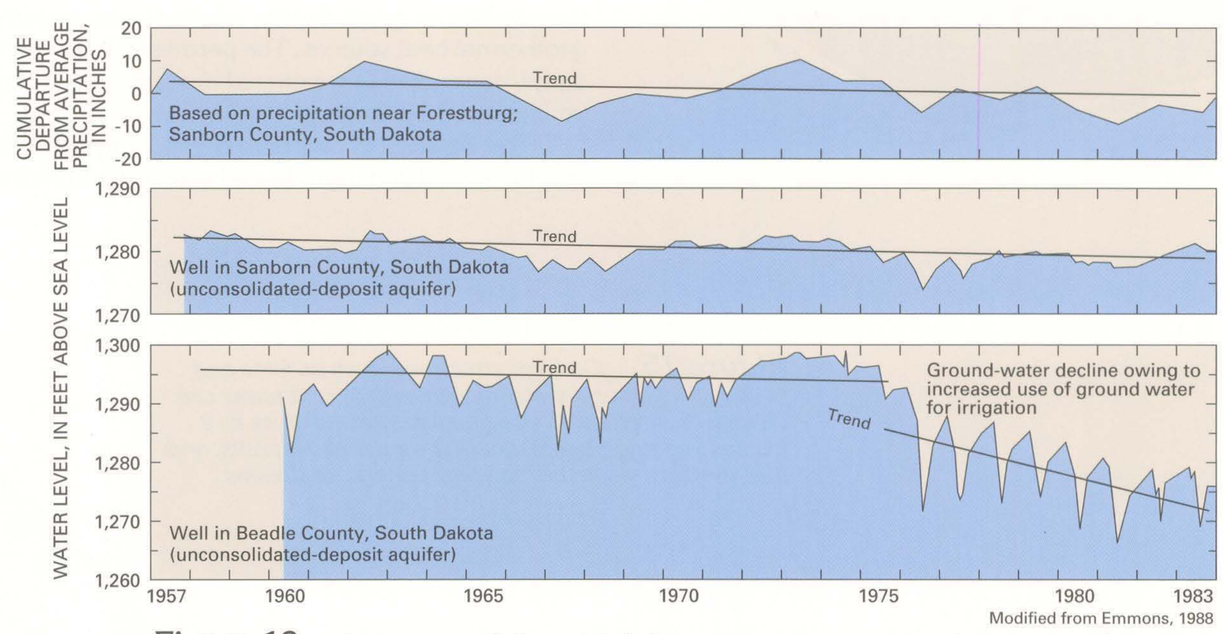


Figure 19. *A strong correlation exists between long-term ground-water levels and precipitation in areas, such as Sanborn County, S. Dak., that are little affected by human activities. Intensive ground-water development, such as an increase in irrigation withdrawals, can cause a sudden decline in the natural trend, as shown in adjacent Beadle County.*

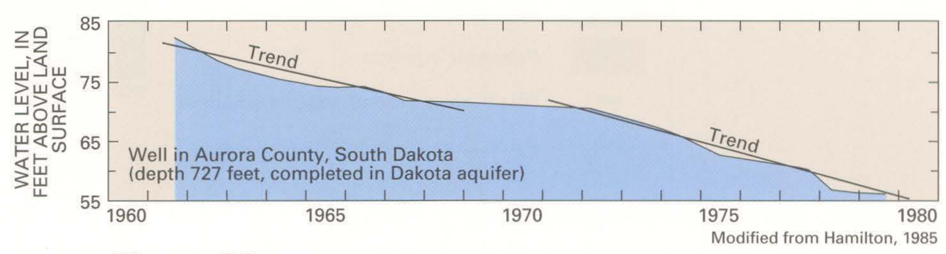


Figure 20. *Uncontrolled flowing wells can cause water levels in an artesian aquifer to decline. Uncontrolled flow was restricted from 1967 to mid-1972, and the rate of decline temporarily decreased. Additional flowing wells constructed beginning in mid-1972 increased the rate of water-level decline.*

GROUND-WATER QUALITY

The concentration of dissolved solids in ground water provides a basis for categorizing the general chemical quality of the water. Dissolved solids in ground water primarily result from chemical interaction between the water and the rocks or the unconsolidated deposits through which the water moves. Rocks or deposits that consist of readily dissolved minerals will usually contain water that has large dissolved-solids concentrations. The rate of movement of water through an aquifer also affects dissolved-solids concentrations; the longer the water is in contact with the minerals that compose an aquifer, the more mineralized the water becomes. Thus, larger concentrations of dissolved solids commonly are in water at or near the ends of long ground-water flow paths. Aquifers that are buried to great depths commonly contain saline water or brine in their deeper parts, and mixing of fresh ground water with this saline water can result in a large increase in the dissolved-solids concentration of the freshwater. Contamination that is the result of human activities can increase the concentration of dissolved solids in ground water; such contamination usually is local but can render the water unfit for human consumption or for many other uses.

The terms used in this report to describe water with different concentrations of dissolved solids are as follows:

Term	Dissolved-solids concentration, in milligrams per liter
Freshwater	Less than 1,000
Slightly saline water	1,000 to 3,000
Moderately saline water	3,000 to 10,000
Very saline water	10,000 to 35,000
Brine	Greater than 35,000

Dissolved-solids concentrations in ground water generally are small in aquifer recharge areas and increase as the water moves downward into the deeper parts of the aquifers. Where the aquifers are deeply buried or where ground water is discharged at the end of long flow paths, dissolved-solids concentrations commonly exceed 3,000 milligrams per liter. In some places, saline water or brine in deep aquifers leaks upward through confining units and contaminates fresher water in shallower aquifers or in surface-water bodies. For example, in easternmost North Dakota, water with more than 3,000 milligrams per liter dissolved solids occurs locally in the shallow, unconsolidated-deposit aquifer and in the Red River of the North and its tributaries. In this area, very saline water discharges upward from bedrock aquifers and moves first into the shallow aquifer, where it mixes with freshwater, and subsequently into the streams.

Throughout large parts of Segment 8, dissolved-solids concentrations in ground water exceed the secondary maximum contaminant level of 500 milligrams per liter recommended for drinking water by the U.S. Environmental Protection Agency. In some places, water with dissolved-solids concentrations of 2,000 milligrams per liter or more is used for human and livestock consumption because no fresher water is available.

Ground-water contamination that results from human activities can take place more rapidly than natural contamination. Such contamination is categorized as being from either a point source or a nonpoint source. A point source is a specific local site, such as an underground storage tank that contains wastes, petroleum, or chemicals; a landfill; a storage pond, pit, or lagoon; a spill of hazardous chemicals or petroleum products; or a disposal or injection well that receives municipal or industrial wastes. Nonpoint contamination sources are large scale and can extend over hundreds of acres. Examples of nonpoint sources are agricultural activities, such as the application of fertilizer or pesticides to fields; urban areas with concentrations of septic tanks and cesspools; encroachment of saltwater or highly mineralized geothermal water; animal feedlots; mining operations; oilfields and associated tank farms; salt from highway deicing; and concentration of salts from mineralized irrigation water in places where evaporation rates are high and the soil is poorly drained.

Aquifers that are shallow, unconfined, and receive recharge at rapid rates are most susceptible to contamination from human activities because water quickly infiltrates from the land surface to such aquifers; thus, contaminants have little potential to be absorbed by soil minerals or dispersed, and might be undiluted or only slightly diluted when they enter the aquifer. Aquifers that consist of limestone, dolomite, or basalt are particularly susceptible to contamination because they commonly contain large openings (solution cavities, joints, or cooling fractures) that allow water to enter the aquifer almost instantaneously. Confined aquifers are less susceptible to contamination than unconfined aquifers because the confined aquifers usually are deeply buried and are overlain by confining units that have minimal permeability. Infiltration of contaminants into confined aquifers, therefore, is slow and the contaminant is more likely to be absorbed by the confining unit. The following table lists some of the features that determine the susceptibility of an aquifer to contamination and indicates the relative vulnerability of the aquifer, based on the characteristics of each feature:

Hydrogeologic framework

Feature determining aquifer vulnerability to contamination	Minimal vulnerability	Substantial vulnerability
Unsaturated zone	Thick unsaturated zone overlying almost impermeable material, such as clay.	Thin unsaturated zone overlying sand and gravel, limestone, or basalt.
Confining unit	Thick confining unit of clay or shale above aquifer.	Thin or absent confining unit.
Aquifer properties	Minimal permeability, such as in silty sandstone or limestone.	Substantial permeability, such as in sand and gravel, cavernous limestone, or basalt.

Ground-water-flow system

Feature determining aquifer vulnerability to contamination	Minimal vulnerability	Substantial vulnerability
Recharge rate	Negligible recharge rate as in arid regions.	Rapid recharge rate as in humid regions.
Location within a flow system (proximity to recharge or discharge area).	Discharge area of a regional flow system or deep parts of that system where water movement is slow.	Recharge area of a regional flow system or area within the cone of depression of a pumping well or well field.

FRESH GROUND-WATER WITHDRAWALS

Total withdrawals of fresh ground water in the four-State area during 1990 were 981 million gallons per day. Almost 40 percent of this amount, or 384 million gallons per day, was withdrawn in Wyoming (**fig. 21**). Withdrawals in Montana, North Dakota, and South Dakota were about 205 million, 141 million, and 251 million gallons per day, respectively. The percentage of water withdrawn for different uses varies from State to State. In each of the States, however, agricultural use, primarily irrigation, is the largest use category (**fig. 21**). In Montana, North Dakota, and South Dakota, public supply is the second largest use category; in Wyoming, however, the second-largest category is industrial, mining, and thermoelectric power uses, with most of the water being used for mining, including oil and gas production. During 1990, 19 million gallons per day of saline water also was withdrawn in Wyoming for mining use, although **figure 21** shows only freshwater withdrawals.

Total fresh ground-water withdrawals, by county, vary considerably, as shown in **figure 22**. Because the largest withdrawals are for agricultural purposes (primarily irrigation), followed by withdrawals for public supply and mining, the withdrawals are not evenly distributed throughout most counties. The distribution of withdrawals for agricultural use, by county, are shown in **figure 23**. Areas of extensive irrigation in northern and southeastern Wyoming, central and southeastern North Dakota, eastern and south-central South Dakota, and some of the intermontane basins of western Montana and Wyoming are prominent in **figure 23**.

Much of the water is withdrawn from the specific sites shown in **figure 24**. Irrigation projects in all four States account for most of the withdrawals, but sites where water is withdrawn for public supply and industrial (primarily mining) uses also are prominent. The tables at right list the major withdrawal sites, by location; identify the aquifer or aquifers from which the water is withdrawn; and indicate the use of the water at each location.

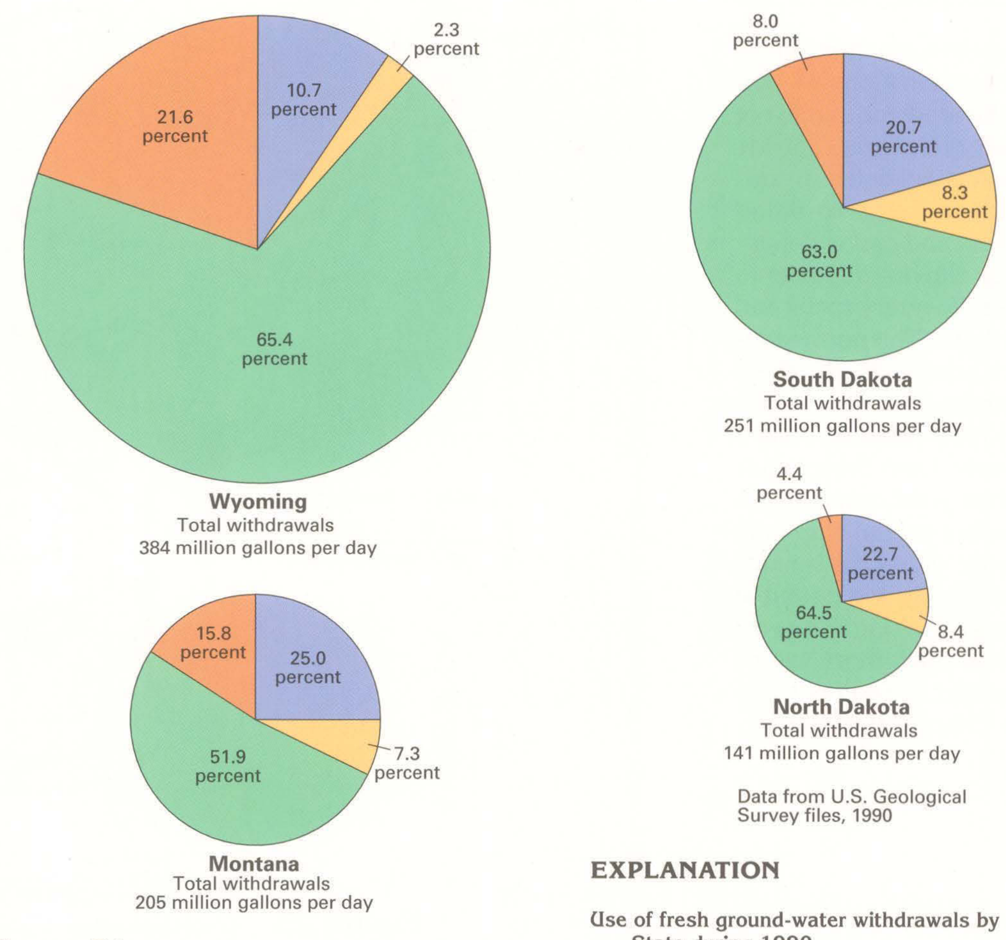


Figure 21. *Total fresh ground-water withdrawals and the percentage of use by category vary significantly among the four States. Wyoming used nearly as much ground water during 1985 as did Montana, North Dakota, and South Dakota combined. Agriculture, primarily irrigation, used the most ground water in each State.*

EXPLANATION

Use of fresh ground-water withdrawals by State during 1990

- Public supply
- Domestic and commercial
- Agricultural
- Industrial, mining, and thermoelectric power

Major withdrawal sites in Montana

Site number (fig. 24)	Geographic area	Aquifers[1]	Principal uses
1	Beaverhead County	A, B	Irrigation.
2	Missoula County	A, B	Irrigation, industrial, public supply.
3	Broadwater County	A, B	Irrigation.
4	Gallatin County	A, B	Do.
5	Yellowstone County	A	Irrigation, public supply, rural domestic.
6	Fallon County	C, D	Public supply, industrial.
7	Sheridan County	A	Irrigation.
8	Blaine County	A	Do.

[1] A, Unconsolidated-deposit aquifers; B, Upper Tertiary aquifers; C, Lower Tertiary aquifers; and D, Upper Cretaceous aquifers.

Major withdrawal sites in North Dakota

Site number (fig. 24)	Geographic area	Aquifers[1]	Principal uses
1	Englevale area	A	Irrigation.
2	Oakes area	A	Do.
3	Page area	A	Do.
4	Minot area	A	Public supply.
5	West Fargo area	A	Public supply, industrial.

[1] A, Unconsolidated-deposit aquifers.

Major withdrawal sites in South Dakota

Site number (fig. 24)	Geographic area	Aquifers[1]	Principal uses
1	Sioux Falls	A	Public supply.
2	Brookings area	A	Public supply, irrigation.
3	Spink County	A	Irrigation.
4	Beadle County	A	Do.
5	Aberdeen area	A	Rural domestic, commercial, livestock.
6	Pennington County	E	Public supply, rural domestic, commercial.
7	Lawrence County	E	Industrial, irrigation, public supply.

[1] A, Unconsolidated-deposit aquifers; and E, Paleozoic aquifers.

Major withdrawal sites in Wyoming

Site number (fig. 24)	Geographic area	Aquifers[1]	Principal uses
1	Laramie County	A, B	Irrigation, public supply, rural domestic, commercial.
2	Goshen County	A, B	Irrigation, public supply, industrial.
3	Niobrara County	A, B, C, D	Irrigation, industrial.
4	Platte County	A, B	Irrigation, industrial, public supply.
5	Fremont County	B, C, D	Public supply, industrial, irrigation, rural domestic, commercial.
6	Natrona County	B, C, D	Do.
7	Big Horn County	A, C, D, E	Irrigation, industrial.
8	Campbell County	A, B, C, D, E	Industrial, public supply, irrigation.

[1] A, Unconsolidated-deposit aquifers; B, Upper Tertiary aquifers; C, Lower Tertiary aquifers; D, Upper Cretaceous aquifers; and E, Paleozoic aquifers.

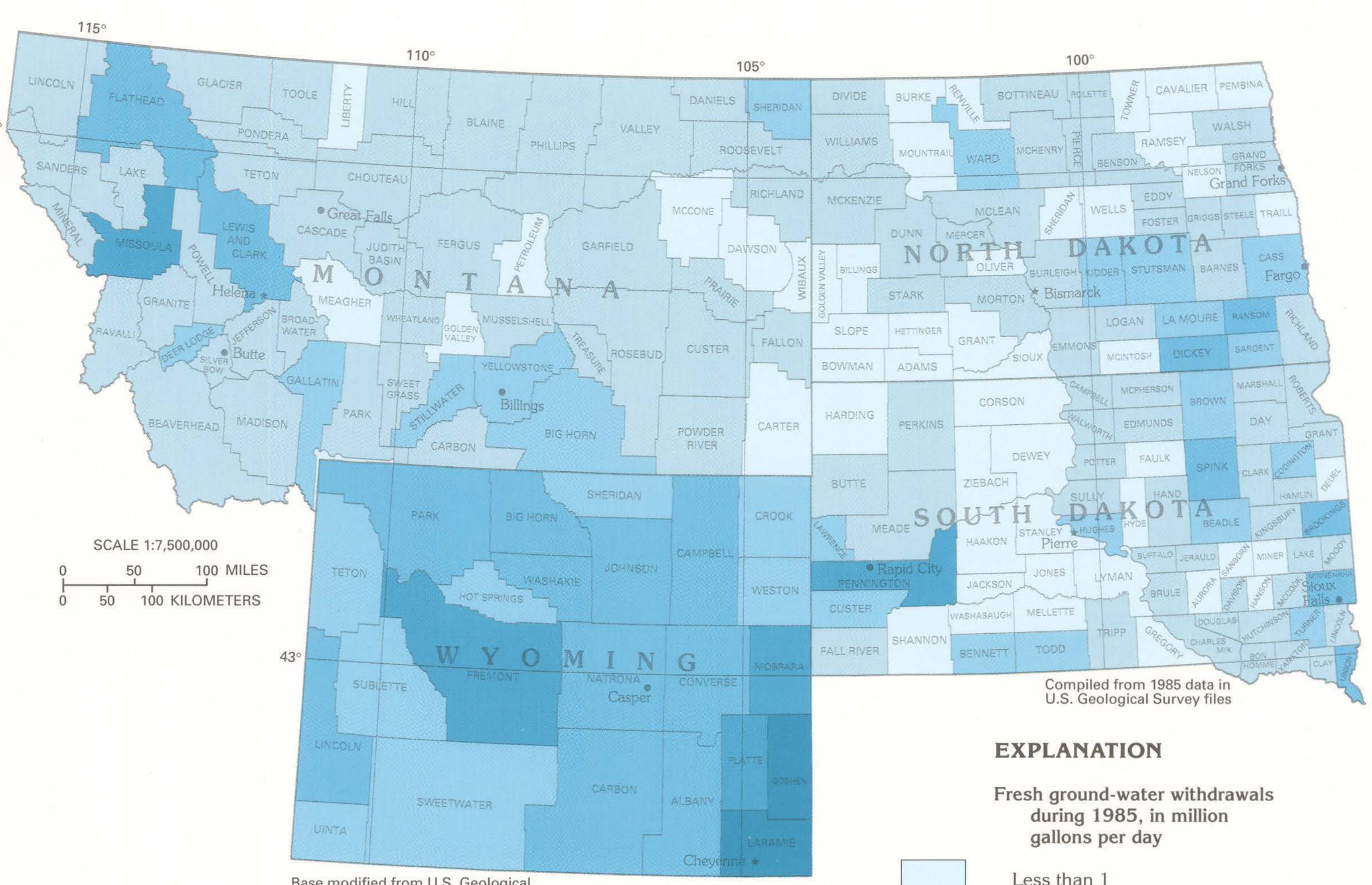


Figure 22. *The largest withdrawals of ground water are in counties that contain major population centers or where irrigation or mining use is extensive. Withdrawals are less than 5 million gallons per day in many counties in Montana and the Dakotas, whereas all counties in Wyoming withdraw more than 5 million gallons per day.*

EXPLANATION

Fresh ground-water withdrawals during 1985, in million gallons per day

- Less than 1
- 1 to 5
- 5 to 10
- 10 to 25
- 25 to 50
- 50 to 115

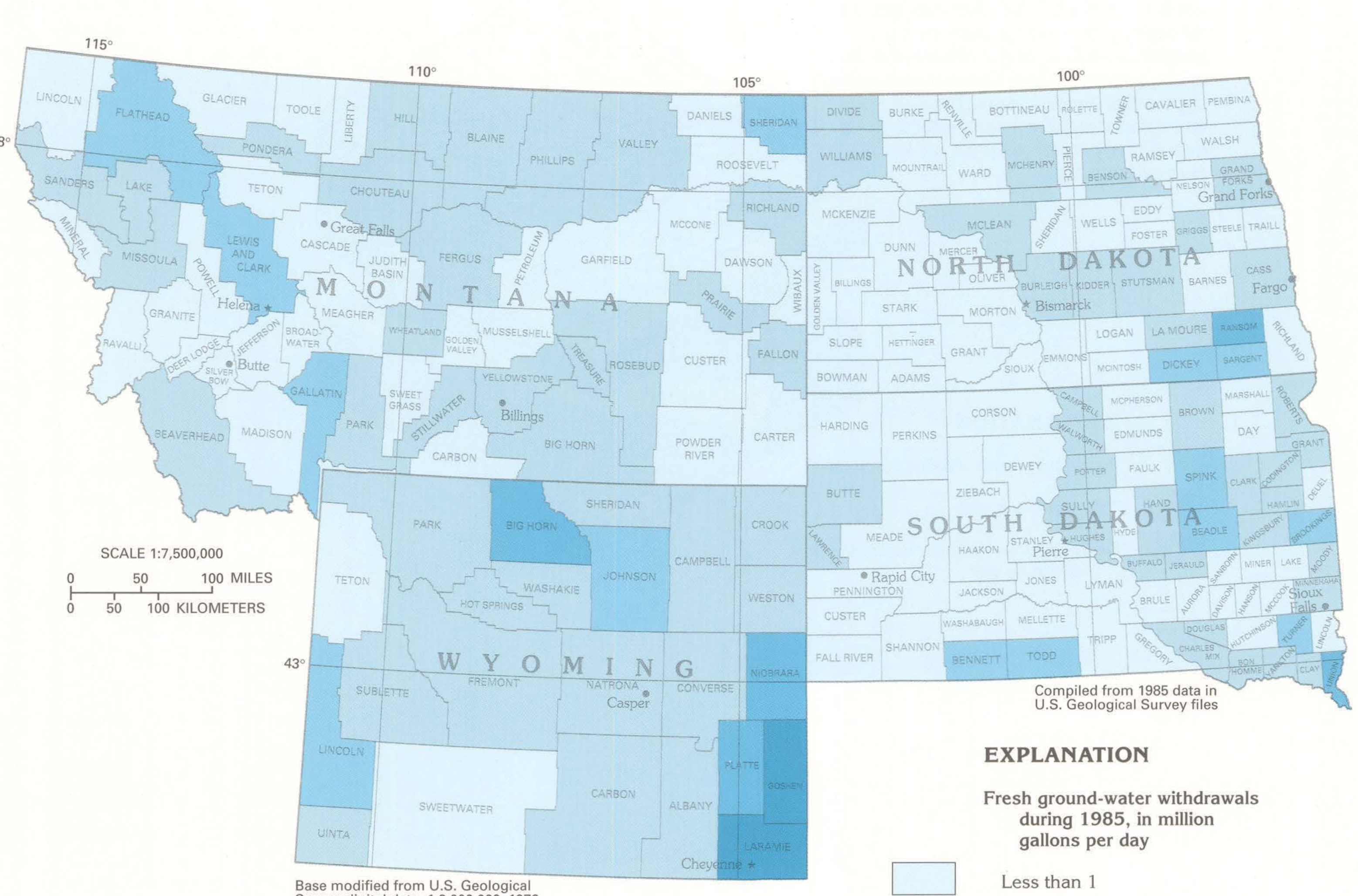


Figure 23. *Ground-water withdrawals for agricultural use, primarily irrigation, exceed other uses and vary greatly by county in each State. Much of the water is withdrawn from the specific sites shown in figure 24.*

EXPLANATION

Fresh ground-water withdrawals during 1985, in million gallons per day

- Less than 1
- 1 to 5
- 5 to 10
- 10 to 50
- Greater than 50

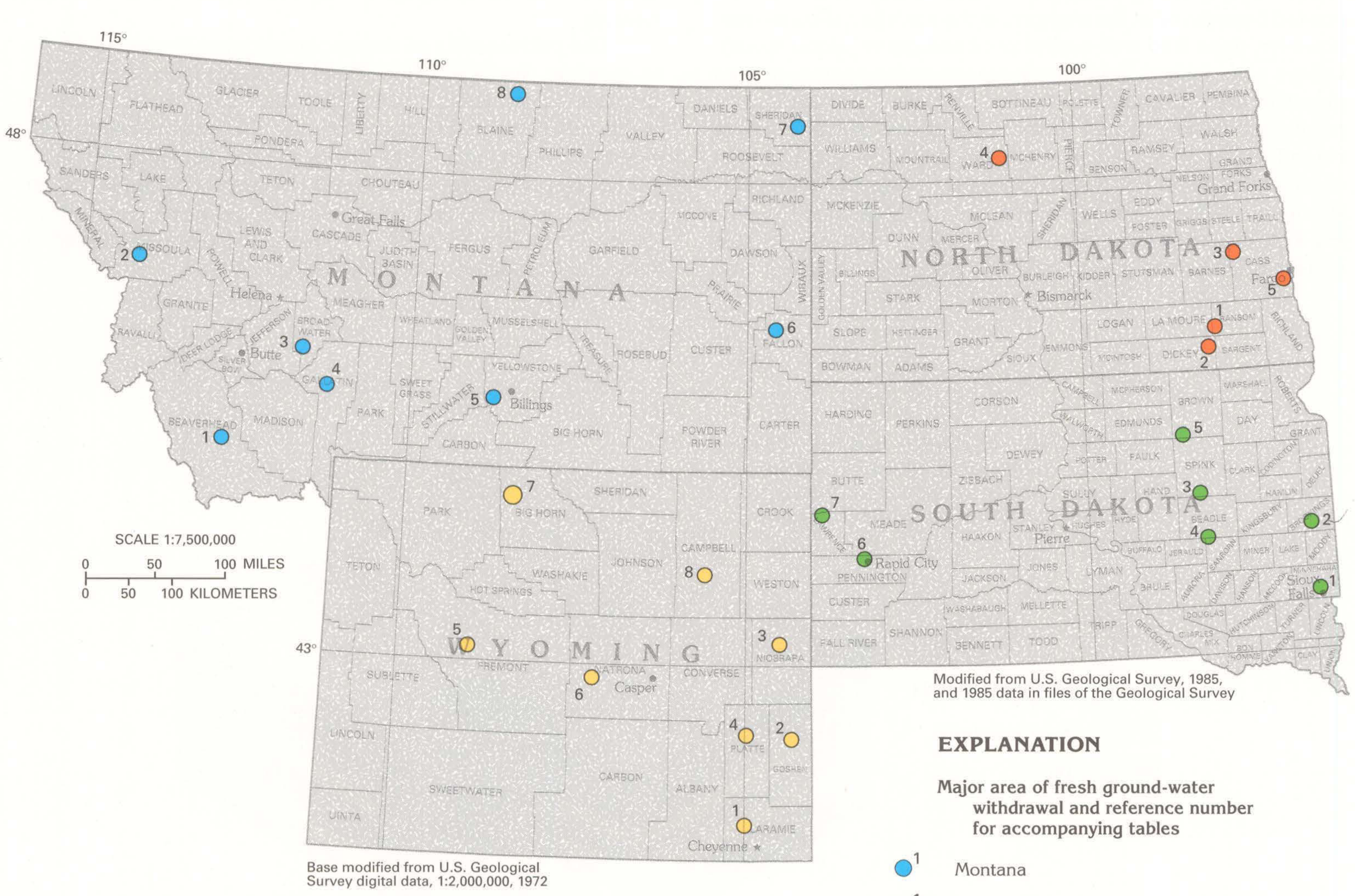


Figure 24. *Sites of major withdrawals of fresh ground water are scattered throughout the four-State area. The water is used primarily for agricultural, public supply, and mining purposes.*

EXPLANATION

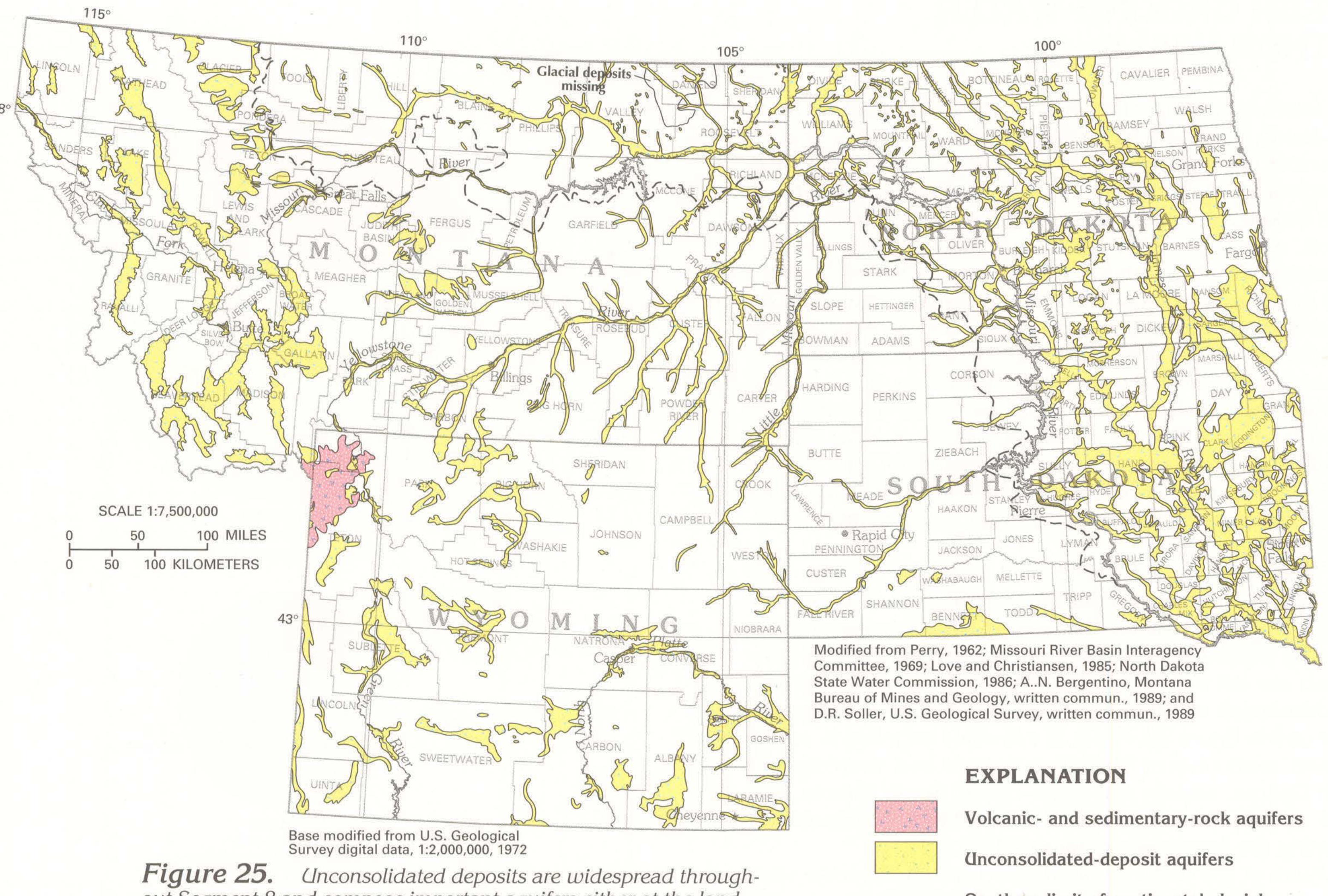
Major area of fresh ground-water withdrawal and reference number for accompanying tables

- 1 Montana
- 1 North Dakota
- 1 South Dakota
- 1 Wyoming

Principal aquifers

VOLCANIC- AND SEDIMENTARY-ROCK AQUIFERS

Volcanic- and sedimentary-rock aquifers are in small areas of northwestern Wyoming and southwestern Montana (**fig. 25**). These aquifers are complexly interbedded and consist of extrusive igneous rocks (primarily basalt and rhyolite), beds of tuff and volcanic ash, and beds of semiconsolidated to consolidated sedimentary rocks that contain large to small amounts of volcanic material. Locally, sand and gravel deposited as outwash from alpine glaciers or alluvial deposits in stream valleys overlie the volcanic and sedimentary rocks and are in direct hydraulic connection with them. The permeability of the volcanic- and sedimentary-rock aquifers is extremely variable because they are complexly interbedded and consist of numerous rock types. In some places, permeability is high, as indicated by the large springs that issue from these aquifers; in most places, however, the aquifers yield only enough water to supply domestic wells. The aquifers extend over only a small part of Segment 8 and are mostly within the boundaries of Yellowstone National Park. Accordingly, the potential to develop these aquifers in the segment is lacking. The volcanic- and sedimentary-rock aquifers are much more extensive and important as a source of freshwater in Segment 7 to the west and are discussed in detail in Chapter H of this Atlas.



EXPLANATION

- Volcanic- and sedimentary-rock aquifers
- Unconsolidated-deposit aquifers
- - - - - - Southern limit of continental glacial deposits

Figure 25. Unconsolidated deposits are widespread throughout Segment 8 and compose important aquifers either at the land surface or buried beneath low-permeability material. The aquifers are particularly widespread at the surface in valleys in the mountainous parts of Montana and Wyoming and in the subsurface in buried glacial valleys in eastern North Dakota and South Dakota. The volcanic- and sedimentary-rock aquifers of northwestern Wyoming and southern Montana are little used.

UNCONSOLIDATED-DEPOSIT AQUIFERS

Unconsolidated-deposit aquifers (**fig. 25**) in sediments of Quaternary age are the most productive aquifers in Segment 8 and are the source of water for thousands of shallow wells. These aquifers consist primarily of sand and gravel but locally contain cobbles and boulders. Commonly, the aquifers contain clay and silt either mixed with the sand and gravel or as beds or lenses; where bedded, the clay and silt form confining units. The unconsolidated-deposit aquifers are important sources of water for all use categories in the four-State area and are in the following settings:

- A broad band of continental glacial deposits in Montana, North Dakota, and South Dakota
- Narrow valleys along major streams, primarily in southeastern Montana and locally in southwestern North Dakota, western South Dakota, and northeastern Wyoming
- Broad valleys in structural or erosional basins in western Montana and central, southern, and western Wyoming

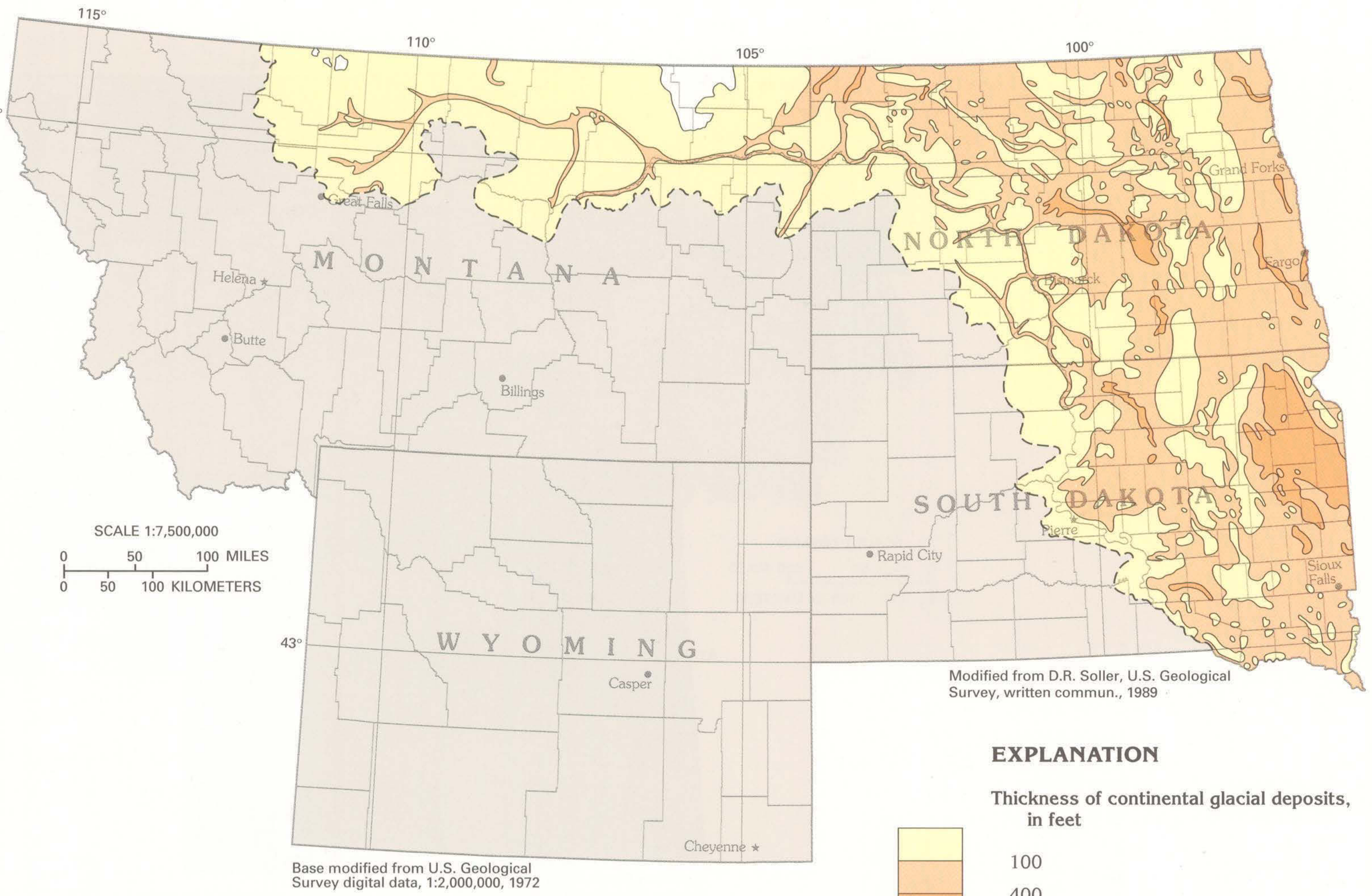
The sediments that compose the unconsolidated-deposit aquifers were deposited as outwash from continental and alpine, or mountain, glaciers and as alluvium from streams. Because of the wide range of depositional environments, the aquifers have a wide range of permeability. Sand and gravel that make up alluvial deposits and glacial outwash generally are extremely permeable, whereas fine-grained lake deposits and poorly-sorted till have minimal permeability and commonly form local confining units.

During the Pleistocene Epoch, massive ice sheets that were part of continental glaciers covered north-central and northeastern Montana, the eastern one-half of South Dakota, and most of North Dakota except for the southwestern corner of the State (**fig. 25**). Glacial deposits range in thickness from a feather edge near the western and southern limits of glaciation to more than 400 feet in some areas of eastern North Dakota and South Dakota (**fig. 26**). In Montana, the glacial deposits commonly are less than 100 feet thick. Most of the continental glacial deposits consist of till, which is a mixture of unsorted clay, silt, sand, gravel, and boulders that was deposited beneath or at the margins of the ice. Glacial meltwater, however, deposited well-sorted sand and gravel along stream valleys and in outwash plains; in places, these coarse-grained deposits are as much as 400 feet thick and are important aquifers. Although some of these sand and gravel aquifers extend to the land surface, most are buried, ancient stream channel deposits that formed in either valleys of meltwater streams or valleys incised into the bedrock (**fig. 27**). The buried valley deposits can be covered with confining units that consist of till or fine-grained glacial lake deposits, which can, in turn, be covered with glacial outwash deposits of sheetlike sand and gravel that compose productive aquifers. Several aquifers in buried valleys have been developed as sources of freshwater; the locations of other valleys are not well known, and many undiscovered buried valleys probably exist. Permeable lenses of sand and gravel within the till form aquifers that yield sufficient water for domestic use, especially where several lenses are penetrated by a well (**fig. 28**). Nearby wells that do not penetrate sand and gravel beds, however, yield little or no water. Lenses of sand and gravel in till beds differ as to thickness, sediment grain size, degree of sorting (**fig. 29**), and iron content and oxidization.

Unconsolidated-deposit aquifers that consist of sand and gravel deposited as alluvium along streams in the central part of Segment 8 (**fig. 25**) generally are thin, narrow bands. These aquifers in stream-valley alluvium locally yield sufficient water for some uses but generally are less productive than the other unconsolidated-deposit aquifers. Many of the aquifers along stream valleys are not shown in **figure 25** because of the scale of the map.

In western Montana and western and central Wyoming, unconsolidated-deposit aquifers are mostly alluvial deposits that partly fill broad valleys in mountainous areas (**fig. 25**). The basins that contain these deposits were formed by faulting or erosion or both. The alluvium was deposited primarily as coalescing alluvial fans by streams that flowed into the valleys from the surrounding mountains (**fig. 30**). In some valleys, the basin-fill alluvial deposits contain glacial outwash and other types of deposits that resulted from alpine glaciation; the extent of the glaciation is not known. Locally, sand and gravel beds of late Tertiary age compose aquifers beneath the Quaternary deposits that form most of the basin fill (**fig. 30**). The upper Tertiary aquifers can be distinguished only with difficulty from the younger unconsolidated-deposit aquifers in most basins. Clayey lake-bed deposits form confining units in some basins; such conditions are particularly common in valleys in Montana. The thickness of the unconsolidated-deposit aquifers is unknown in most basins because no wells totally penetrate the aquifers but is known to be as much as 900 feet in some basins. Basin-fill deposits typically are coarse grained near basin margins and finer grained toward basin centers.

The permeability of the unconsolidated-deposit aquifers is variable. Average yields of wells completed in these aquifers range from about 1 to 1,000 gallons per minute. Yields of wells completed in thick sequences of coarse sand and gravel, however, can exceed 3,500 gallons per minute. Depths of wells completed in glacial outwash deposits generally are less than 300 feet; wells completed in alluvium along stream valleys generally are less than 100 feet deep; and wells completed in basin-fill deposits are as deep as 900 feet.



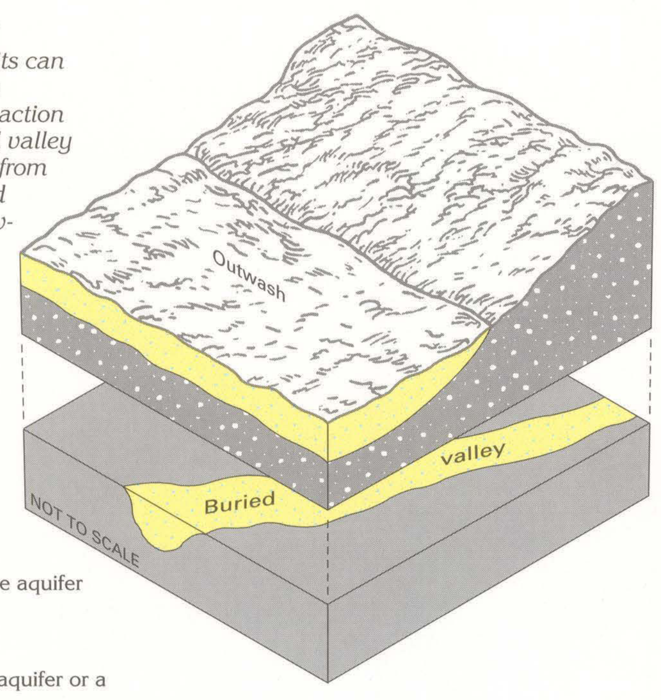
EXPLANATION

Thickness of continental glacial deposits, in feet

- 100
- 400
- Deposits absent
- - - - - - Southern limit of continental glacial deposits

Figure 26. Sediments deposited by continental glaciers are thin or absent near the southern limit of the extent of the ice, but are more than 400 feet thick in parts of eastern North Dakota and South Dakota.

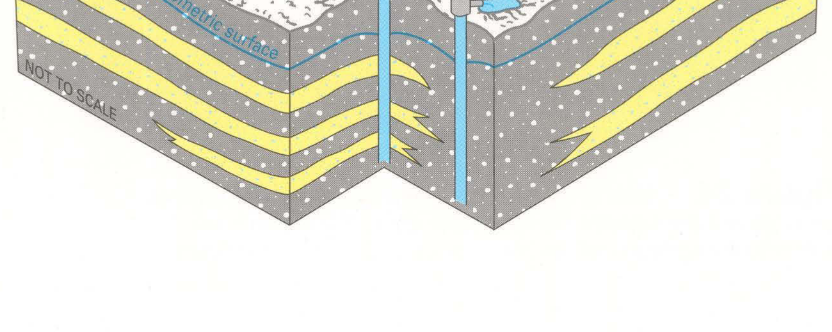
Figure 27. Sand and gravel aquifers in glacial outwash deposits can fill valleys incised into bedrock by preglacial erosion or the erosional action of the advancing ice. These buried valley deposits commonly are separated from overlying sheetlike, coarse-grained deposits of glacial outwash by low-permeability till.



EXPLANATION

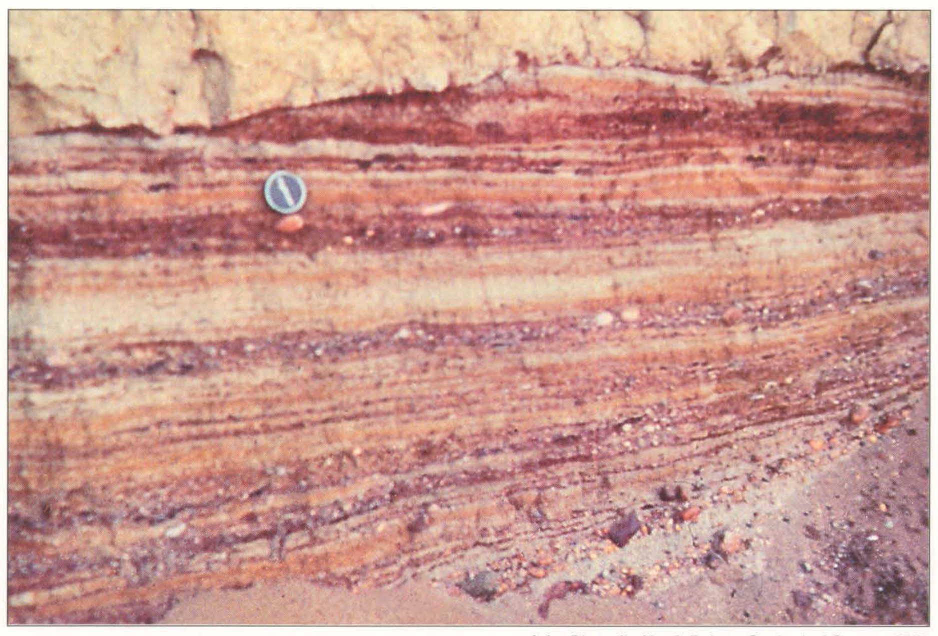
- **Sand and gravel**—Productive aquifer
- **Till**—Confining unit
- **Bedrock**—Can be either an aquifer or a confining unit

Figure 28. Discontinuous lenses of sand and gravel in deposits of till can be aquifers, especially if several lenses are penetrated by wells. Wells completed in till yield little or no water.



EXPLANATION

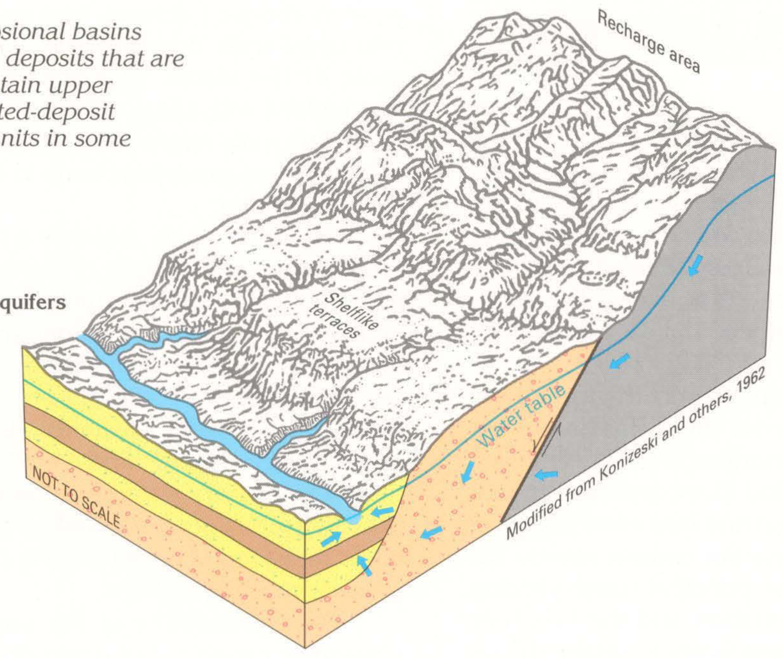
- Sand and gravel
- Till



John Bluemle, North Dakota Geological Survey, 1990

Figure 29. Permeable lenses of sand and gravel within till show a wide variation in bed thickness, grain size, and sorting of grains.

Figure 30. Valleys in structural or erosional basins between mountain ranges contain basin-fill deposits that are productive aquifers. Some of the basins contain upper Tertiary aquifers in addition to unconsolidated-deposit aquifers. Clayey lake beds form confining units in some basins.



UPPER TERTIARY AQUIFERS

Upper Tertiary aquifers (**fig. 31**) are mostly beds of unconsolidated to semiconsolidated sand and gravel of Pliocene and Miocene age. Fine-grained deposits of clay and silt commonly are interbedded or mixed with the sand and gravel. Thin beds of basalt and volcanic ash are interbedded locally with the sediments that compose the upper Tertiary aquifers in Montana. In some places, especially in Montana, thin, discontinuous deposits of Quaternary age are included in the upper Tertiary aquifers in this report.

In southern South Dakota and southeastern Wyoming, upper Tertiary aquifers consist of broad, extensive sheets of alluvium that were deposited by a network of branching and rejoining streams. The source of the alluvium was the Middle Rocky Mountains to the west. Thick sequences of sand and gravel in the alluvium compose productive aquifers, especially in the Miocene Ogallala Formation and the Miocene and Oligocene Arikaree Formation. The upper Tertiary aquifers in this area are part of the High Plains aquifer system, which is as much as 1,000 feet thick in southeastern Wyoming.

Upper Tertiary aquifers in western Montana and central and western Wyoming are mostly in the same small structural and erosional basins that contain unconsolidated-deposit aquifers, whereas in central Wyoming, the aquifers are in the large Wind River, the Great Divide, and the Washakie structural basins. The upper Tertiary aquifers in these basins consist of sand and gravel that were deposited as overlapping and coalescing alluvial fans by streams that entered the basins from the surrounding mountains. In places, the alluvial fans have been partly eroded, and the upper Tertiary aquifers are exposed as shelflike terraces cut in or near the basin walls (**fig. 30**). The alluvial deposits in the terraces generally are extremely permeable and allow water to percolate rapidly downward through the deposits to the water table. Upper Tertiary aquifers generally are less than 2,000 feet thick but are as much as 6,000 feet thick in some basins.

The permeability of the upper Tertiary aquifers is variable and directly related to the grain size and sorting of the deposits that compose the aquifers. Where the aquifers consist primarily of sand and gravel, they are extremely permeable; permeability decreases as clay content increases. Generally, the upper Tertiary aquifers become more clayey and less permeable as depth increases. Yields of wells completed in these aquifers are reported to range from 5 to 800 gallons per minute, but yields of a few wells exceed 2,000 gallons per minute. In South Dakota, most wells yield 100 gallons per minute or less and yields rarely exceed 1,500 gallons per minute.

Because the upper Tertiary aquifers usually are at shallow depths, most wells completed in the aquifers are less than 600 feet deep. However, some well depths exceed 1,000 feet in southeastern Wyoming.

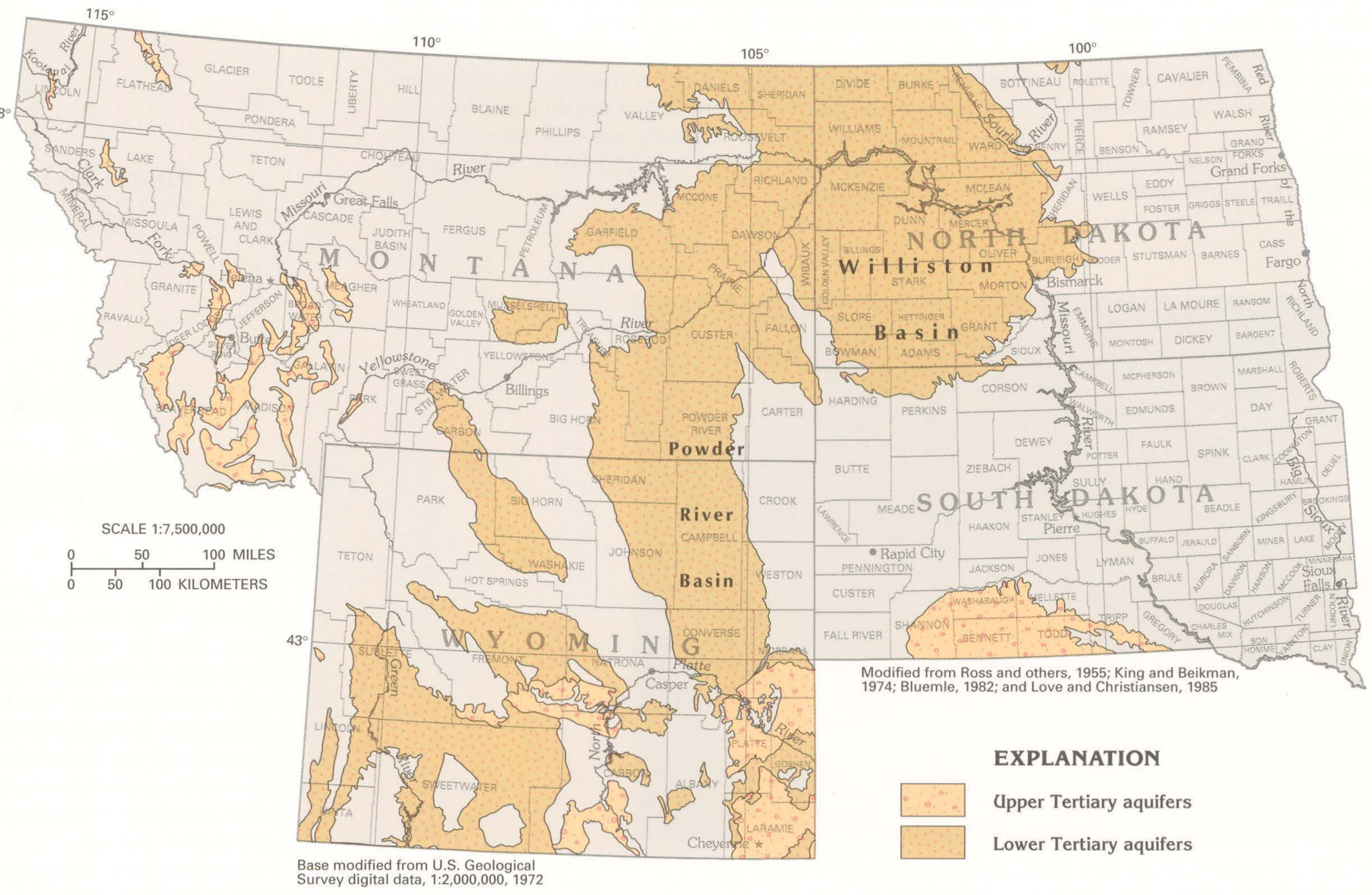


Figure 31. In Montana, South Dakota, and Wyoming, upper Tertiary aquifers are important sources of water even though they do not extend over large areas. Lower Tertiary aquifers are much more extensive but are less permeable than the upper Tertiary aquifers.

LOWER TERTIARY AQUIFERS

Lower Tertiary aquifers (**fig. 31**) consist mostly of semiconsolidated to consolidated sandstone beds of Oligocene to Paleocene age. The water-yielding sandstones are interbedded with shale, mudstone, siltstone, lignite, and coal and locally with beds of limestone, none of which are considered to be aquifers. Some coal beds yield water, particularly if the coal is fractured or has been partially burned and has formed clinker zones. Most of the lower Tertiary rocks were deposited in continental environments, but some of the shale and limestone beds were deposited in a marine environment and form confining units. The lower Tertiary aquifers contain freshwater over a larger area of Segment 8 than any other aquifers. Because of their wide extent, the lower Tertiary aquifers are an important source of supply even though they are not highly permeable.

Lower Tertiary aquifers in eastern Montana, western North Dakota and South Dakota, and northeastern Wyoming consist mostly of sandstone beds in the Fort Union Formation of Paleocene age. Lower Tertiary rocks in this area include those of the Fort Union coal region (shown in **figure 54** in the Northern Great Plains aquifer system section of this report), which contains a major part of the Nation's reserves of coal. The lower Tertiary aquifers in this area are downwarped into the Williston and the Powder River Basins and consist of parts of the uppermost consolidated-rock formations in these basins. Lower Tertiary rocks generally are less than 1,000 feet thick in the Williston Basin, but not all these rocks yield water. The rocks that compose the lower Tertiary aquifers contain more shale in their eastern parts than elsewhere, and the transmissivity of the aquifers, therefore, decreases to the east.

In the western two-thirds of Wyoming and adjacent areas of Montana, the lower Tertiary aquifers usually are in structural basins that have been downwarped to great depths. The lower Tertiary aquifers in these basins are mostly in sandstone beds of the Eocene and locally Paleocene Wasatch Formation and the Paleocene Fort Union Formation. The total thickness of lower Tertiary rocks in some of these basins is as much as 10,000 feet; however, the cumulative thickness of the aquifers rarely exceeds 3,000 feet because not all the lower Tertiary rocks are permeable.

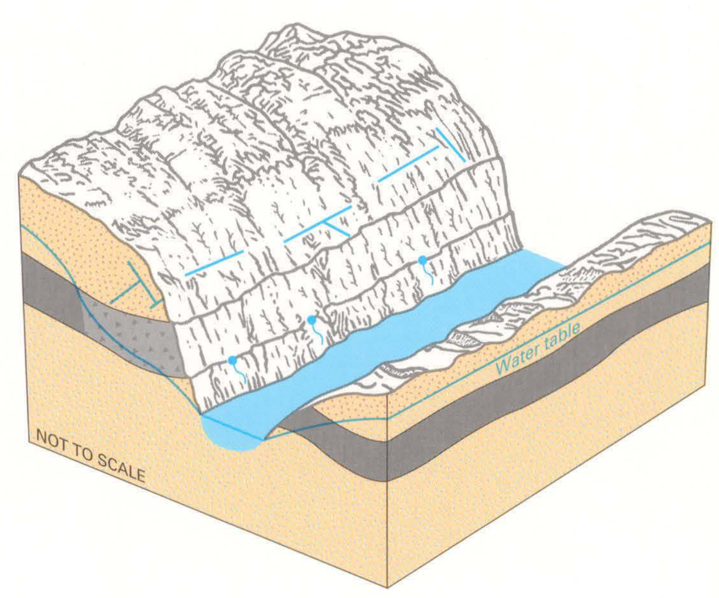
The permeability of the lower Tertiary aquifers is variable and is directly related to the amount of interconnected pore space in the sandstone beds that compose the aquifers. Most of the pore space consists of openings between individual sand grains, but some is secondary openings, such as bedding planes and joints. Thick coal seams, which are interbedded with sandstone (**fig. 32**) or with fine-grained sediments, also can have joints and bedding planes that store and transmit water. Where erosion has exposed coal beds at the land surface, wildfires or lightning have ignited some of the beds. The coal then burned until the oxygen supply in the beds was exhausted and, thus, formed clinker zones (**fig. 33**) that are extremely permeable and can extend a considerable distance into the buried parts of the coal beds. Where the clinker zones are saturated, they form productive aquifers from which springs issue. However, most known clinker zones are above the water table.

Yields of most wells completed in the lower Tertiary aquifers range from 1 to 50 gallons per minute in Montana, South Dakota, and Wyoming and from 1 to 100 gallons per minute in North Dakota. Maximum yields exceed 500 gallons per minute in South Dakota and 1,000 gallons per minute in Wyoming. These aquifers are deeply buried or overlain by fine-grained rocks in many places. Wells completed in the aquifers commonly are 300 to 900 feet deep and locally are 1,000 to 3,000 feet deep.

R.E. Davis, U.S. Geological Survey, 1988

Figure 32. Dark coal seams are in stark contrast with overlying and underlying sandstone beds. The coal and sandstone can form productive aquifers. The coal seam shown here is about 25 feet thick.

Figure 33. Clinker zones that result from burning of parts of coal beds are extremely permeable and are sources of springs in some places. Most clinker zones are unsaturated, but they form local aquifers where they are below the water table. Overlying sandstone beds may be fractured and provide conduits for recharge where the sandstone has subsided because the coal has burned.



UPPER CRETACEOUS AQUIFERS

Upper Cretaceous aquifers extend over a wide area in the central parts of Segment 8 (**fig. 34**). These aquifers are widespread in the subsurface but contain freshwater only where they crop out and for a short distance downdip of where they are covered by younger rocks. Beds of consolidated sandstone compose most of the upper Cretaceous aquifers. The sandstone is interbedded with shale, siltstone, and occasional thin, lenticular beds of coal.

Upper Cretaceous aquifers crop out mostly around the edges of the Williston and the Powder River Basins but are exposed in smaller areas along the margins of the Green River, the Great Divide, the Hanna, the Wind River, and the Bighorn Basins. The aquifers are downwarped and faulted to depths of several thousand feet in these basins but contain mostly saline water in their deeper parts. The principal water-yielding formations are the Hell Creek Formation and the Fox Hills Sandstone. In western Wyoming, some water is obtained from the Lance Formation, which is equivalent to the Hell Creek, and from the deeper Mesaverde Formation. The Judith River Formation and the Eagle Sandstone in west-central Montana also are used as a source of supply; these formations are not sufficiently permeable to yield water in eastern Montana. Small volumes of water are obtained locally from wells completed in calcareous lenses of the chalky, shaly Niobrara Formation in North Dakota and South Dakota and from the Greenhorn Limestone and the Codell Sandstone Member of the Carlisle Shale in eastern South Dakota.

Most of the water in the sandstone aquifers is in pore spaces between individual grains of sand, but some of the aquifers contain fractures, bedding planes, and joints that provide large-scale openings (**fig. 35**) which store and transmit most of the water. Where sandstone beds are thin and interbedded with shale or other rocks that have minimal permeability, wells might need to be drilled deep enough to penetrate several sandstone beds in order to obtain an adequate supply of water.

The Pierre Shale, which is a major confining unit in eastern Montana and in most of North Dakota and South Dakota, is more than 3,000 feet thick in places. The Pierre Shale underlies the Fox Hills Sandstone and separates it from deeper aquifers. Locally, the Pierre Shale yields small volumes of water from thin sandstone beds or from highly weathered or fractured zones in the uppermost shale beds. The water usually is highly mineralized, however, and the Pierre Shale is not considered to be a principal aquifer even though it yields sufficient water to supply many domestic wells. The Pierre Shale subcrops over about one-third of eastern North Dakota and about two-thirds of eastern South Dakota.

The permeability of the upper Cretaceous aquifers is somewhat variable, but generally not as great as that of the aquifers in younger rocks. Wells completed in the Hell Creek Formation and the Fox Hills Sandstone have yields that range from 5 to 50 gallons per minute. Locally, these formations yield about 200 gallons per minute in Montana, 300 gallons per minute in North Dakota, and 1,000 gallons per minute in some of the structural basins in Wyoming. Yields of wells completed in the Judith River Formation and the Eagle Sandstone commonly range from 5 to 20 gallons per minute, but locally exceed 200 gallons per minute. Wells that obtain water from the upper Cretaceous aquifers generally are less than 800 feet deep but a few wells are as deep as 2,000 feet in Montana and 3,000 feet in Wyoming.

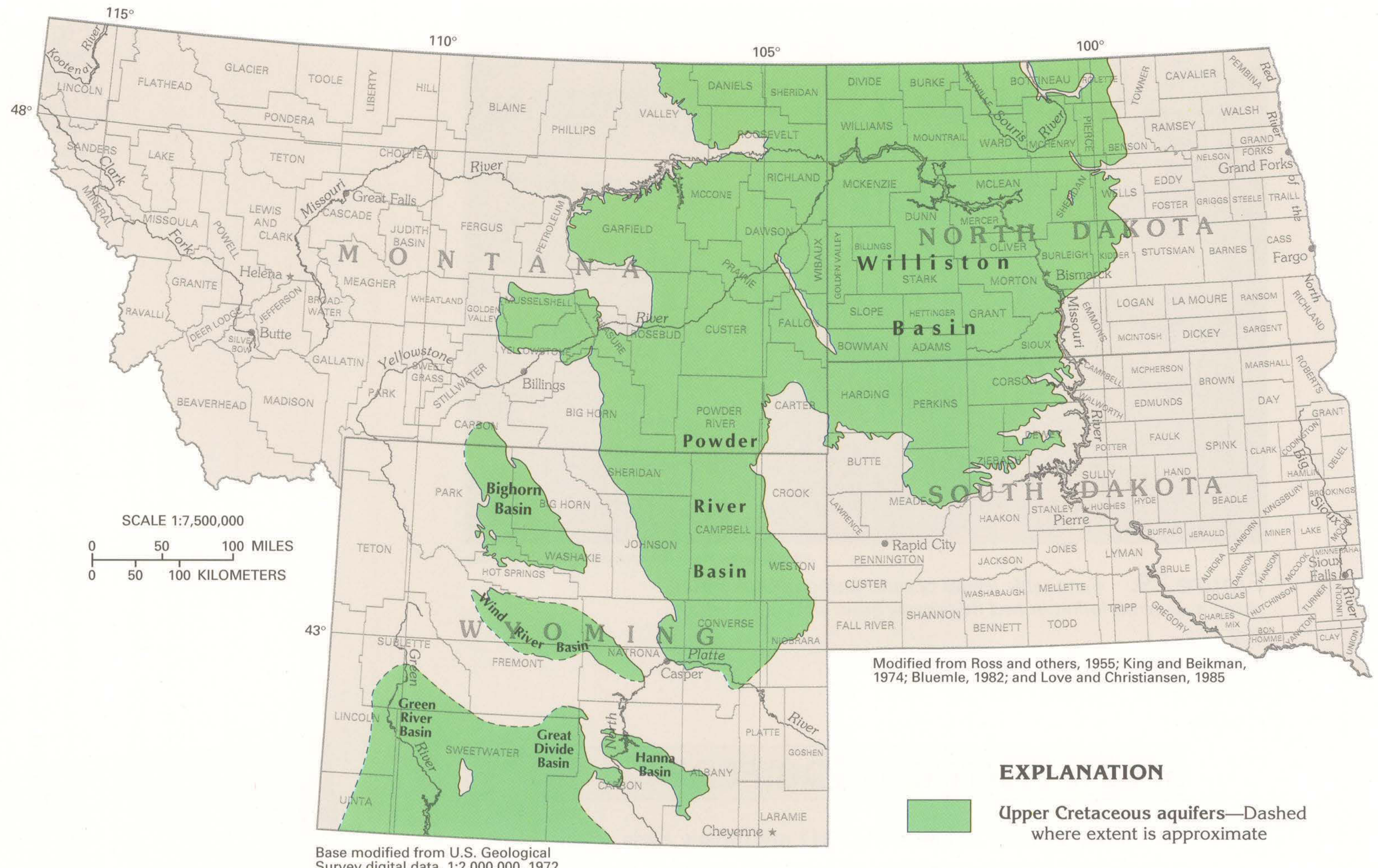


Figure 34. *Upper Cretaceous aquifers extend throughout much of Segment 8 but are principally in the subsurface, where they contain mostly saline water.*

Figure 35. *Fractures, joints, and bedding planes, such as these in the Eagle Sandstone, can store and transmit large volumes of water.*

LOWER CRETACEOUS AQUIFERS

Lower Cretaceous aquifers extend over about two-thirds of Segment 8 (**fig. 36**) but are exposed at the land surface mostly as wide to narrow bands that completely or partly encircle basins or uplifted areas. Tectonic forces that acted on the Earth's crust warped formerly flat-lying rocks into several such structures. Subsequent erosion has exposed older rocks at the centers of the folds; progressively younger rocks surround the centers as concentric bands. The lower Cretaceous aquifers commonly contain highly mineralized water where they are deeply buried.

Formations of consolidated sandstone compose the lower Cretaceous aquifers. Perhaps one of the best known and earliest described artesian aquifers in the Nation is the Dakota aquifer (locally called the Inyan Kara aquifer), which is in Lower Cretaceous rocks that are exposed on the flanks of the Black Hills Uplift and extend more than 300 miles across South Dakota in the subsurface (**fig. 37**). The Newcastle Sandstone merges eastward in the subsurface with sandstones of the Inyan Kara Group to become the Dakota Sandstone. In Montana, North Dakota, and Wyoming, the Muddy Sandstone and equivalent water-yielding rocks overlie the Skull Creek Shale and are equivalent to the Newcastle Sandstone. Sandstones equivalent to the Inyan Kara Group in North Dakota and South Dakota are part of the Kootenai Formation in central and western Montana. The Cloverly Formation in Wyoming, which is equivalent to the Dakota Sandstone, is an important aquifer.

Because the sandstones of the Dakota aquifer receive some recharge at high altitudes and some by upward leakage from deeper aquifers, the water in the aquifer is under high artesian pressure. When development of the Dakota aquifer began in the late 19th century, many wells completed in the aquifer flowed at the land surface. The rate of flow of some wells was as much as 4,000 gallons per minute, and much water was wasted because these wells were allowed to flow continuously. Water levels in the aquifer declined 700 feet or more in some places.

Water in the Dakota aquifer moves hundreds of miles from recharge areas to places where the water discharges upward to shallower aquifers, surface-water bodies, or wells. Because the water is in contact with aquifer minerals for a long time, it commonly contains large concentrations of dissolved minerals. The aquifer contains water with dissolved-solids concentrations of greater than 10,000 milligrams per liter in about one-half of North Dakota and in a large part of northwestern South Dakota. Locally, in parts of the Williston Basin in extreme northeastern Montana, the aquifer is more than 5,500 feet below the land surface and contains brine.

Sandstone beds of Jurassic age locally form minor aquifers in Segment 8. For example, sandstone of the Jurassic Sundance Formation yields water in several counties in east-central South Dakota. In general, however, the Jurassic sandstones are thin, of limited extent, and little used for water supply in Segment 8. The local Jurassic aquifers are included in the lower Cretaceous aquifers in this report.

Porosity and permeability are variable in the lower Cretaceous aquifers. Yields of most wells completed in these aquifers range from about 5 to 60 gallons per minute, which is about the same as that reported for wells in the upper Cretaceous aquifers. Yields of some wells completed in the lower Cretaceous aquifers exceed 500 to 1,000 gallons per minute, however. Wells must be drilled to considerable depths in many places because the lower Cretaceous aquifers commonly are deeply buried. Some wells completed in these aquifers are 5,000 feet deep or more.

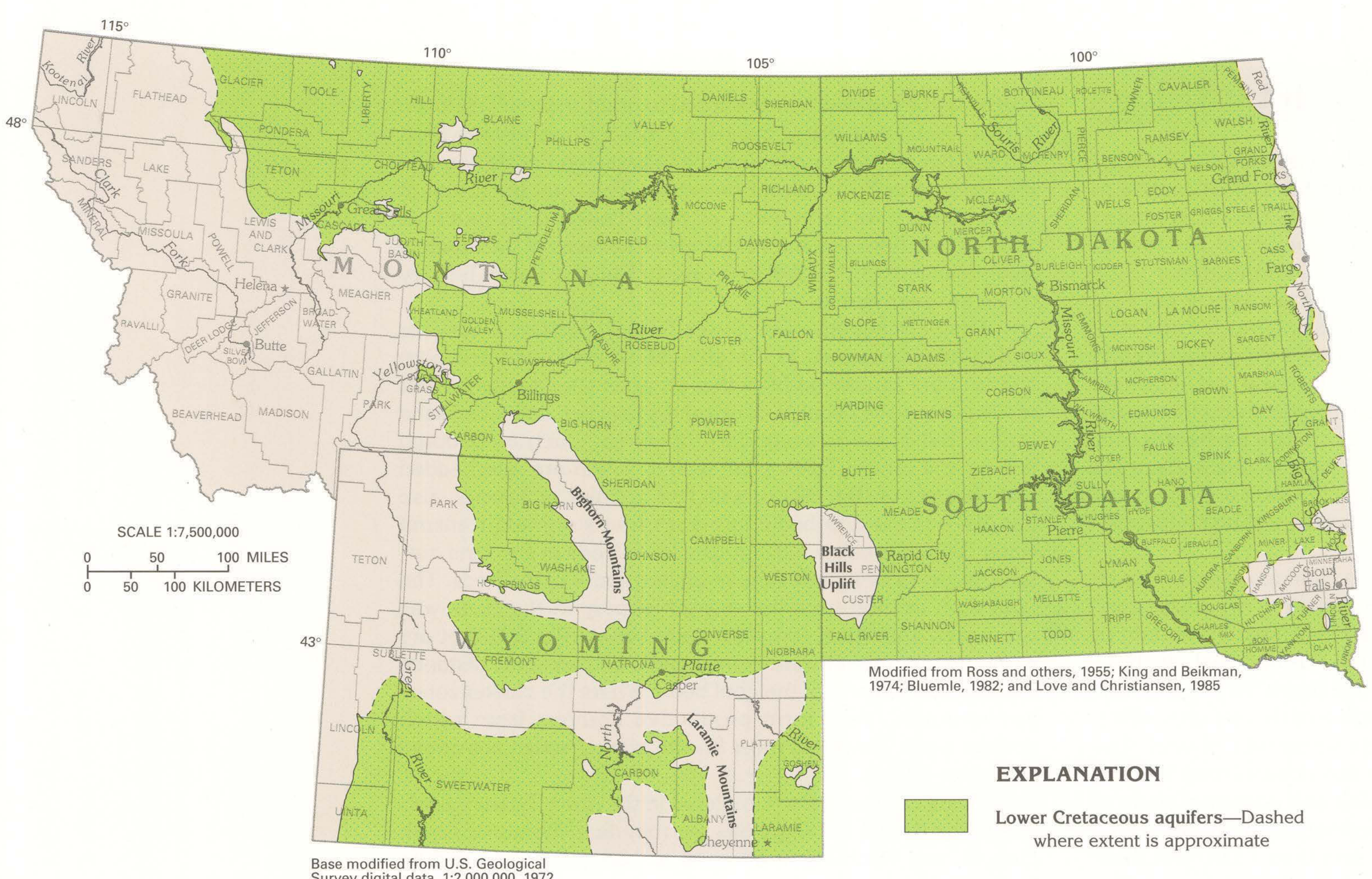


Figure 36. *Lower Cretaceous aquifers are in the subsurface throughout about two-thirds of Segment 8. The rocks that compose the aquifers have probably been removed from the crests of uplifts, such as the Bighorn and the Laramie Mountains and the Black Hills.*

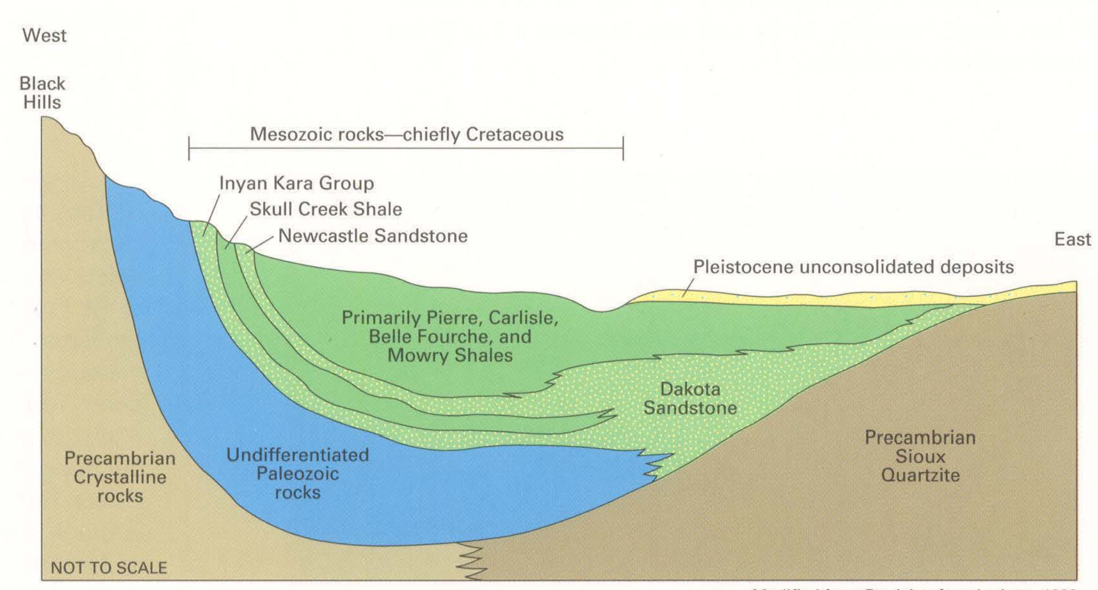


Figure 37. *Lower Cretaceous aquifers in South Dakota consist of sandstone in the Inyan Kara Group and the Newcastle and the Dakota Sandstones. The sandstones are exposed at the land surface on the flanks of uplifts, such as the Black Hills, and extend for hundreds of miles in the subsurface. Thick shale beds create confined conditions in the aquifers.*

PALEOZOIC AQUIFERS

Paleozoic aquifers extend over about three-fourths of Segment 8 in the subsurface (**fig. 38**) but are exposed at the land surface only in small areas. Small areas in western Montana and western Wyoming are underlain by Paleozoic aquifers in outcrop and in the subsurface, but these areas are separated by faults from the main body of the aquifers. The Paleozoic aquifers consist mostly of limestone and dolomite, but some Paleozoic sandstones also yield water. Confining units that overlie and separate the aquifers consist of shale and siltstone with some beds of anhydrite and halite (rock salt). The Paleozoic aquifers can be separated into two groups—those in upper Paleozoic rocks and those in lower Paleozoic rocks—but they are mapped together in **figure 38** because of the scale of the map.

Although some water is obtained from wells completed in the Tensleep Sandstone and in sandstone beds of the Minnelusa Formation and equivalent rocks, which are of Pennsylvanian and Permian age, the most productive aquifer in upper Paleozoic rocks is the Madison Limestone of Devonian and Mississippian age. The Madison Limestone, or Group, was deposited in warm, shallow marine waters and originally contained much lime mud. Initially, the limestone had minimal permeability until it was altered by the processes of dolomitization, dedolomitization, and partial dissolution, all of which increased the permeability. In some places, large solution cavities, through which large volumes of water can move rapidly, have developed in the limestone (**fig. 39**). Wells that penetrate such solution cavities can yield extremely large volumes of water, especially where several cavities are interconnected. Springs commonly issue from solution openings in the Madison Limestone (**fig. 40**); the flow of one of these springs in Montana is reported to be 300 cubic feet per second, or about 194 million gallons per day.

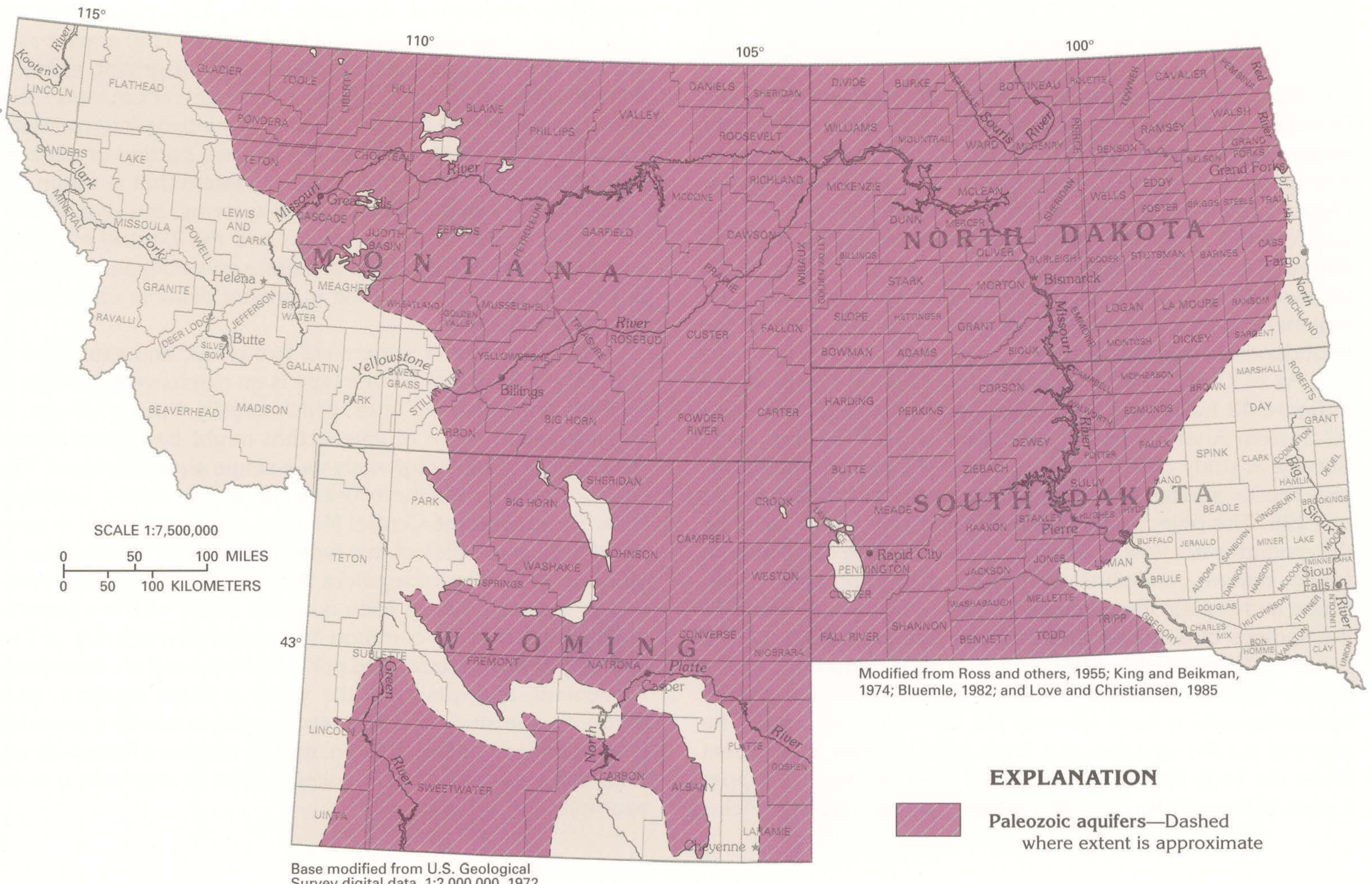
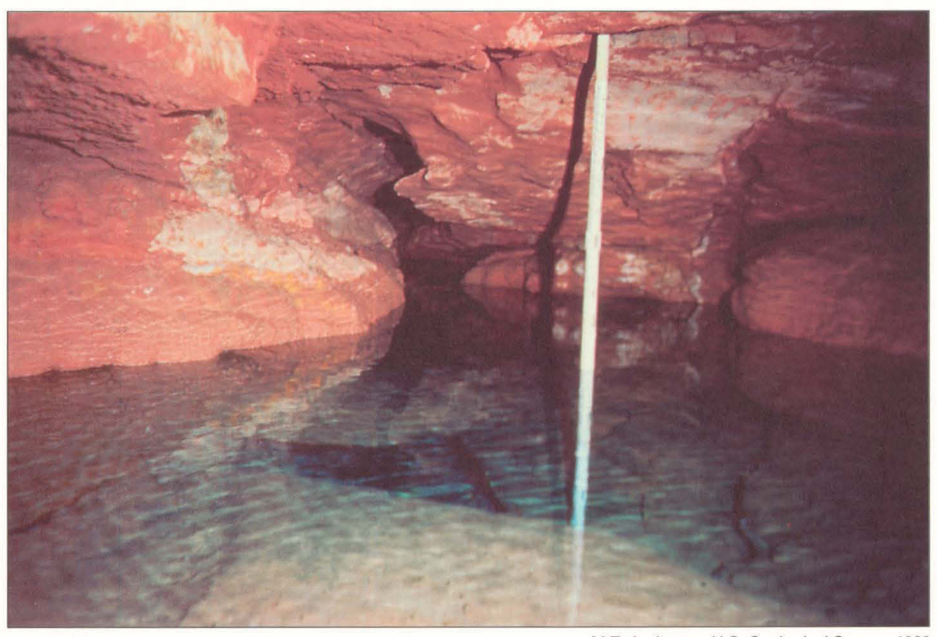


Figure 38. *Paleozoic aquifers extend over large areas in the subsurface of Segment 8. The aquifers commonly contain highly mineralized water where they are deeply buried.*



M.T. Anderson, U.S. Geological Survey, 1989

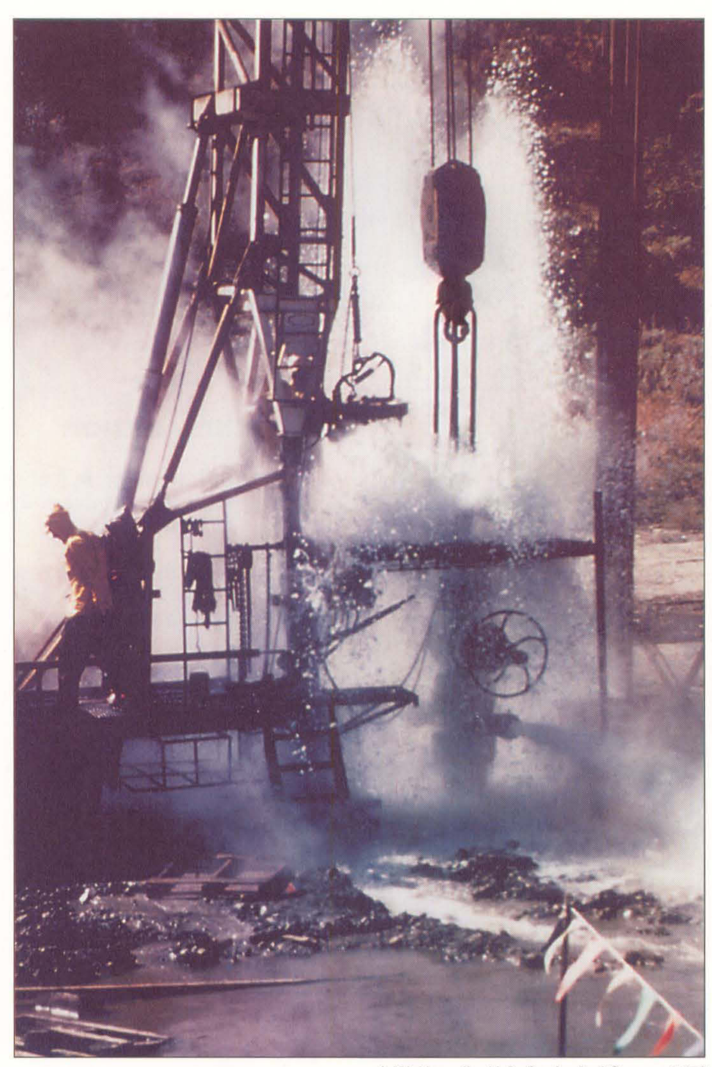
Figure 39. *Large solution cavities, such as this one in the Madison Limestone in western South Dakota, provide conduits that store and transmit large volumes of water. The post extends about 8 feet above the water, which is about 5 feet deep.*

Aquifers in lower Paleozoic rocks consist mostly of the Bighorn and the Whitewood Dolomites and limestone and dolomite beds in the Red River Formation, which are all of Ordovician age. Locally, limestone and dolomite of the Darby Formation (Devonian and Mississippian), sandstones of the Winnipeg Formation (Ordovician), the Deadwood Formation (Cambrian and Ordovician) and the Flathead Sandstone (Cambrian) yield small volumes of water. Confining units of shale, shaly carbonate rocks, anhydrite beds, and halite of Devonian, Silurian, and Cambrian age locally separate the aquifers in lower Paleozoic rocks from the Madison Limestone. Except near the mountains, the aquifers in lower Paleozoic rocks are deeply buried and, therefore, are not a major source of water.

The Paleozoic aquifers receive recharge where they are exposed at the land surface on the flanks or crests of anticlines or by downward leakage from shallower aquifers in places where the shallower aquifers have higher hydraulic heads. From aquifer outcrop areas, ground water moves down the dip of the aquifers into major structural basins, such as the Powder River, the Wind River, and the Bighorn in Wyoming and the Williston in Montana, North Dakota, and South Dakota. The water eventually discharges by upward leakage to shallower aquifers or moves to the land surface where the aquifers are exposed on the borders of the basins. Where they are buried to great depths, the Madison Limestone and older, permeable Paleozoic rocks contain oil, gas, and brine in places. Fresh ground water that moves around the margins of bodies of brine can become highly mineralized as it mixes with the dense brine. Water that discharges from the Paleozoic aquifers in northeastern North Dakota and the Canadian Province of Manitoba contains large concentrations of dissolved solids as a result of this type of mixing. Recharge areas of the Paleozoic aquifers generally are at high altitudes, and, in the subsurface, the aquifers are overlain by confining units in most places. As a result, water in these aquifers is under high artesian pressure, and wells completed in the aquifers commonly flow at the land surface (**fig. 41**). The flow from the well shown in **figure 41** is obtained from the Madison Limestone. The well, which is located just east of Billings, Mont., is about 5,000 feet deep and artesian pressure is sufficient to push water about 1,000 feet above land surface.

K.G. Goddard, U.S. Geological Survey, 1989

Figure 40. *Springs issue from some of the interconnected openings created by partial dissolution of the Madison Limestone.*



L.W. Howells, U.S. Geological Survey, 1979

Figure 41. *Wells, such as this one being completed in the Madison Limestone in Yellowstone County, Mont., flow at the land surface because of high artesian pressure in the aquifer.*

Regional aquifer systems

REGIONAL AQUIFER SYSTEMS

Most of the aquifers in Montana, North Dakota, South Dakota, and Wyoming are parts of five large regional aquifer systems. An aquifer system consists of two or more aquifers that function similarly. The aquifers can be hydraulically connected so that a change in hydrologic conditions in one of the aquifers will affect the other aquifers or separated but with common geologic and hydrologic characteristics. Much of the freshwater that is withdrawn in Segment 8 is obtained from the regional aquifer systems, some of which extend far beyond the boundaries of the segment.

As of 1996, four of the regional aquifer systems shown in **figure 42** have been studied as part of the Regional Aquifer-System Analysis (RASA) Program of the U.S. Geological Survey. A study of the Northern Rocky Mountains Intermontane Basins aquifer system is underway, but not completed as of 1996. The objectives of each RASA study are to describe the ground-water flow system as it existed before development (under natural conditions) and as it exists at present, to describe and explain the changes in the flow system, to combine the findings of previous studies of the aquifer system, and to evaluate the probable effects of future development of the aquifer system. A digital computer simulation of the aquifer system usually is used to meet the last objective listed. The regional aquifer systems that have been studied in Segment 8 are the High Plains, the Northern Great Plains, the Upper Colorado River Basin, and the Central Midwest. The High Plains was referred to only as an aquifer in the RASA study, but will be referred to as an aquifer system herein. All the aquifer systems extend beyond the boundaries of the segment, some of them for great distances. However, the segment contains more than one-half of the Northern Rocky Mountains Intermontane Basins aquifer system and all but a small portion of the part of the Northern Great Plains aquifer system that is within the United States. Three of the aquifer systems, the High Plains, the Upper Colorado River Basin, and the Central Midwest, extend for tens of thousands of square miles beyond Segment 8 (**fig. 42**) and are discussed in greater detail in other chapters of this Atlas.

Regional aquifer systems of two types, and examples of both, are in Segment 8. One type is an extensive sequence of aquifers and confining units, which usually, but not always, is arranged as a stack of layers, that might be discontinuous locally but function regionally as a single aquifer system. The High Plains, the Northern Great Plains, the Upper Colorado River Basin, and the Central Midwest aquifer systems in Segment 8 are examples of this type. The second type is a set of virtually independent aquifers that might be partly or completely separated from each other by rocks with low permeability but that share common hydrologic characteristics. The same hydrologic factors and principles control the occurrence, movement, and quality of the water in these aquifers, and, therefore, the study of a few representative aquifers provides a basic understanding of them all. The Northern Rocky Mountains Intermontane Basin aquifer system in Segment 8 is an example of this type.

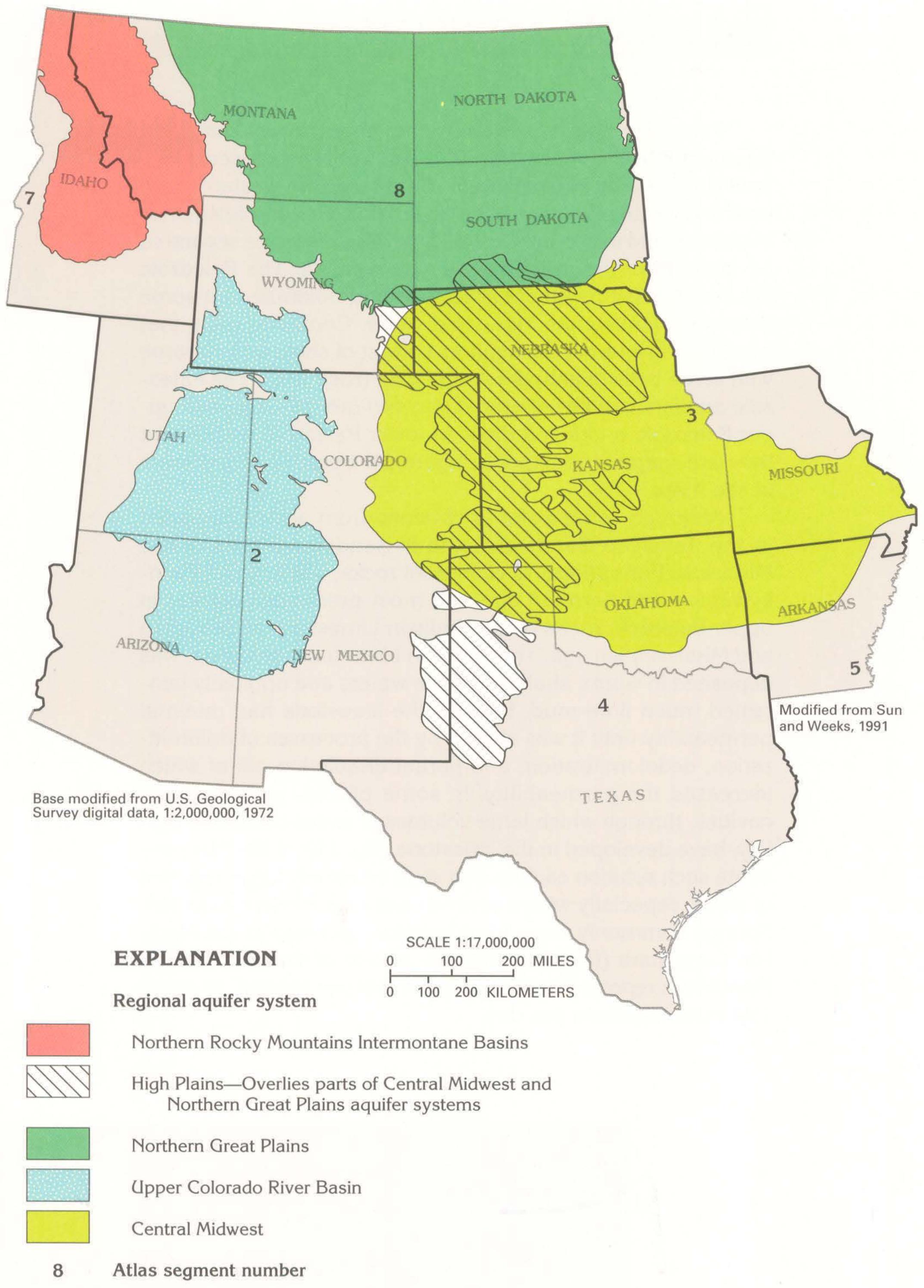
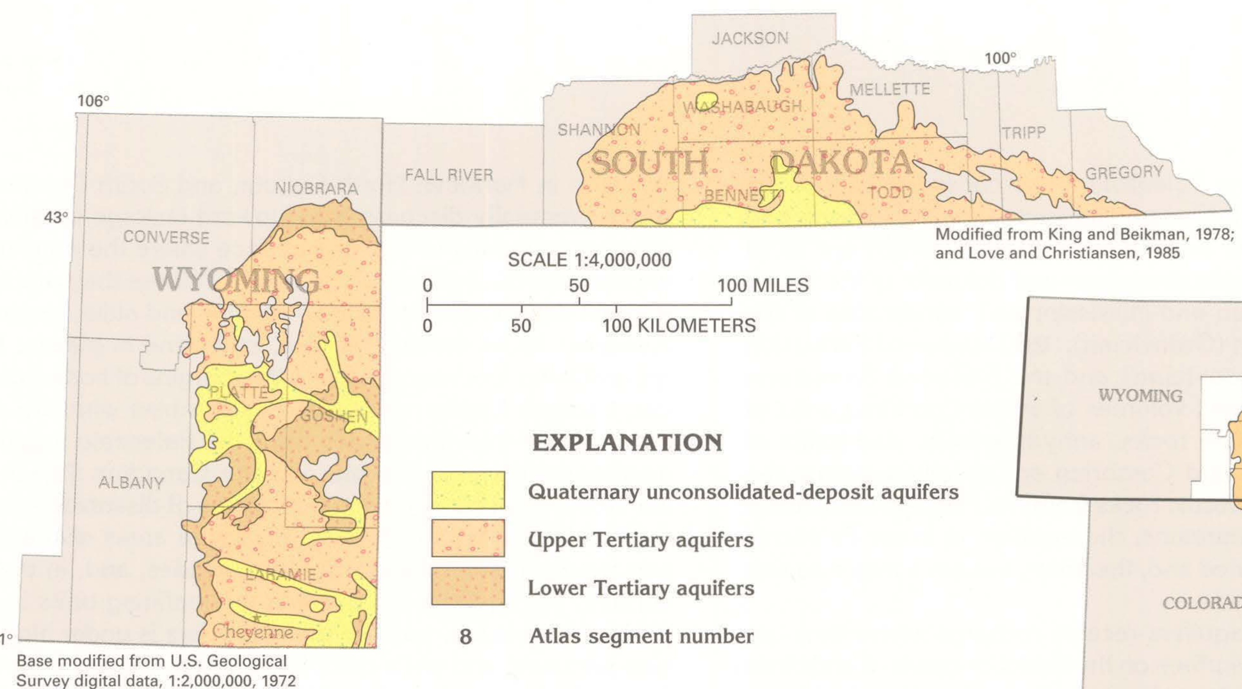


Figure 42. *The five regional aquifer systems in Segment 8 extend into adjacent States; some extend over tens of thousands of square miles beyond the segment.*



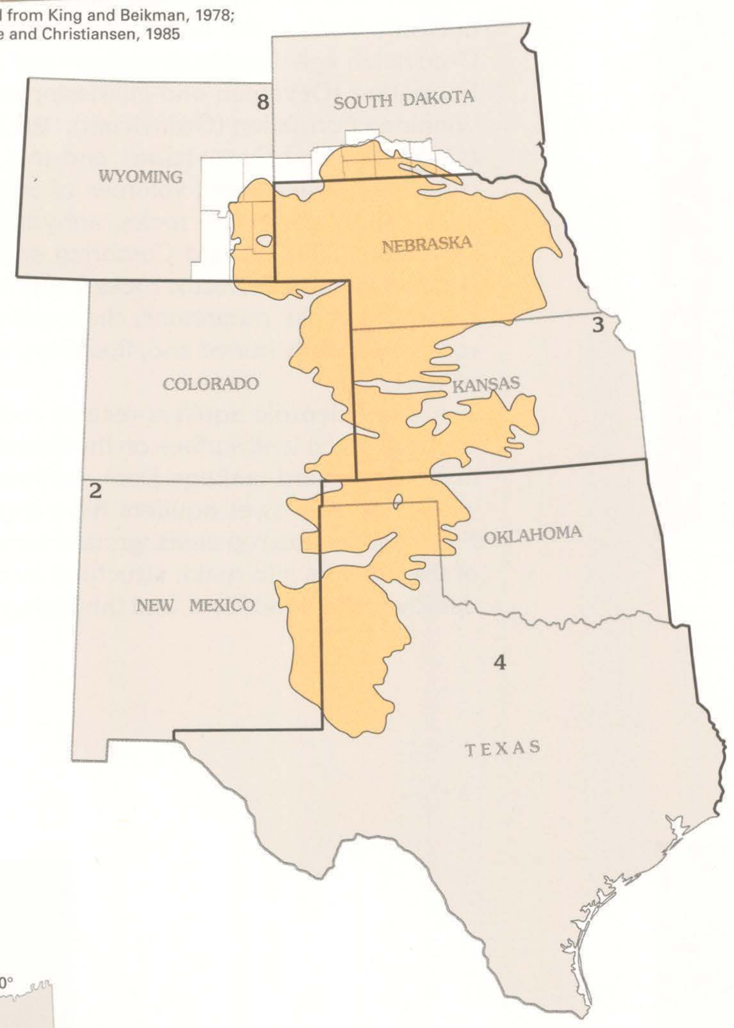


Figure 43. *The High Plains aquifer system consists mostly of aquifers in upper Tertiary rocks but also includes water-yielding deposits in Quaternary and lower Tertiary rocks.*

Era	System		Series	Geologic unit		Hydrologic unit		Lithology
Cenozoic	Quaternary		Holocene and Pleistocene	Valley-fill deposits and dune sand		Unconsolidated-deposit aquifers	High Plains aquifer system	Gravel, sand, silt, and clay. Dunes in South Dakota
	Tertiary	Upper	Miocene	Ogallala Formation		Upper Tertiary aquifers		Unconsolidated, poorly sorted gravel, sand, silt, and clay
				Arikaree Formation				Sandstone, fine to very fine. Local beds of volcanic ash, siltstone, claystone, and marl
		Lower	Oligocene	Brule Formation	White River Group	Lower Tertiary aquifers		Siltstone with sandstone as beds and channel deposits
				Chadron Formation		Confining unit		Clay and silt

Modified from Gutentag and others, 1984

Figure 44. *Several geologic units of Oligocene age and younger compose the aquifer system in South Dakota and Wyoming.*

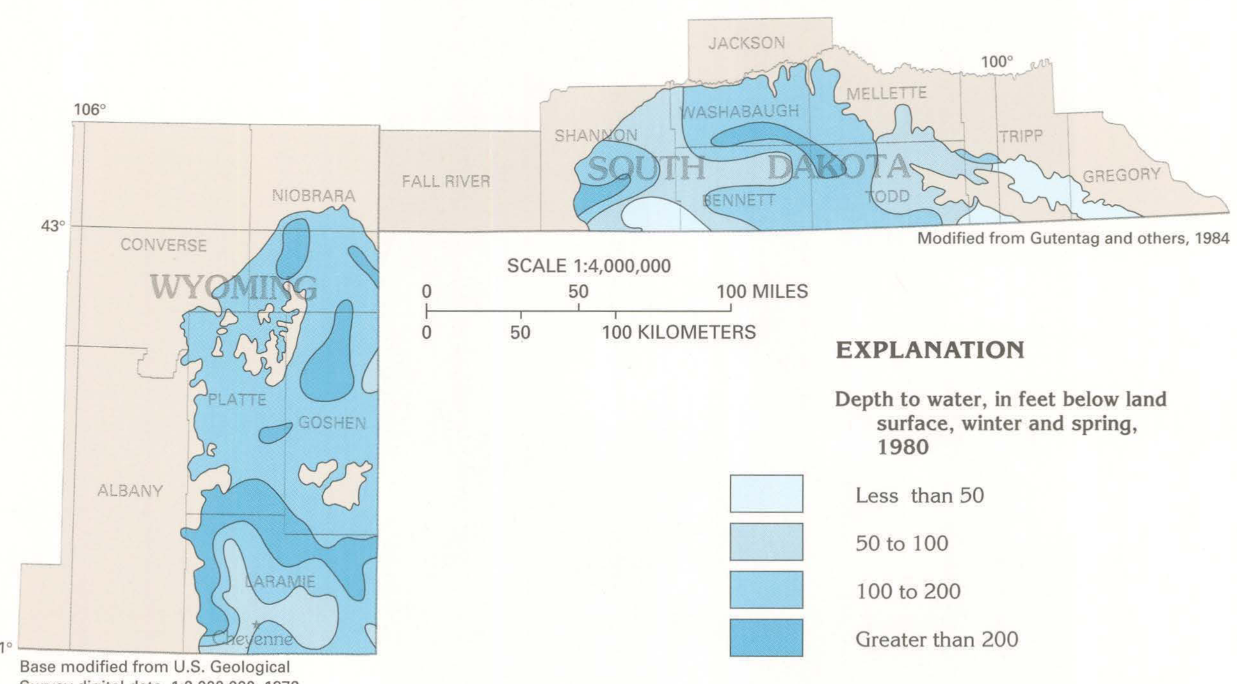


Figure 45. *Water in the High Plains aquifer system is at depths of less than 200 feet in most places.*

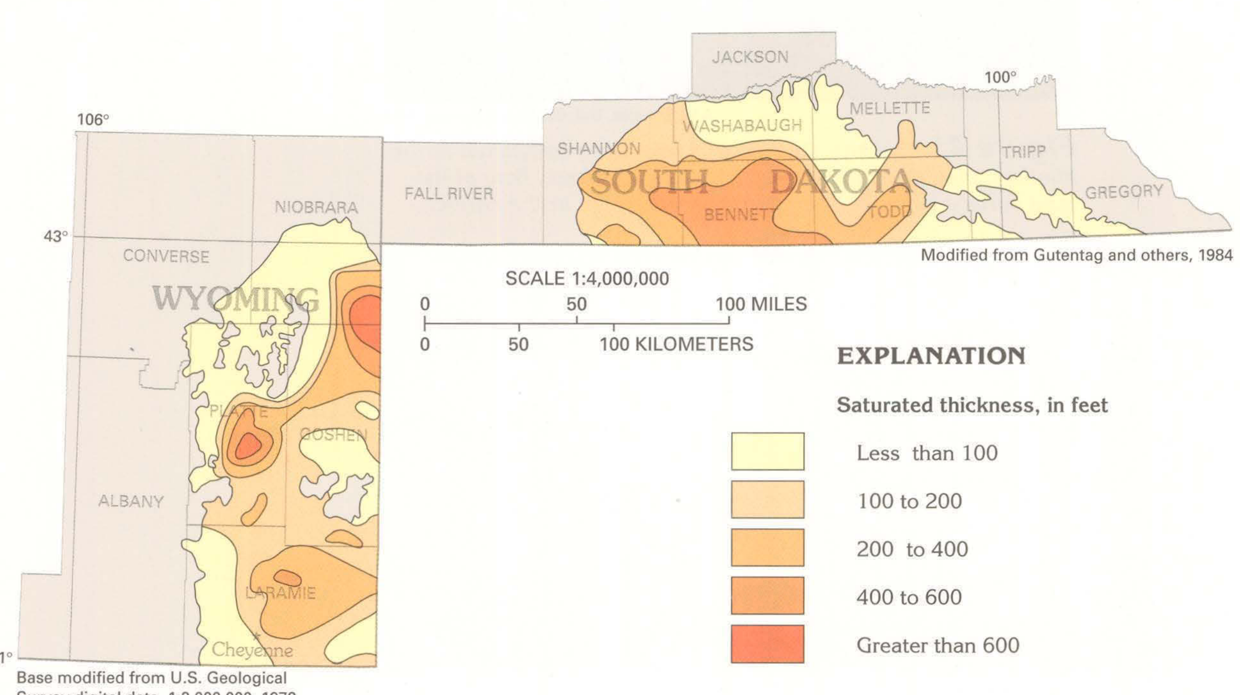


Figure 46. *The saturated thickness of the High Plains aquifer system represents the vertical distance between the top of the water table of the aquifer system and the base of the system. Saturated thickness in South Dakota and Wyoming generally is less than 400 feet.*

HIGH PLAINS AQUIFER SYSTEM

The High Plains aquifer system, which is called the High Plains aquifer in many reports, covers an area of about 4,800 square miles in South Dakota and about 8,000 square miles in Wyoming (**fig. 43**). Although the aquifer system is an important source of water in both States, most water is withdrawn from the system outside Segment 8. During 1980, for example, less than 1 percent of the water pumped from the aquifer system for agricultural irrigation was withdrawn in South Dakota and Wyoming. At present (1996), withdrawals in the two States are slightly greater than those in 1980.

Most wells completed in the High Plains aquifer system obtain water from upper Tertiary aquifers that consist of the Ogallala Formation of Miocene age and the Arikaree Formation of Miocene and Oligocene age (**fig. 44**). The unconsolidated sand and gravel beds of the Ogallala Formation yield water much more readily than the sandstone beds of the Arikaree Formation. The consolidated siltstone and sandstone of the Brule Formation of Oligocene age yield highly variable volumes of water; yields are greatest where the beds have been fractured. Valley-fill and dune deposits of Quaternary age are hydraulically connected to the aquifers in Tertiary rocks and are included in the High Plains aquifer system. These permeable deposits are important recharge areas because they readily absorb and temporarily store precipitation before it percolates downward to recharge underlying permeable beds. Except for the dune sands, which were deposited by wind, all the rocks and deposits that compose the High Plains aquifer system were deposited by streams. The streams probably were braided streams that flowed eastward from the Rocky Mountains and constantly shifted their channels across a broad plain that sloped gently to the east.

Depth to water in the High Plains aquifer system ranges from less than 50 to almost 300 feet (**fig. 45**). Depth to water in the aquifer system in late winter and early spring 1980 generally was less than 200 feet below land surface in South Dakota and Wyoming. Locally in South Dakota the depth to water was less than 50 feet below land surface. The map in **figure 45** represents the shallowest depth to water during 1980 because the water levels used to construct the map were measured during the time of year when precipitation is greatest and evaporation and the use of water by plants is least.

Recharge enters the aquifer system as direct infiltration of precipitation and as seepage through the beds of streams or from irrigated land. Recharge is rapid where the surficial material consists of dune sand, stream-valley deposits of sand and gravel, or highly weathered sediments and is slower where sandstone or local beds of fine-grained sediments are at the land surface. Discharge is by the movement of water to streams, evapotranspiration, and withdrawal from wells. The thickness of saturated aquifer material (**fig. 46**) represents the vertical distance between the water table and the base of the aquifer system and reflects the balance between recharge and discharge at a given time. The saturated-thickness map shown in **figure 46** is for the late winter and early spring months of 1980 and probably represents the maximum saturated thickness for that year. Saturated thickness ranged from zero at the boundary of the aquifer system to more than 600 feet in local areas in Wyoming, and more than 400 feet in places in South Dakota. In most places, saturated aquifer material was less than 400 feet thick. Although the volume of water in the saturated aquifer material in South Dakota and Wyoming in 1980 was more than 1.6 billion acre-feet (1 acre-foot is the volume of water that will cover 1 acre of land surface to a depth of 1 foot), this does not mean that all the water can be withdrawn by wells. The hydraulic characteristics of the High Plains aquifer system are such that only about 130 million acre-feet, or about 8 percent of the water in the saturated aquifer material, can be withdrawn. Even though the volume of 1.6 billion acre-feet of saturated material in South Dakota and Wyoming seems large, this represents only about 7 percent of the saturated volume of material in the aquifer system. The remaining 93 percent is in the vast part of the system that extends southward as far as Texas.

Water in the High Plains aquifer system generally moves from west to east but locally moves from south to north (**fig. 47**). Much of the water is under unconfined conditions, but clay beds and lenses of other fine-grained materials locally create confined conditions. The hydraulic head in the aquifer system is greatest near Cheyenne, Wyo. (**fig. 47**), and least in south-central South Dakota. The water moves eastward at an estimated average velocity of about 1 foot per day.

The hydraulic conductivity of the High Plains aquifer system (**fig. 48**) varies little in South Dakota and Wyoming. Hydraulic conductivity is a measure of the rate at which water will pass through an aquifer and is directly related to the permeability of the aquifer. The greater the hydraulic conductivity value, the easier water is able to move through the aquifer (or, the higher the permeability of the aquifer). Well yields are directly related to hydraulic conductivity; the greater the hydraulic conductivity, the larger the yields of wells completed in a given thickness of the aquifer. The lithology of the aquifer is the property that most directly affects hydraulic conductivity. Coarse-grained, well-sorted sand, for example, has a high hydraulic conductivity, whereas sediments with much admixed or interbedded clay do not. The different geologic formations that compose the High Plains aquifer system vary somewhat in lithology and, therefore, their hydraulic conductivity and the yields of wells completed in them also vary. The Brule Formation usually is the least productive part of the aquifer system, and high-capacity wells completed in the Brule typically yield less than 300 gallons per minute. However, wells completed in the Brule where it is fractured, as in southeasternmost Wyoming, have been reported to yield as much as 1,500 gallons per minute. The Arikaree Formation yields slightly more water, with average high-capacity well yields of about 350 gallons per minute and maximum yields of about 600 gallons per minute reported. Yields of high-capacity wells completed in the Ogallala Formation commonly are 1,000 gallons per minute. Well yields that range from 250 to 750 gallons per minute can be expected from the High Plains aquifer system throughout about 80 percent of its extent in South Dakota and Wyoming.

The quality of the water in the High Plains aquifer system in South Dakota and Wyoming is suitable for most uses practically everywhere. Locally, dissolved-solids concentrations in the water exceed the 500-milligram-per-liter secondary maximum contaminant level recommended for drinking water by the U.S. Environmental Protection Agency. In much of South Dakota and in small areas south of the North Platte River in Wyoming, the water contains sodium concentrations that range from 50 to 100 milligrams per liter. Continued application of irrigation water with large concentrations of sodium can adversely affect some plants and can decrease soil permeability, but neither effect has been observed in Segment 8 at present (1996). In some areas in South Dakota, selenium concentrations in the water exceed the drinking-water standard of 10 micrograms per liter. Selenium concentrations are greatest in areas where the High Plains aquifer system directly overlies the Pierre Shale; the selenium is leached from the shale by ground water.

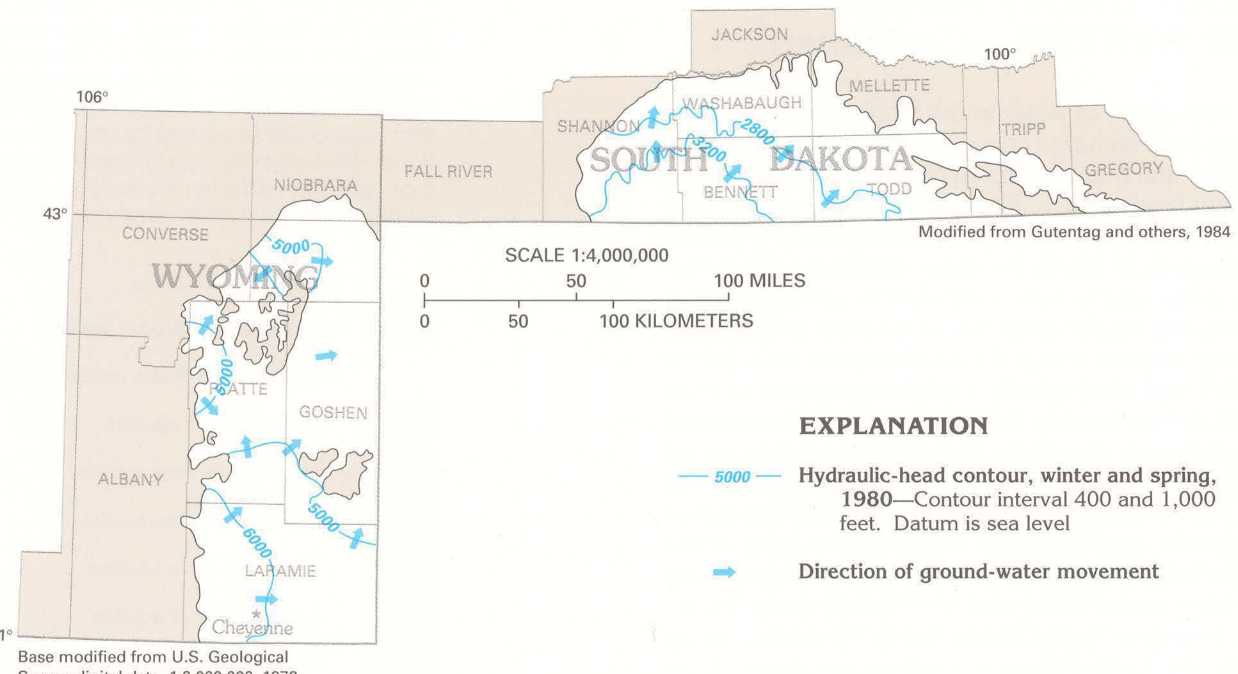


Figure 47. Hydraulic head in the High Plains aquifer system is highest in southeastern Wyoming. The water in the aquifer system generally moves eastward toward areas of lower head.

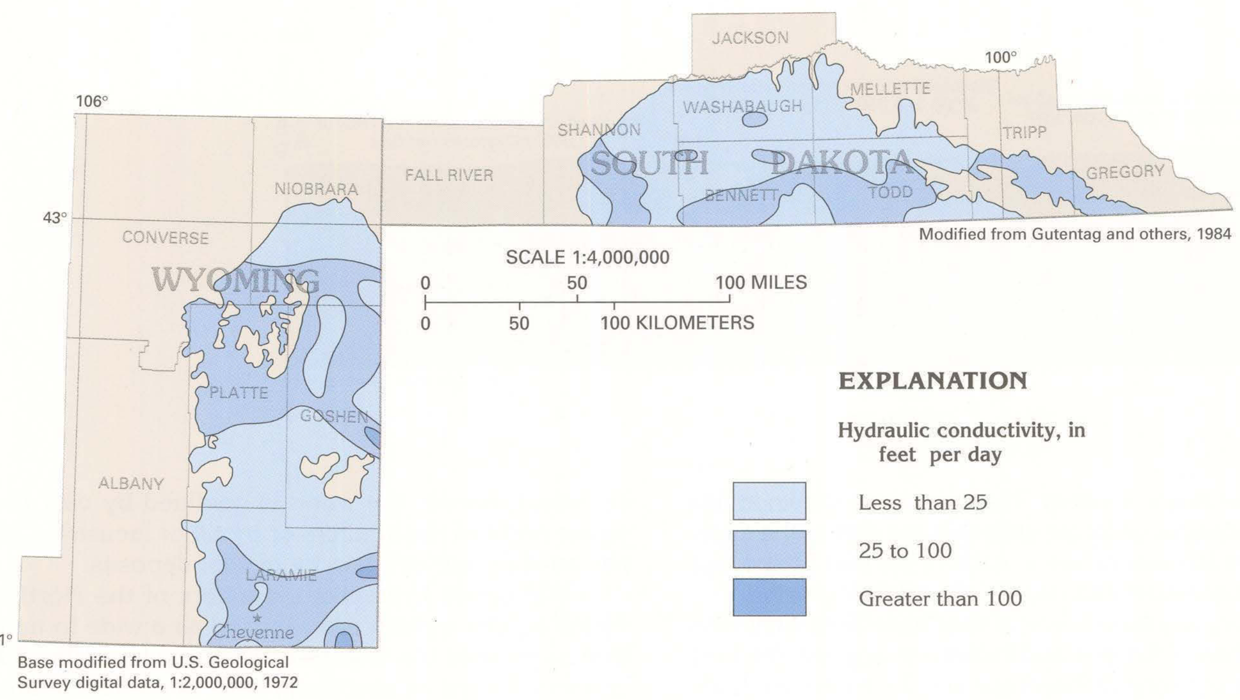


Figure 48. The hydraulic conductivity of the High Plains aquifer system in South Dakota and Wyoming is greater where the system contains more sand and gravel and, thus, is more permeable.

NORTHERN GREAT PLAINS AQUIFER SYSTEM

The Northern Great Plains aquifer system underlies most of North Dakota and South Dakota, about one-half of Montana, and about one-third of Wyoming (**fig. 49**). The aquifer system is mostly within the Williston Basin, which is a large structural trough that extends from Montana into North Dakota, South Dakota, and Canada; the Powder River Basin in northeastern Wyoming; and areas of structural uplifts that flank these basins. The Canadian part of the aquifer system is not described in this report. The United States part of the aquifer system extends over about 300,000 square miles, all of which is within Segment 8 except for a small area in northwestern Nebraska.

The major aquifers of the Northern Great Plains aquifer system are sandstones of Tertiary and Cretaceous age and carbonate rocks of Paleozoic age (**fig. 50**). These aquifers, along with regional confining units that separate some of them, form one of the largest confined aquifer systems in the United States. In some places, local confining units separate the major aquifers into smaller, individual aquifers, but each major aquifer can be treated regionally as a single, large aquifer. Unconsolidated glacial and alluvial deposits of Quaternary age, some of which are highly permeable, locally overlie the aquifer system, but are not included in it because the shallow ground-water flow system in these deposits is very different from the deep, confined flow in the Northern Great Plains aquifer system. Crystalline rocks that underlie the aquifer system yield little water and are considered to be the base of the system. Open spaces in the sandstone aquifers are mostly pores between individual sand grains, but local larger openings include bedding planes, fractures, or faults. By contrast, large open spaces are common in carbonate rocks (**fig. 51**) where part of the rock has been dissolved by circulating ground water. Water moves freely through the dissolution openings, and carbonate rocks accordingly form high-yielding aquifers in many places.

Era	System, Series, and other subdivisions	Powder River Basin (Wyoming and Montana)	Williston Basin (Montana, North Dakota, and South Dakota)	Hydrologic unit: RASA study 5/	Hydrologic unit: This report	Principal lithology
Cenozoic	Quaternary	Alluvium	Alluvium and glacial deposits	Not included in aquifer system	Not included in aquifer system	
	Tertiary, Upper: Pliocene					
	Tertiary, Upper: Miocene					
	Tertiary, Lower: Oligocene	White River Formation	White River Formation or Group			
	Tertiary, Lower: Eocene	Wasatch Formation		Northern Great Plains aquifer system: Upper Cretaceous aquifer	Northern Great Plains aquifer system: Lower Tertiary aquifers	Sandstone, some siltstone
	Tertiary, Lower: Paleocene	Fort Union Formation	Fort Union Formation or Group			Sandstone, some coal
Mesozoic	Cretaceous, Upper	Lance Formation	Hell Creek Formation		Upper Cretaceous aquifers	Sandstone, some claystone, siltstone and coal
		Fox Hills Sandstone	Fox Hills Sandstone			
		Lewis Shale	Pierre Shale	Confining layer	Confining unit	Shale, some chalk, some bentonite. Minor sandstone
		Mesaverde Formation				
		Steele Shale	Niobrara Formation			
		Cody Shale 1/	Carlile Shale			
		Frontier Formation	Greenhorn Formation			
			Belle Fourche Shale			
		Mowry Shale	Mowry Shale			Shale
	Cretaceous, Lower	Muddy Sandstone	Newcastle/Dakota Sandstone 2/	Lower Cretaceous aquifer	Lower Cretaceous aquifers	Sandstone
		Thermopolis Shale	Skull Creek Shale			Shale
		Inyan Kara Group: Fall River Formation	Inyan Kara Group: Fall River Sandstone			Sandstone. Minor conglomerate and silty shale
			Inyan Kara Group: Fuson Formation			
		Inyan Kara Group: Lakota Formation	Inyan Kara Group: Lakota Formation			
	Jurassic	Morrison Formation	Morrison Formation	Confining layer	Confining unit	Shale and silty shale with interbedded sandstone
		Sundance Formation 3/	Swift Formation 3/			
			Rierdon Formation 3/			
		Gypsum Spring Formation	Piper Formation 3/			Shale and limestone
	Triassic	Chugwater Formation				Shale and siltstone
Paleozoic	Permian	Goose Egg Formation	Spearfish Formation			
			Minnekahta Limestone			
			Opeche Formation			
	Pennsylvanian	Tensleep 4/ Sandstone; Minnelusa 4/ Formation	Amsden Formation; Minnelusa 4/ Formation	Pennsylvanian aquifer system		Interbedded sandstone, shale and carbonate rocks. Minor anhydrite
		Amsden Formation	Tyler Formation			Shale and sandstone
	Mississippian		Big Snowy Group	Confining layer		Shale with some sandstone
		Madison Limestone	Madison Group: Charles Formation	Mississippian aquifer	Upper 6/ Paleozoic aquifers	Limestone, dolomite, and minor anhydrite
			Madison Group: Mission Canyon Limestone			
			Madison Group: Lodgepole Limestone			
			Bakken Formation	Confining layer	Confining unit	Shale and siltstone
	Devonian	Darby Formation and equivalents	Three Forks Formation through Ashern Formation			Shale, shaly limestone, some evaporite beds and salt
	Silurian		Interlake Formation			Shaly limestone
	Ordovician	Bighorn Dolomite; Whitewood Dolomite	Stonewall Formation	Cambrian-Ordovician aquifer	Lower 6/ Paleozoic aquifers	Limestone, shaly limestone
			Red River Formation			Limestone and dolomite
		Harding Sandstone; Winnipeg Formation	Winnipeg Formation or Group			Shale, sandstone, and shaly limestone
	Cambrian	Gallatin Limestone	Deadwood Formation			Sandstone, dolomitic limestone, and shale
		Gros Ventre Formation				
		Flathead Sandstone				Sandstone

1/ Equivalent in part to Judith River Formation and Eagle Sandstone in Central Montana
2/ Locally extends into Upper Cretaceous
3/ Included in Lower Cretaceous aquifers of this report, where permeable
4/ Included in Upper Paleozoic aquifers of this report, where permeable
5/ Downey and Dinwiddie, 1988
6/ Not differentiated in figure 49

Modified from Downey and Dinwiddie, 1988; and Love and others, 1993

Figure 50. Numerous geologic units are part of the Northern Great Plains aquifer system, but only beds of sandstone and carbonate rocks form aquifers. The gray areas represent missing rocks.

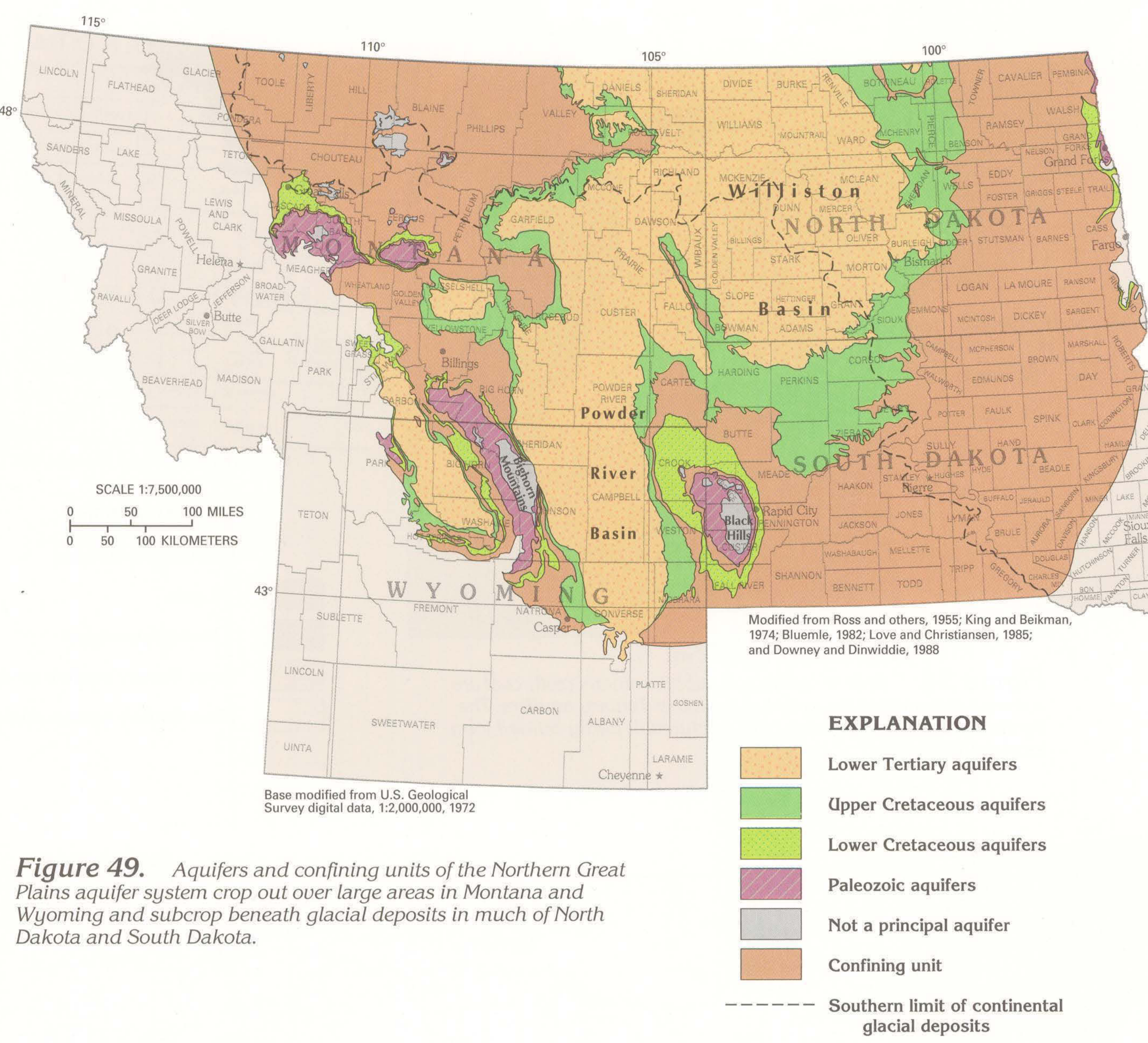


Figure 49. Aquifers and confining units of the Northern Great Plains aquifer system crop out over large areas in Montana and Wyoming and subcrop beneath glacial deposits in much of North Dakota and South Dakota.

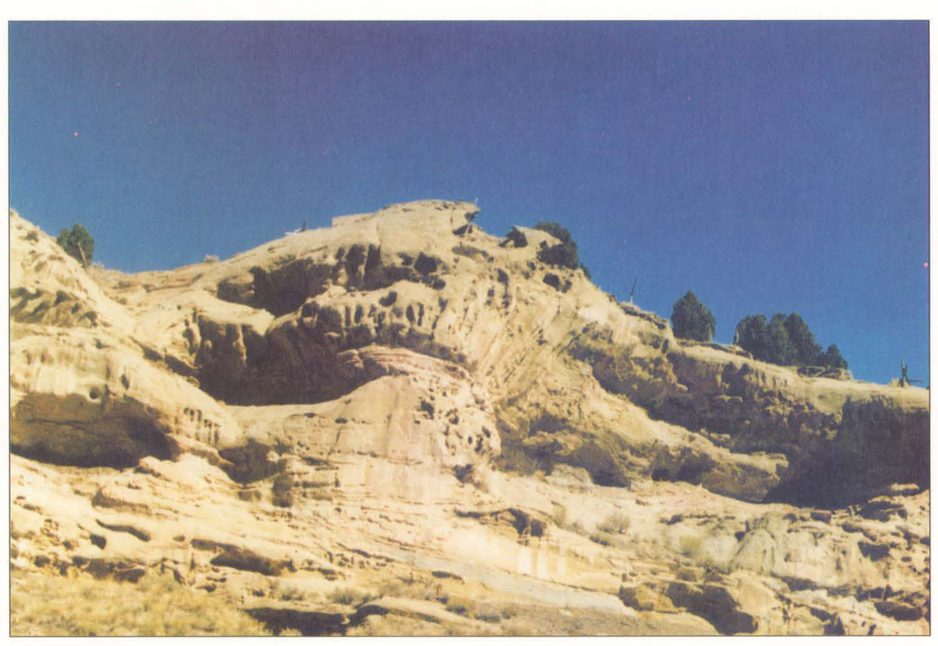


Figure 51. Large solution openings, which are produced when part of the rock is dissolved by ground water, are common in carbonate rocks. These openings store and transmit large quantities of water.

Regional movement of water in the Northern Great Plains aquifer system is from recharge areas at high altitudes, down the dip of the aquifers and then upward to discharge into shallower aquifers or to the land surface. Much of the water moves into and through the Powder River and the Williston Basins (**fig. 52**). The regional direction of flow in the deep, confined aquifers follows long flow paths and is from southwest to northeast. Most of the recharge to the aquifer system is either from precipitation that falls on outcrop areas where the aquifers have been folded or faulted upward and subsequently exposed by erosion or from snowmelt that runs into streams that cross aquifer outcrops and seeps downward through the stream beds into the aquifers. Some local recharge is by seepage of excess irrigation water. Much of the discharge from the aquifer system is by upward leakage of water into shallower aquifers where the hydraulic head in the shallower aquifer is less than that of a deeper aquifer. Some water discharges to lakes and streams near the North Dakota/Minnesota State line. In eastern North Dakota, highly mineralized water discharges from the lower Paleozoic aquifers by upward leakage through confining units into overlying unconsolidated deposits that are mostly till and glacial-lake sediments (**fig. 53**). Some of this saline water moves through permeable parts of the unconsolidated deposits into lakes, streams, and wetlands that are in depressions. Where confining units are absent, the saline water can move directly from the lower Paleozoic aquifers into the unconsolidated deposits and then into streams as shown near the right side of **figure 53**. Some discharge from the Northern Great Plains aquifer system also is by withdrawals from wells or from flowing wells in places where artesian pressure is sufficient to allow water in confined aquifers to rise above the land surface. Some of the saline water in the soils, lakes, and streams of northeastern North Dakota has reached the surface through flowing wells.

Local ground-water flow systems are in aquifer outcrop areas or where unconsolidated-deposit aquifers overlie the Northern Great Plains aquifer system. Much of the water that enters the aquifers where they crop out moves along short flow paths and discharges to small streams or springs. Where the Northern Great Plains aquifers are covered by a thin layer of unconsolidated deposits, water percolates downward through the permeable parts of the deposits to recharge the underlying aquifers in consolidated rocks (**fig. 52**). The water moves along short to intermediate-length flow paths and discharges to large streams, such as the Missouri River. The upper two aquifers of the Northern Great Plains aquifer system are characterized by local flow systems.

The permeable rocks of the Northern Great Plains aquifer system have been grouped into five major aquifers. From shallowest to deepest, these are lower Tertiary, upper Cretaceous, lower Cretaceous, upper Paleozoic, and lower Paleozoic aquifers (**fig. 50**). All or parts of several geologic formations are included in each of the five major aquifers. The formations shown in **figure 50** are the principal geologic units that are part of the aquifer system. Other formations are in each of the four States, but are mostly of local extent and usually are confining units.

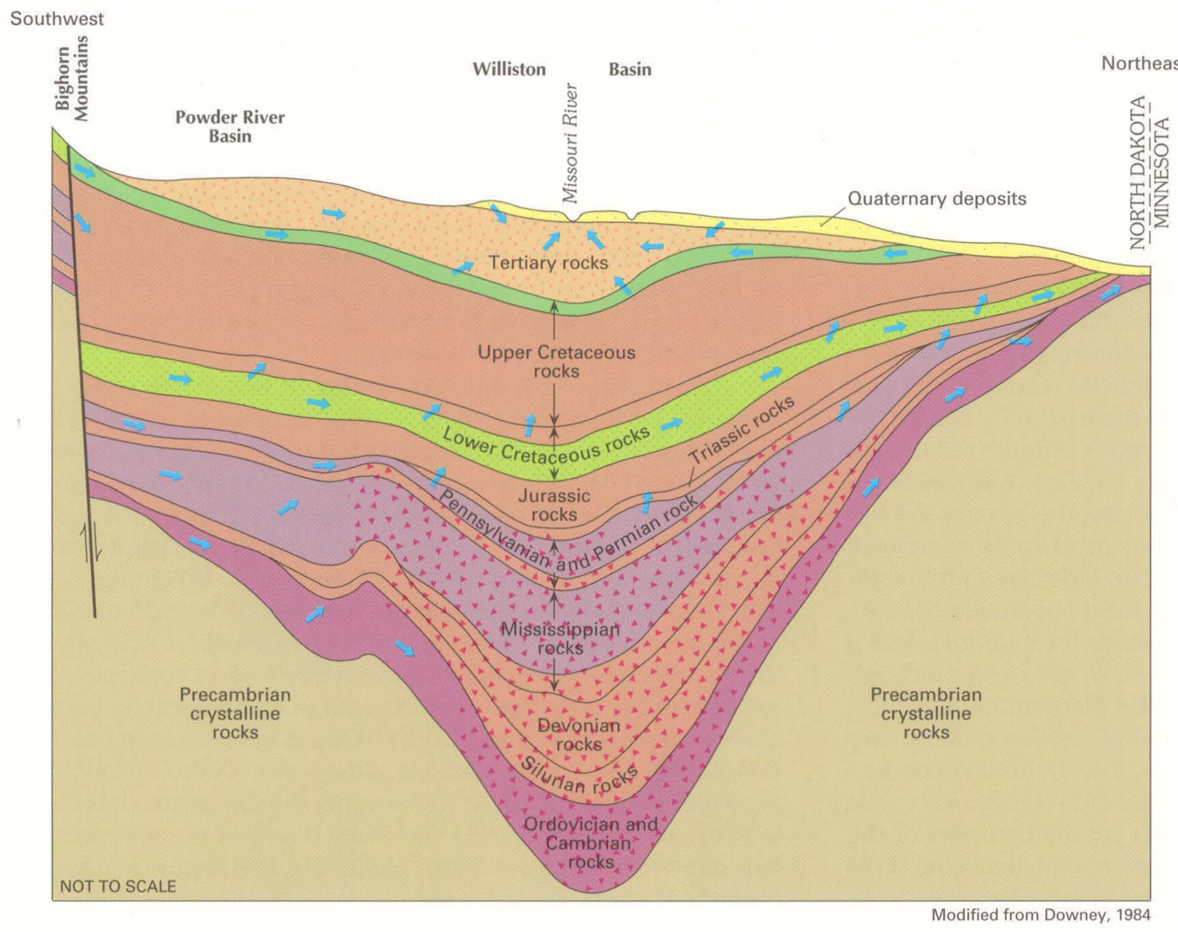


Figure 52. *A diagrammatic section shows that regional ground-water movement in the deep, confined aquifers is northeastward from aquifer outcrop areas through the Powder River and the Williston Basins to discharge areas in eastern North Dakota. Water discharges upward from deep aquifers that have high artesian pressure to shallow aquifers that have lower pressure.*

EXPLANATION

- Unconsolidated-deposit aquifers
- **Northern Great Plains aquifer system**
  - Lower Tertiary aquifers
  - Upper Cretaceous aquifers
  - Lower Cretaceous aquifers
  - Upper Paleozoic aquifers
  - Lower Paleozoic aquifers
  - Confining unit
- Brine with dissolved-solids concentrations greater than 100,000 milligrams per liter
- Direction of ground-water movement
- Fault—Arrows indicate relative vertical movement

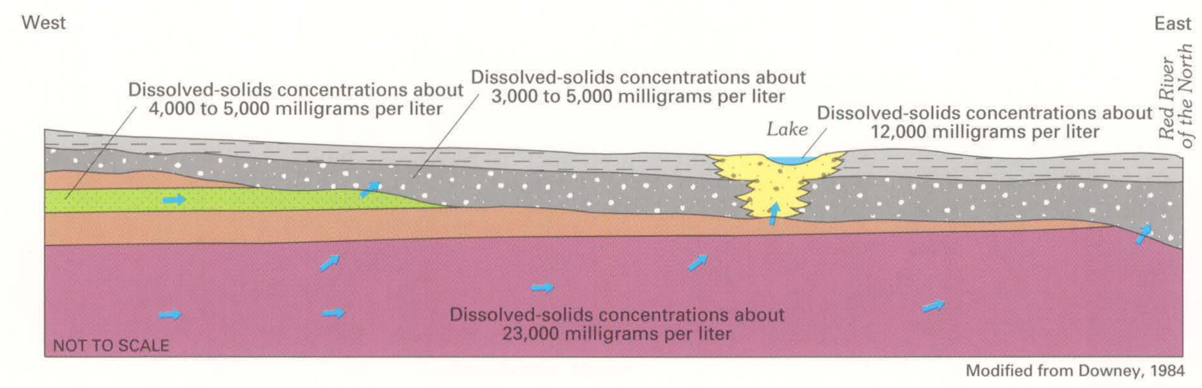


Figure 53. *In eastern North Dakota, saline water in deep, confined aquifers is under artesian pressure and can move upward into unconsolidated deposits. Saline lakes or seeps can form in depressions where the unconsolidated deposits are permeable.*

EXPLANATION

- **Unconsolidated deposits**
  - Till—Permeable to almost impermeable
  - Glacial lake deposits— Almost impermeable
  - Fine sand and gravel—Permeable
- **Northern Great Plains aquifer system**
  - Lower Cretaceous aquifers
  - Lower Paleozoic aquifers
  - Confining unit
- Direction of ground-water movement

Lower Tertiary aquifers consist of sandstone beds within the Wasatch Formation of Eocene and Paleocene age and the Fort Union Formation or Group of Paleocene age. Both geologic units were deposited primarily in continental environments and consist of alternating beds of sandstone, siltstone, and claystone; both commonly contain beds of lignite and subbituminous coal (**fig. 54**). The area of the coal beds is known as the Fort Union coal region and contains a major part of the Nation's reserves of coal. The lignite or coal beds that have been fractured or partially burned after being ignited by lightning or wildfires form local aquifers. Most water in the lower Tertiary aquifers, however, is stored in and moves through the sandstone beds.

The thickness of the formations that compose the lower Tertiary aquifers is variable. The Fort Union Formation is as much as 3,600 feet thick in the Powder River Basin, but the Fort Union Group is much thinner in the Williston Basin. In northeastern Montana and western North Dakota, for example, the Fort Union is only about 300 feet thick. The thickness of permeable sandstone in the Fort Union in both basins, however, is much less than that of the formation. The sandstone beds of the Fort Union are more coarse grained and permeable in the Powder River Basin than the Williston Basin. The Wasatch Formation, which is only in the Powder River Basin, is as much as 1,000 feet thick. Not all the beds in the Wasatch yield water; like the Fort Union, most permeable beds in the Wasatch are sandstones.

A map of the potentiometric surface of the lower Tertiary aquifers indicates the general movement of water is northward and northeastward from recharge areas in northeastern Wyoming, eastern Montana, and southwestern North Dakota (**fig. 55**). The water-level measurements used to construct this map are mostly from wells completed in the Wasatch Formation in Wyoming and the Fort Union Formation or Group elsewhere. The complex shape of the potentiometric contours is partly the result of topography; the higher altitudes of the potentiometric surface generally correspond to higher altitudes of the land surface. Some of the complexity, however, results from the influence of major streams, such as the Yellowstone and the Missouri Rivers. These streams are discharge areas for the lower Tertiary aquifers and coincide with low areas of the potentiometric surface. Water in the lower Tertiary aquifers commonly is under unconfined conditions. Locally, however, the water is confined by clay beds in the upper parts of the aquifers or by till or lacustrine clay where the aquifers are overlain by glacial deposits.

The upper Cretaceous aquifers of the Northern Great Plains aquifer system are exposed as a wide to narrow band that surrounds the lower Tertiary aquifers (**fig. 49**). These aquifers consist of sandstone beds in the Lance and the Hell Creek Formations and the Fox Hills Sandstone (**fig. 50**). The Lance Formation and the equivalent Hell Creek Formation range in thickness from about 350 to 3,400 feet. Both formations consist of interbedded sandstone, siltstone, claystone, and local thin beds of coal or lignite, all of which were deposited in a continental environment. The underlying Fox Hills Sandstone ranges from about 300 to 450 feet thick and is one of the most continuous water-yielding formations in the aquifer system. The Fox Hills consists primarily of sandstone that was deposited mostly in a deltaic to marine environment and contains local beds of siltstone and shale.

The shape of the potentiometric surface of the upper Cretaceous aquifers (**fig. 56**) closely resembles that of the overlying lower Tertiary aquifers (compare **figs. 55 and 56**). Water in the upper Cretaceous aquifers moves from aquifer recharge areas at higher altitudes toward discharge areas along major rivers where the potentiometric surface is lower. As shown by the arrows in **figure 56**, the general movement of water is northward in the Powder River Basin and northeastward in the Williston Basin. The complex shape of the potentiometric-surface contours indicates that the water in most places is under unconfined conditions. Because the shape of the water table generally conforms to that of the land surface, local high areas of the potentiometric surface correspond to high areas of the land surface. Likewise, the influence of major streams is reflected by low areas of the potentiometric surface.

The altitude of the potentiometric surface of the upper Cretaceous aquifers is similar to that of the overlying lower Tertiary aquifers in eastern Montana and western North Dakota and South Dakota (compare **figs. 55 and 56**). In these areas, no continuous confining unit separates the two groups of aquifers and water moves freely between the aquifers. By contrast, in Wyoming and parts of central Montana, the potentiometric surface of the lower Tertiary aquifers is as much as 400 feet higher than that of the upper Cretaceous aquifers, which indicates that confining units separate the aquifers. Under these conditions, some water probably leaks downward from the lower Tertiary aquifers through the confining units to recharge the upper Cretaceous aquifers.

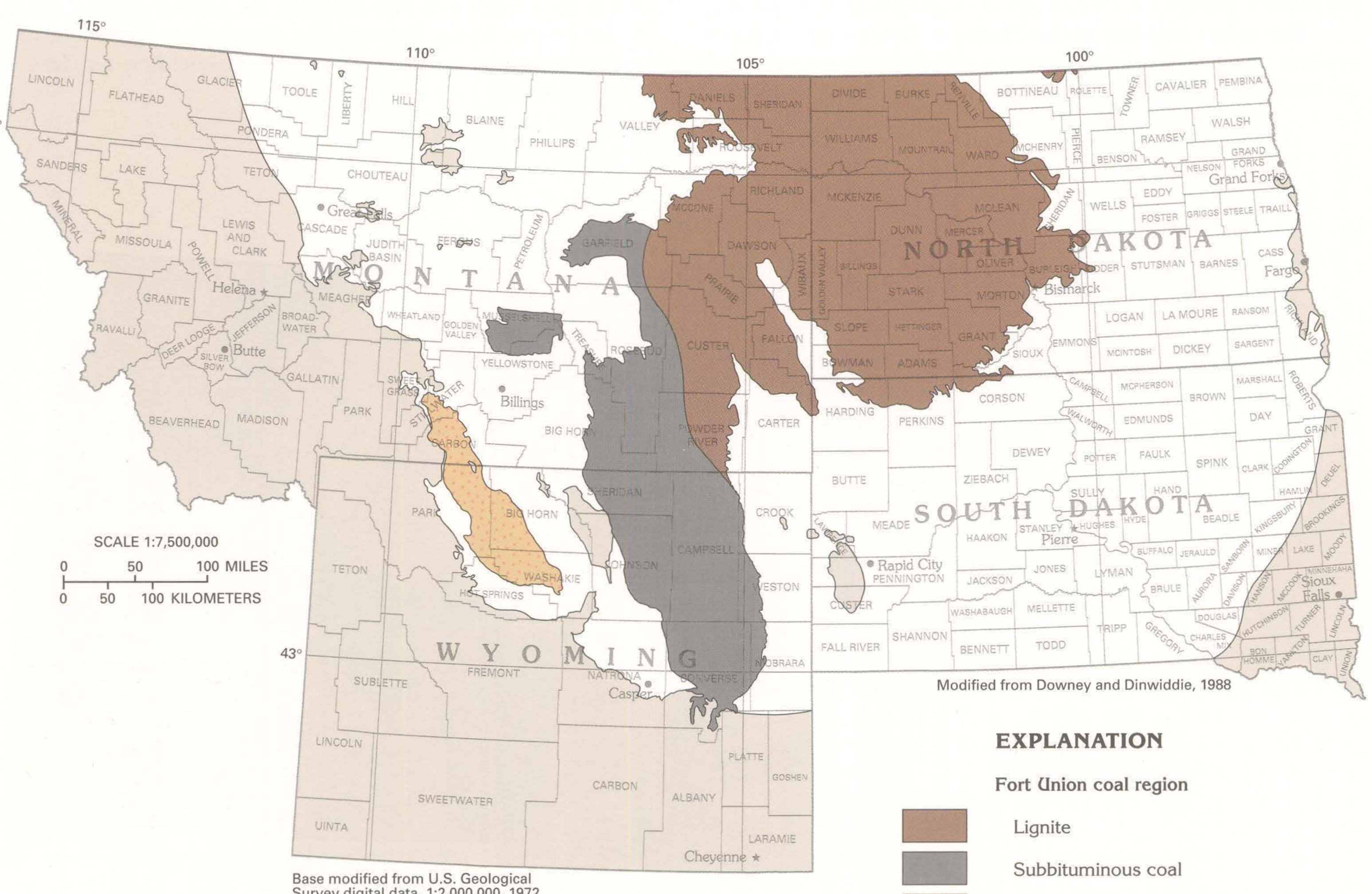


Figure 54. *Beds of lignite and subbituminous (soft) coal are common throughout the extent of the lower Tertiary aquifers. The lignite or coal beds that have been fractured or partly burned form local aquifers.*

EXPLANATION

- **Fort Union coal region**
  - Lignite
  - Subbituminous coal
- Lower Tertiary aquifers outside coal region
- Lower Tertiary aquifers absent

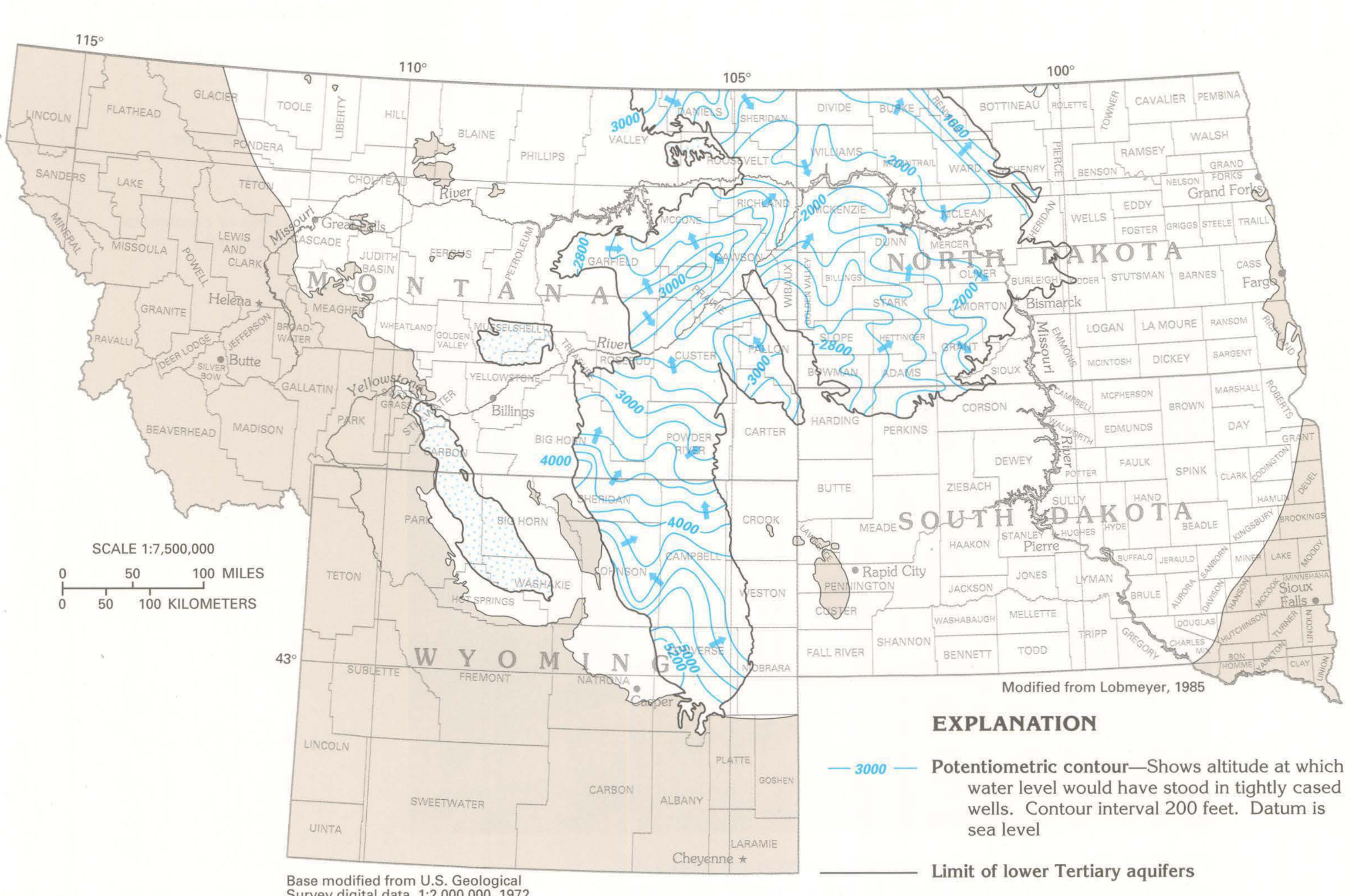


Figure 55. *Water in the lower Tertiary aquifers generally moves northward and northeastward from recharge areas at higher altitudes. The regional trend of movement changes locally where the aquifer discharges water to large streams.*

EXPLANATION

- 3000 — Potentiometric contour—Shows altitude at which water level would have stood in tightly cased wells. Contour interval 200 feet. Datum is sea level
- Limit of lower Tertiary aquifers
- Direction of ground-water movement
- No data

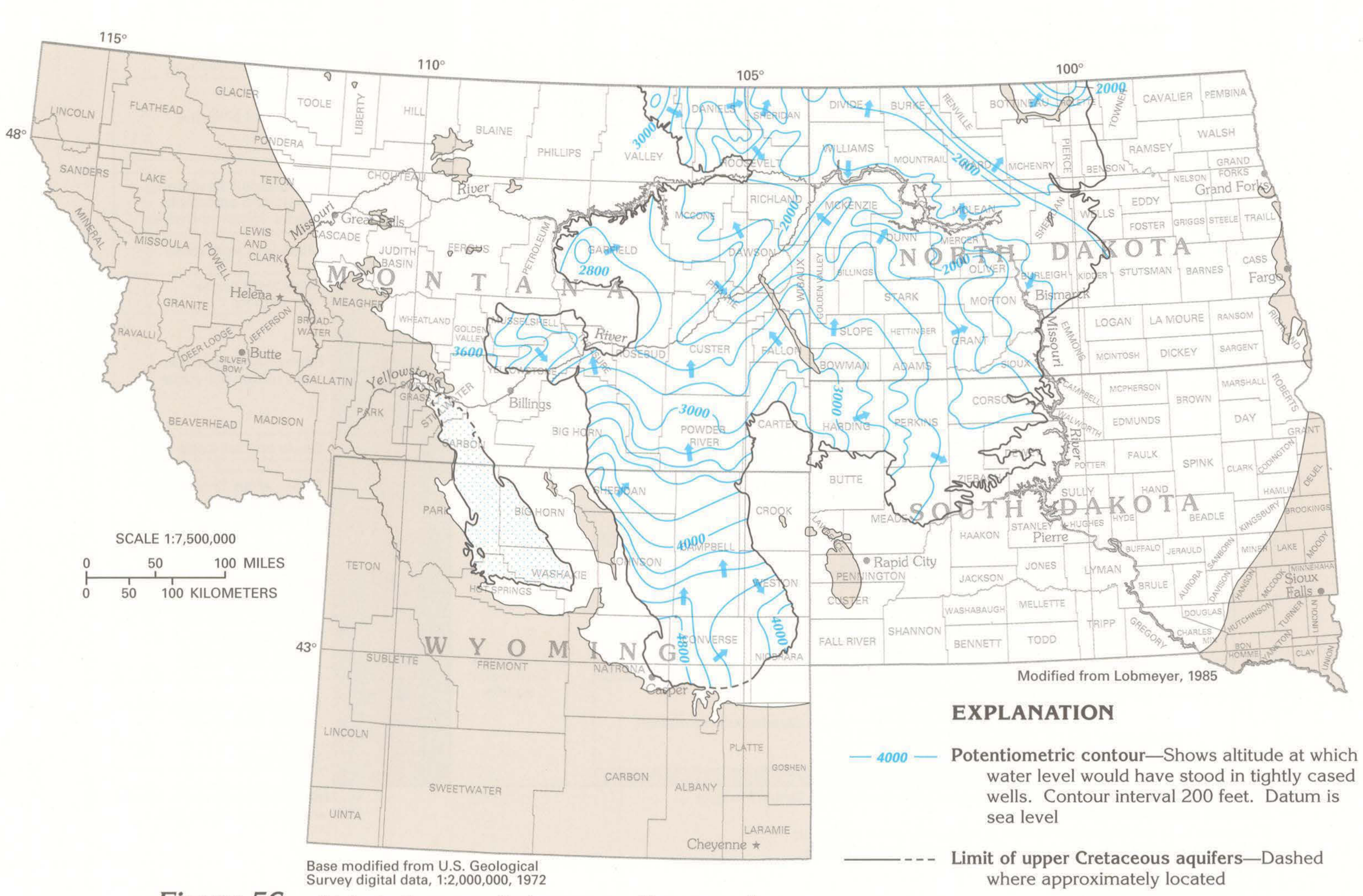


Figure 56. *Water in the upper Cretaceous aquifers generally moves northward in Wyoming and northeastward elsewhere. Regional movement is from aquifer recharge areas at higher altitudes toward low-lying major streams.*

EXPLANATION

- 4000 — Potentiometric contour—Shows altitude at which water level would have stood in tightly cased wells. Contour interval 200 feet. Datum is sea level
- Limit of upper Cretaceous aquifers—Dashed where approximately located
- Direction of ground-water movement
- No data

Water in the upper Cretaceous aquifers contains less than 3,000 milligrams per liter dissolved solids everywhere except for small areas in North Dakota and South Dakota where concentrations are as large as 10,000 milligrams per liter (**fig. 57**). Water with dissolved-solids concentrations of less than 1,000 milligrams per liter is mostly near the Black Hills Uplift and in smaller areas near the boundaries of the aquifers. The major dissolved ions in water from the upper Cretaceous aquifers are sodium, sulfate, and bicarbonate; locally, calcium and magnesium are dominant. In the small area in North Dakota where water in the upper Cretaceous aquifers contains more than 3,000 milligrams per liter dissolved solids, however, the water is a sodium chloride type. Even though the water contains dissolved-solids concentrations of less than 3,000 milligrams per liter in most places, large sodium concentrations make the water unsuitable for irrigation. Water from the upper Cretaceous aquifers provides domestic and livestock-watering supplies in large parts of Segment 8 and is the source of supply for several small communities in southeastern Montana and northwestern South Dakota.

The lower Cretaceous aquifers are separated from the overlying upper Cretaceous aquifers by several thick shales that form an effective confining unit. The Pierre Shale and its partial equivalents, the Lewis and the Steele Shales (**fig. 50**), are the thickest and most extensive formations of the confining unit. The Pierre Shale is as much as 3,000 feet thick in places and is the principal confining unit in North Dakota and South Dakota (**fig. 49**). Although thin sandstones are interbedded with the shales of the confining unit, the sandstones yield little water. Locally, they provide sufficient water for domestic supplies, but the water generally is highly mineralized. Recent studies indicate that water in storage in the Pierre Shale provides some recharge to the underlying upper Cretaceous aquifers, particularly where the shale is fractured.

Several sandstones compose the lower Cretaceous aquifers of the Northern Great Plains aquifer system (**fig. 50**). The principal water-yielding units are the Newcastle Sandstone (also called the Dakota Sandstone) and the Inyan Kara Group in the Williston Basin, and the Muddy Sandstone and the Inyan Kara Group in the Powder River Basin. The Fuson and the Lakota Formations cannot be separated in the southwestern part of the Powder River Basin where they are collectively mapped as the Inyan Kara Group. Locally, permeable parts of the Sundance, the Swift, the Rierdon, and the Piper Formations of Jurassic age yield small to moderate quantities of water to wells. These local aquifers in Jurassic rocks are included in the lower Cretaceous aquifers in this report.

The Newcastle Sandstone is only a few tens of feet thick where it crops out on the flanks of the Black Hills Uplift, but its subsurface equivalent, the Dakota Sandstone, is more than 400 feet thick in southeastern South Dakota. The Newcastle (or Dakota) Sandstone is absent in much of North Dakota, and the thickness of the Muddy Sandstone, which is its equivalent in Montana and Wyoming, is a few tens of feet. In many places, the Skull Creek Shale separates the Newcastle Sandstone from sandstones of the underlying Inyan Kara Group. The Inyan Kara Group is about 700 feet thick in central Montana, but the group merges eastward into the lower part of the Dakota Sandstone in eastern North Dakota and South Dakota. Most of the water-yielding sandstones included in the lower Cretaceous aquifers are of fluvial or deltaic origin.

Water in the lower Cretaceous aquifers is confined except in aquifer outcrop areas that encircle structural uplifts, such as the Black Hills Uplift and the Bighorn Mountains (**fig. 49**). In eastern North Dakota and South Dakota, the aquifers contain water under confined to semiconfined conditions; poorly permeable till and glacial-lake deposits overlie the aquifers in these areas. The lower Cretaceous aquifers contain water with dissolved-solids concentrations of greater than 3,000 milligrams per liter in most of North Dakota, because the water has moved along flow paths hundreds of miles long, has been in contact with aquifer minerals for a long time, and has partially dissolved the mineral material. Isotopic dating of water in these aquifers near their easternmost extent in South Dakota indicates that water locally entered the aquifers during Pleistocene glaciation.

The general movement of water in the lower Cretaceous aquifers is northeastward from aquifer recharge areas at high altitudes to discharge areas in eastern North Dakota and South Dakota (**fig. 58**). The closely spaced contours near the structural uplifts in the western parts of the aquifer represent steep hydraulic gradients. As indicated by the widely spaced contours, the hydraulic gradient is much flatter in the Williston Basin where the aquifers are deeply buried and are as much as 10,000 feet below the land surface. The hydraulic gradient becomes slightly steeper in eastern North Dakota near aquifer discharge areas. The potentiometric surface of the lower Cretaceous aquifers is not as irregular as that of the lower Tertiary or upper Cretaceous aquifers (compare **figs. 55, 56, and 58**). This is because the lower Cretaceous aquifers generally are overlain by a thick, effective confining unit and do not discharge to streams except locally. The depressions in the potentiometric surface of the lower Cretaceous aquifers in eastern and southeastern Montana might be the result of petroleum withdrawal from deep oil reservoirs in these areas. When the oil is pumped from underlying geologic formations, pressure on the oil reservoir decreases. As a result, water might leak downward from the lower Cretaceous aquifers through confining units that underlie the aquifers and create an area of low hydraulic head in the aquifers. Another possibility is that the depressions represent water-level measurements from isolated sandstone beds that are not connected to the regional ground-water flow system of the lower Cretaceous aquifers.

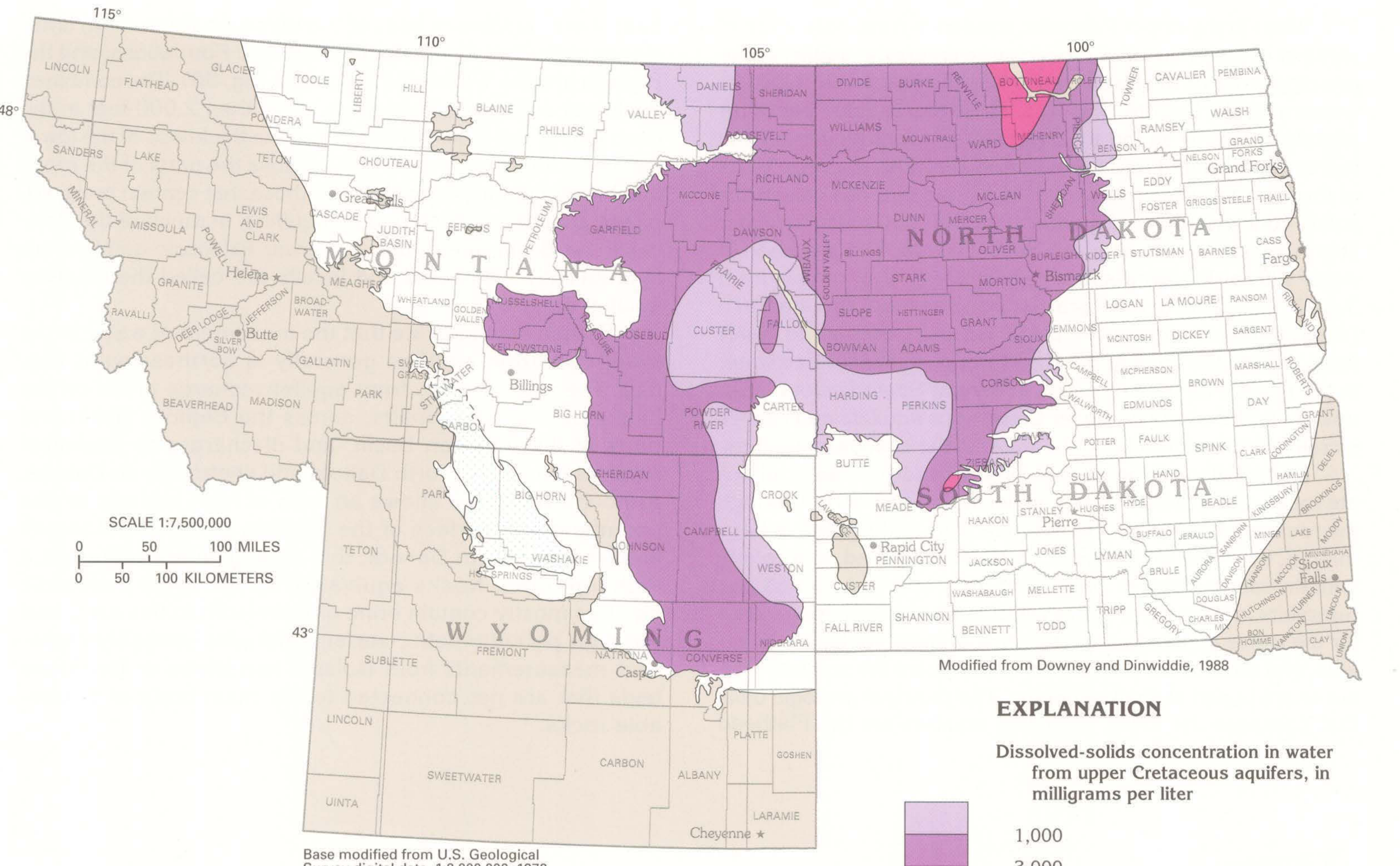


Figure 57. Water in the upper Cretaceous aquifers contains less than 3,000 milligrams per liter dissolved solids except in small areas of North Dakota and South Dakota.

EXPLANATION

Dissolved-solids concentration in water from upper Cretaceous aquifers, in milligrams per liter

1,000

3,000

No data

Aquifers absent

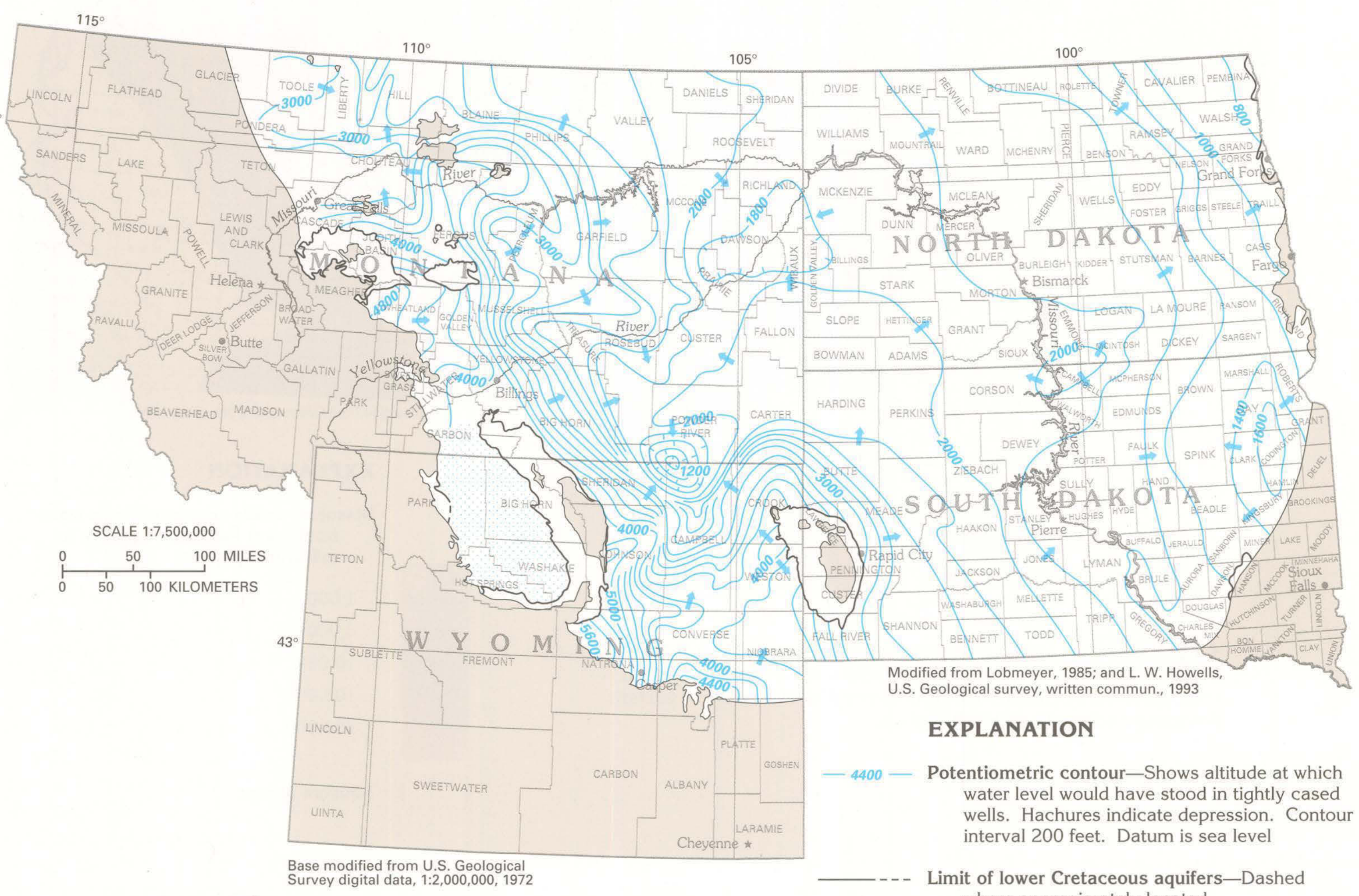
The lower Cretaceous aquifers are the most widespread aquifers in the Northern Great Plains aquifer system, but contain little freshwater (**fig. 59**). Water with dissolved-solids concentrations of less than 1,000 milligrams per liter (freshwater) is only in small areas in central and south-central Montana, and north and east of the Black Hills Uplift (**fig. 59**). Even though the water in the lower Cretaceous aquifers is slightly saline throughout most of South Dakota and a large area in southeastern North Dakota, the aquifers are the principal source of water for livestock watering and domestic supply because they are the shallowest consolidated-rock aquifers in these areas. Much of the slightly saline water is believed to result from upward leakage of highly mineralized water from underlying aquifers in Paleozoic rocks. Over about one-half of the lower Cretaceous aquifers (**fig. 59**), the water in the aquifers is moderately saline. The water is very saline or a brine in the deep parts of the Williston and the Powder River Basins.

Paleozoic aquifers in the Northern Great Plains aquifer system are divided into upper Paleozoic aquifers and lower Paleozoic aquifers (**fig. 50**). Although the Paleozoic aquifers extend over large areas of Segment 8, they are deeply buried in most places and contain little freshwater. Few water wells penetrate these aquifers, and much of what is known about them has been determined from data gathered from test holes drilled for oil and gas exploration.

Upper Paleozoic aquifers consist primarily of the Madison Limestone of Devonian and Mississippian age. In the Powder River Basin, the Madison is undivided; in the Williston Basin, however, it is separated into three formations and is called the Madison Group (**fig 50**). Sandstones of Pennsylvanian and Permian age, primarily the Tensleep Sandstone in the western parts of the Powder River Basin and sandstone beds of the Minnelusa Formation in the Williston Basin and the eastern part of the Powder River Basin, were treated as a separate aquifer by a regional study of the Northern Great Plains aquifer system. The sparse data available for the Pennsylvanian sandstones, however, show that they yield much less water than the Madison Limestone or Group, and contain freshwater only in local areas where the sandstones crop out. Pennsylvanian rocks are not considered to be a principal aquifer in this report. The Madison Limestone consists of marine limestone that contains some clay, chert, and anhydrite, and has been altered to dolomite in places. In the Williston Basin, the Lodgepole Limestone, which is the lowest formation in the Madison Group, mostly consists of limestone and dolomite beds; the overlying Mission Canyon Limestone consists of crystalline limestone with beds of dolomite and anhydrite; and the Charles Formation, which overlies the Mission Canyon Limestone in the deepest parts of the Williston Basin, chiefly consists of evaporite deposits and is a confining unit. In the subsurface, the dolomite is the most permeable rock type. The Madison Limestone or Group ranges in thickness from a featheredge at its limits to more than 2,800 feet in western North Dakota.

Where the Madison Limestone is exposed at the land surface, the carbonate rocks that compose the formation have been partly dissolved by circulating ground water. This dissolution can produce large openings in the rock, some of which become interconnected to form cave systems. Partial collapse of the roofs of the solution features create sinkholes and other types of openings that allow surface water to move into the limestone. The topography that forms where carbonate rocks contain sinkholes and caves is called karst topography. Karst features have been described in outcrop areas of the Madison Limestone in central Montana, north-central Wyoming, and western South Dakota. Several large springs issue from some of the solution conduits in the Madison. The Thermopolis hot springs system in central Wyoming discharges about 3,000 gallons per minute of geothermal water from the Madison Limestone. The water has become heated because it has circulated to great depths.

A map of the potentiometric surface of the upper Paleozoic aquifers (**fig. 60**) shows that the water moves regionally northeastward from recharge areas where the aquifers crop out adjacent to structural uplifts near the southern and western limits of the aquifer system. Locally, the water moves outward in all directions from the Black Hills Uplift and inward from all directions toward local depressions in the potentiometric surface in eastern Montana. These depressions are possibly the result of the production of oil and gas from deeper strata. Withdrawal of the oil and gas lowers the pressure in the hydrocarbon reservoir and can allow water to leak downward from the upper Paleozoic aquifers through confining units into deeper permeable zones. This leakage could locally reduce the hydraulic head in the upper Paleozoic aquifers and result in the small depressions. Water in the upper Paleozoic aquifers is confined everywhere except in recharge areas. Discharge is by upward leakage of water to the lower Cretaceous aquifers in eastern North Dakota and central South Dakota.



EXPLANATION

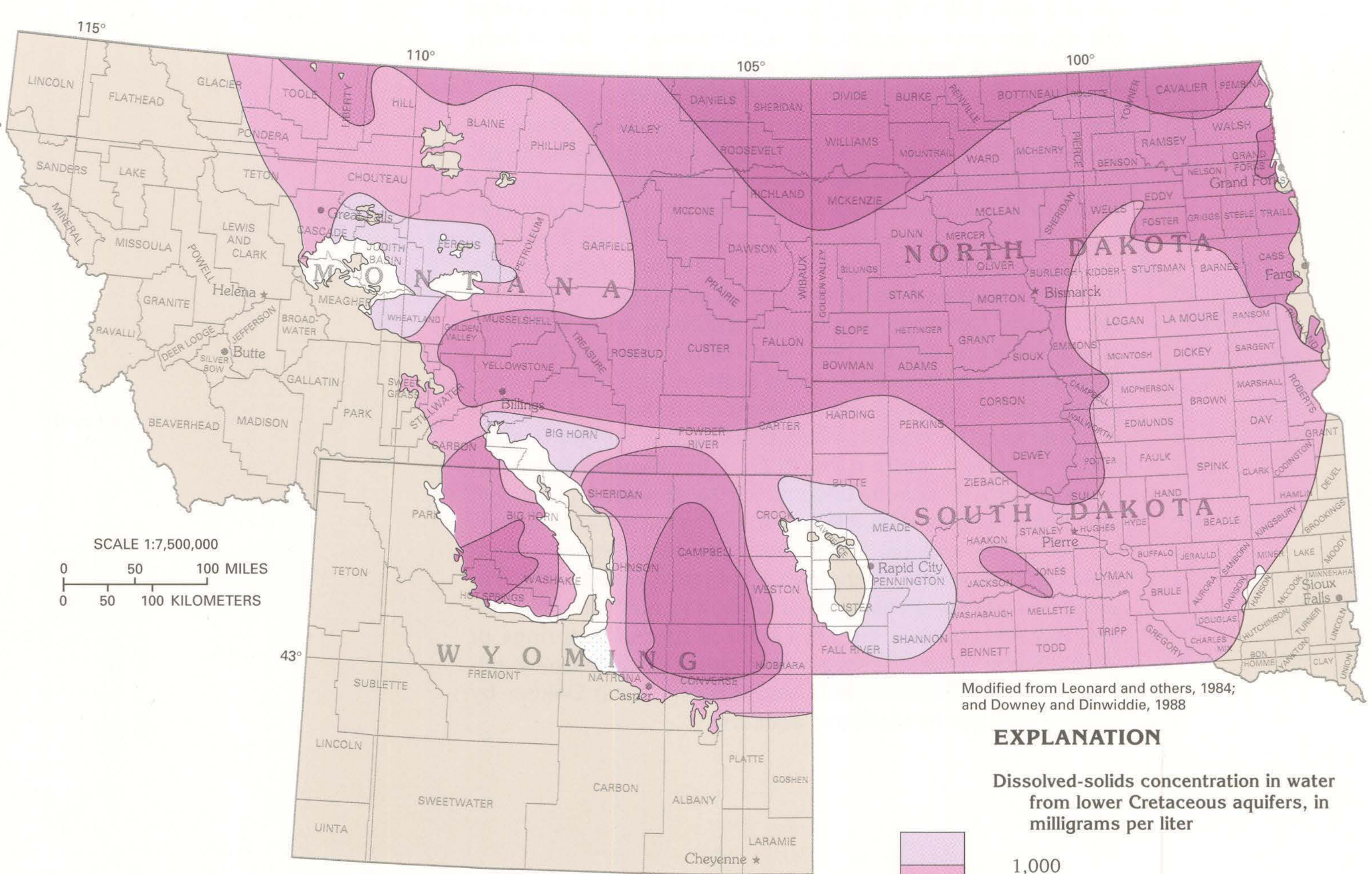
4400 — **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells. Hachures indicate depression. Contour interval 200 feet. Datum is sea level

Limit of lower Cretaceous aquifers—Dashed where approximately located

Direction of ground-water movement

No data

Figure 58. Water moves regionally northeastward through the deeply buried lower Cretaceous aquifers. Some of the water moves hundreds of miles from aquifer recharge areas around structural uplifts on the west to discharge areas in eastern North Dakota and South Dakota.



EXPLANATION

Dissolved-solids concentration in water from lower Cretaceous aquifers, in milligrams per liter

1,000

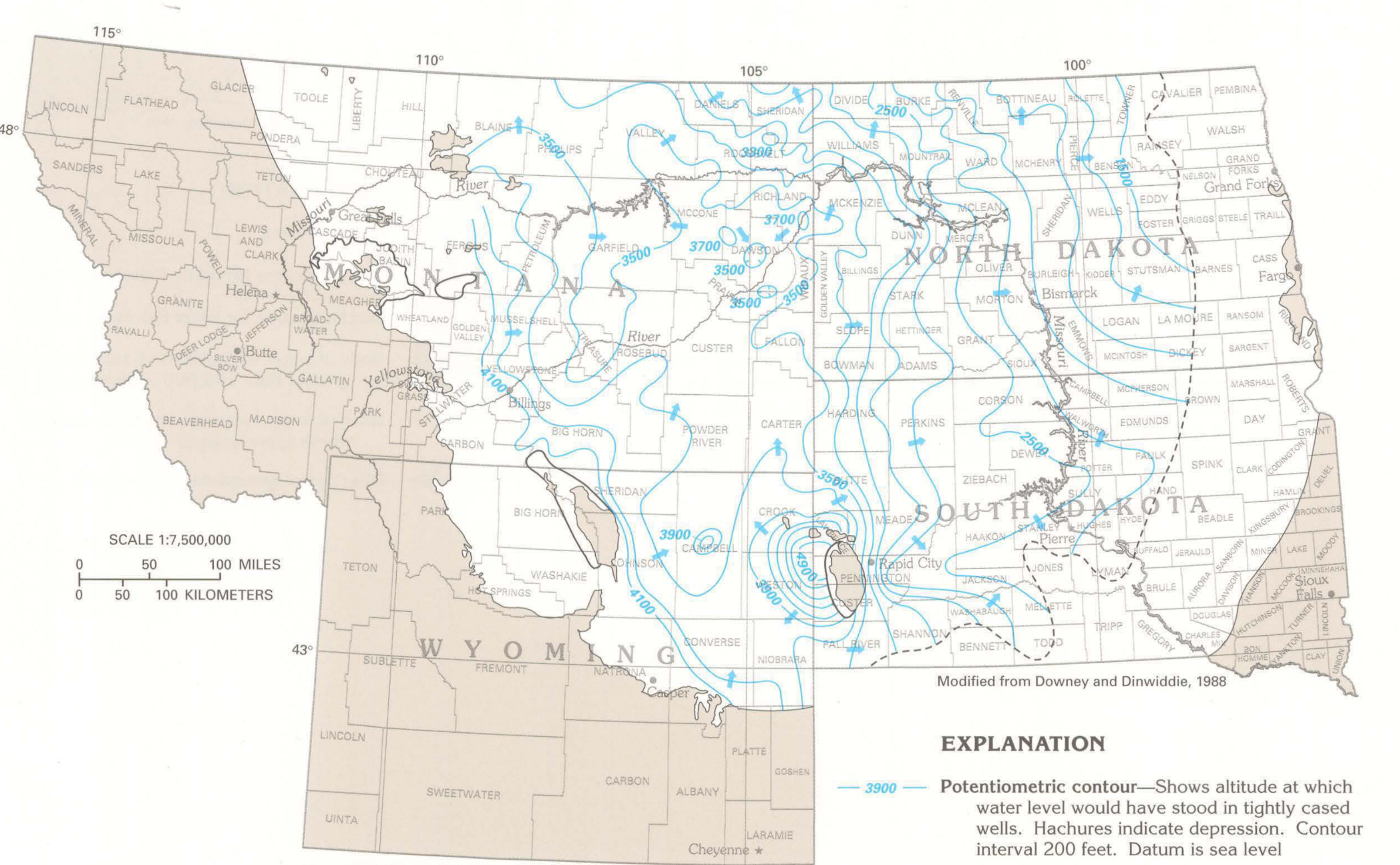
3,000

10,000

No data

Aquifers absent

Figure 59. The lower Cretaceous aquifers contain freshwater only near where the aquifers receive recharge. Dissolved-solids concentration in the water is largest in the deep parts of the Powder River and the Williston Basins.



EXPLANATION

3900 — **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells. Hachures indicate depression. Contour interval 200 feet. Datum is sea level

Limit of upper Paleozoic aquifers—Dashed where approximately located

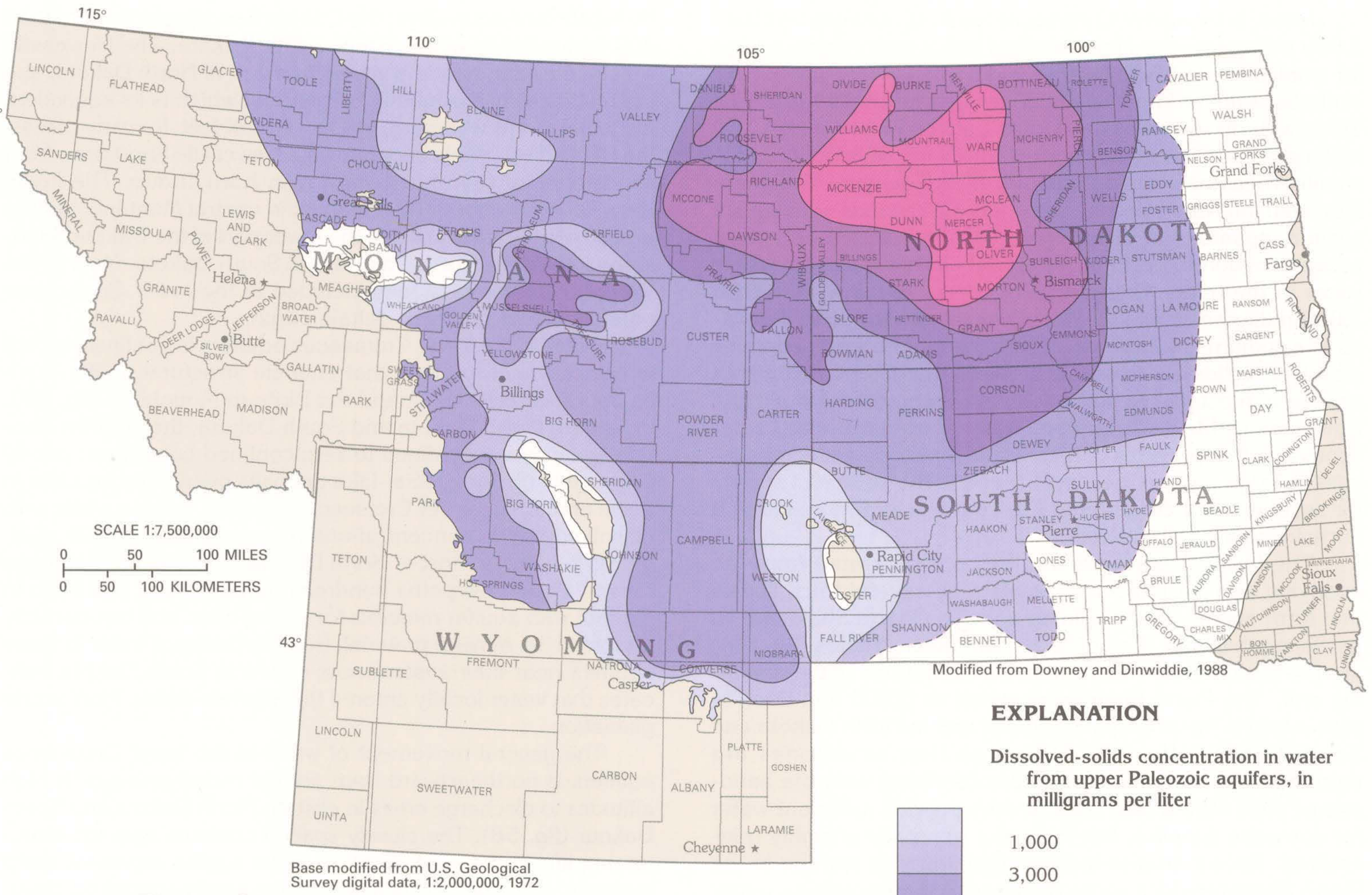
Direction of ground-water movement

Figure 60. Water in the upper Paleozoic aquifers moves regionally northeastward from aquifer recharge areas that are on the flanks of structural uplifts. Locally, the water moves radially away from the Black Hills Uplift or toward depressions.

Water in the upper Paleozoic aquifers is fresh only in small areas at or near places where recharge enters the aquifers. The principal area of freshwater encircles the Black Hills Uplift in western South Dakota (**fig. 61**). The water quickly becomes slightly saline to saline as it moves downgradient from the recharge areas and into the Williston Basin. In the deep parts of the Williston Basin, the water is a brine that has dissolved-solids concentrations of greater than 300,000 milligrams per liter in a large area in western North Dakota. The presence of water with a dissolved-solids concentration that ranges from 3,000 to 10,000 milligrams per liter on the eastern (downgradient) side of the brine indicates that some water flows around the brine rather than through it. Mineralized water in the upper Paleozoic aquifers in central South Dakota leaks upward to the overlying upper Cretaceous aquifers and causes increased mineralization in the water in the shallower aquifers.

Lower Paleozoic aquifers consist of sandstone and carbonate rocks of Cambrian and Ordovician age (**fig. 50**). Although the rocks that compose these aquifers are widespread in Segment 8, they are, for the most part, deeply buried, commonly contain saline water or brine, and are important oil and gas reservoirs in deep parts of the Williston Basin. Only sparse data for the water-yielding characteristics of these rocks are available, and most of the data are for areas where the aquifers crop out or are buried at shallow depths. The principal geologic units that compose the lower Paleozoic aquifers are the Flathead Sandstone, sandstone beds of the Winnipeg Formation, limestones of the Red River and the Stonewall Formations, and the Bighorn and the Whitehead Dolomites (**fig. 50**). The combined thickness of these formations is more than 2,000 feet in the deep part of the Williston Basin, but the thickness of the lower Paleozoic aquifers is much less because the parts of the rocks that have minimal permeability or those that contain brine, oil, or gas are not considered to be aquifers. In much of the Powder River Basin, the upper and lower Paleozoic aquifers are hydraulically connected and locally are called the Madison aquifer system.

Sparse data indicate that the movement of water in the lower Paleozoic aquifers generally is northeastward (**fig. 62**). The water moves from aquifer recharge areas on the flanks of structural uplifts, across the Bighorn Basin and parts of the Williston Basin, and discharges to shallower aquifers in eastern North Dakota and central South Dakota. Although **figure 62** shows an area of high altitude on the potentiometric surface of the aquifers in eastern Montana and western North Dakota, this area does not represent a recharge area. Rocks equivalent to the lower Paleozoic aquifers mostly contain brine or petroleum in this area, and the high potentiometric-surface altitudes probably represent measurements from isolated sandstone or limestone beds that are not connected to the main body of permeable rocks.



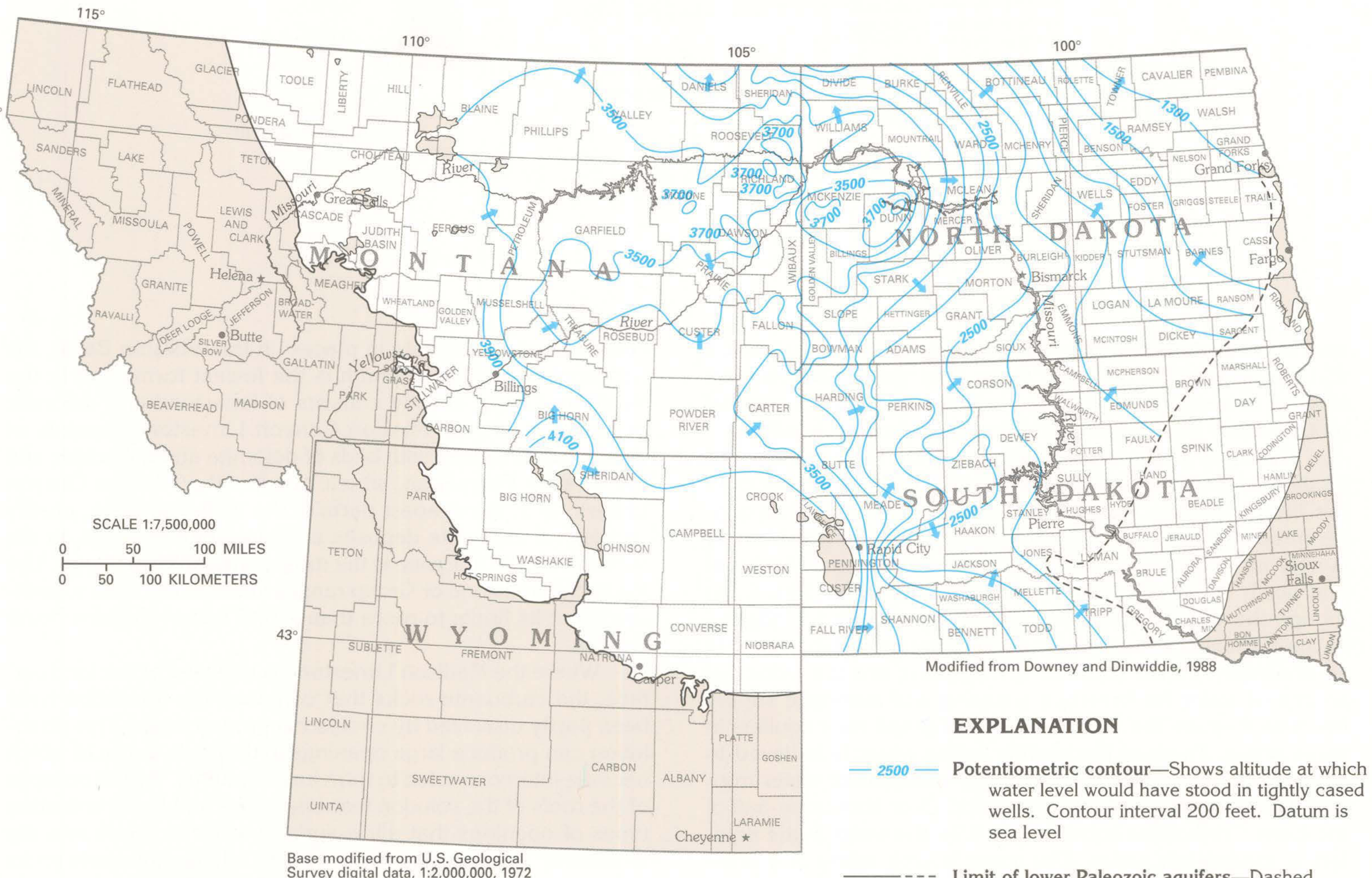
EXPLANATION

Dissolved-solids concentration in water from upper Paleozoic aquifers, in milligrams per liter

1,000
3,000
10,000
100,000
300,000

Aquifers absent

Figure 61. Freshwater in the upper Paleozoic aquifers is mostly in and slightly downgradient of aquifer outcrop areas. The water becomes increasingly mineralized as it moves northeastward toward the deep parts of the Williston Basin. Some of the water moves laterally to the east and north around the brine.



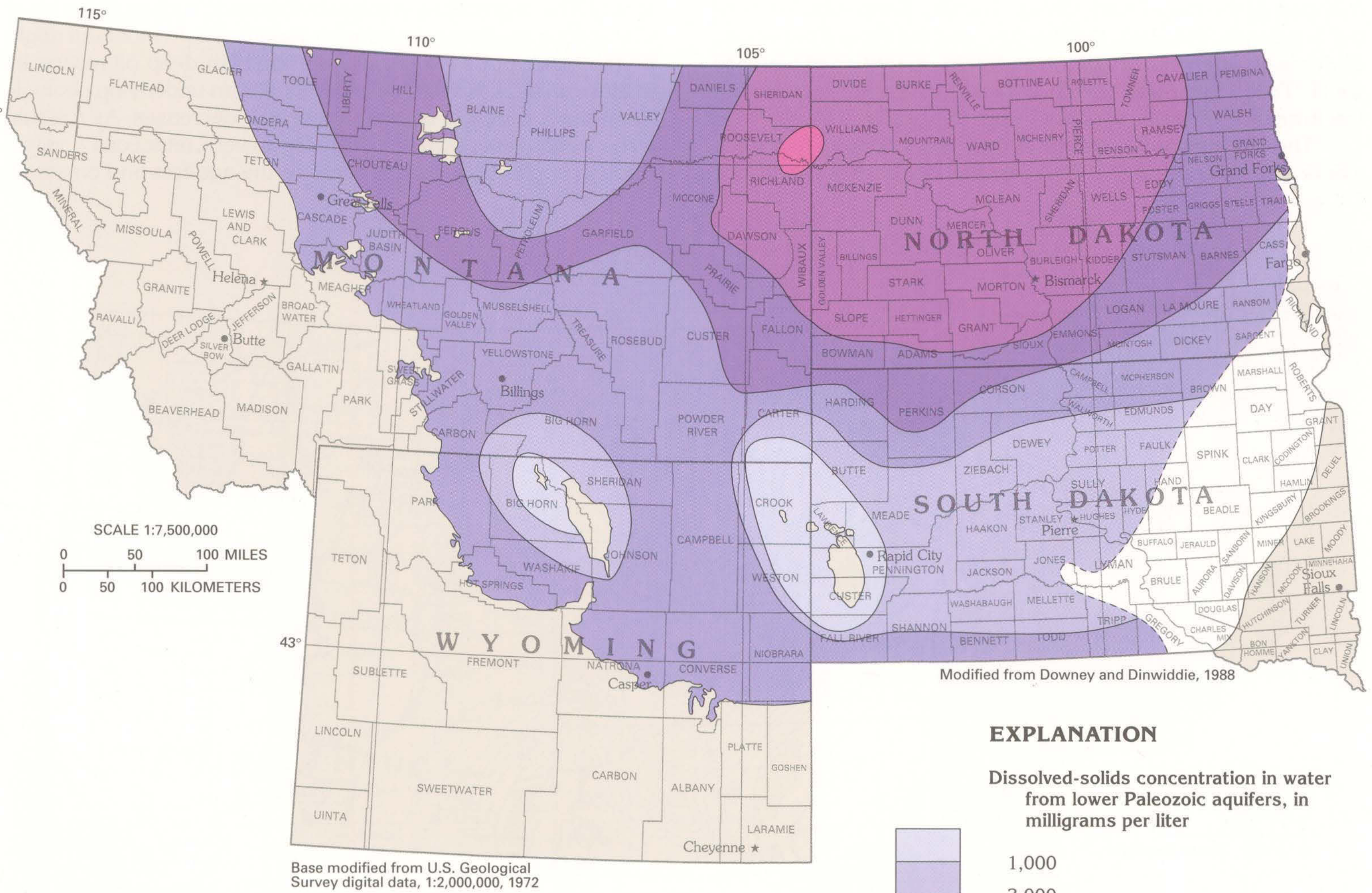
EXPLANATION

2500 — Potentiometric contour—Shows altitude at which water level would have stood in tightly cased wells. Contour interval 200 feet. Datum is sea level

Limit of lower Paleozoic aquifers—Dashed where approximately located

Direction of ground-water movement

Figure 62. Water in the lower Paleozoic aquifers moves northeastward across the Williston Basin. Movement is from aquifer recharge areas on the flanks of uplifts toward discharge areas in eastern North Dakota and central South Dakota.



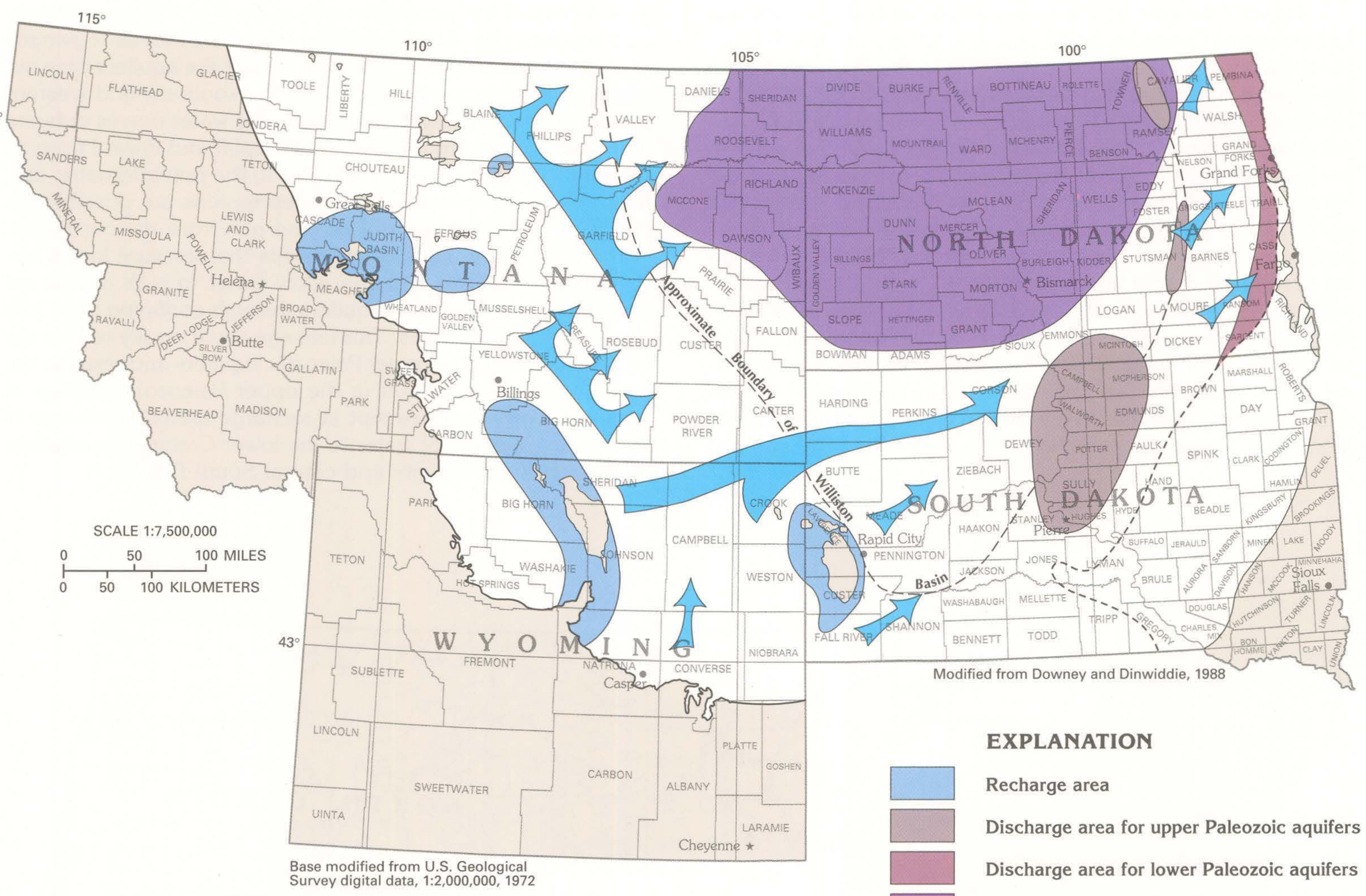
EXPLANATION

Dissolved-solids concentration in water from lower Paleozoic aquifers, in milligrams per liter

1,000
3,000
10,000
100,000
300,000

Aquifers absent

Figure 63. Lower Paleozoic aquifers contain freshwater only in two small areas. A large area of brine with a dissolved-solids concentration of 100,000 milligrams per liter or more is in eastern Montana and much of North Dakota.



EXPLANATION

Recharge area

Discharge area for upper Paleozoic aquifers

Discharge area for lower Paleozoic aquifers

Body of water with dissolved-solids concentrations greater than 100,000 milligrams per liter

Limit of lower Paleozoic aquifers—Dashed where approximately located

Direction of ground-water movement

Figure 64. Water enters the Paleozoic aquifers in recharge areas on the flanks of structural uplifts, moves through the Williston Basin, and discharges mostly as saline springs and seeps in eastern North Dakota. Most of the water moves around the southeastern and northwestern margins of a body of brine.

Lower Paleozoic aquifers contain freshwater only in a small area in north-central Wyoming and a somewhat larger area that surrounds the Black Hills Uplift (**fig. 63**). These aquifers contain slightly saline to moderately saline water throughout the southern one-half of their extent. In eastern Montana and western and central North Dakota, the aquifers contain brine that has dissolved-solids concentrations of greater than 100,000 milligrams per liter. Most of the water in the aquifers moves around the southeastern or northwestern margins of the body of brine. In a large area in central South Dakota, some of the slightly saline water in the lower Paleozoic aquifers leaks upward into shallower aquifers where the deeper aquifers pinch out eastward against Precambrian rocks.

The ground-water flow system in the Paleozoic aquifers of the Northern Great Plains aquifer system is summarized in **figure 64**. Recharge areas for the upper and lower Paleozoic aquifers are on the flanks of structural uplifts where the aquifers have been warped upward and subsequently exposed by erosion. Water generally moves northeastward from these recharge areas toward the deep parts of the Williston Basin. A large body of brine is in the deep parts of the Williston Basin where little or no water moves. Most of the water moves laterally around the margins of the brine and discharges to shallower aquifers in eastern North Dakota. Some of the water leaks upward through the unconsolidated deposits aquifers that overlie the Northern Great Plains aquifer system and ultimately discharges to springs, lakes, and streams in eastern North Dakota. Because the discharged water has traveled along flow paths that are hundreds of miles long, the water is highly mineralized and reaches the land surface as saline springs or seeps. Some water discharges from the lower Paleozoic aquifers in central South Dakota and eastern North Dakota by upward leakage to shallower aquifers.

UPPER COLORADO RIVER BASIN AQUIFER SYSTEM

The Upper Colorado River Basin aquifer system in Segment 8 is in southwestern Wyoming and extends over about one-fourth of the State (**fig. 65**). The aquifer system underlies large areas of eastern Utah and western Colorado and small parts of northeastern Arizona and northwestern New Mexico and is described in detail for those four States in Chapter C of this Atlas. The Wyoming part of the aquifer system extends over about 20,000 square miles and is mostly in the Green River, the Great Divide, and the Washakie structural basins.

Layered sedimentary rocks in numerous geologic formations that range in age from Cenozoic to Paleozoic compose the aquifers of the Upper Colorado River Basin aquifer system in Wyoming. The formations are grouped into five principal aquifers in this report (**fig. 66**). From shallowest to deepest, they are the Laney aquifer; the Wasatch–Fort Union aquifer (together with the Laney aquifer, equivalent to the lower Tertiary aquifers elsewhere in Segment 8); the Mesaverde aquifer (equivalent to the upper Cretaceous aquifers); the Dakota through the Nugget aquifers (equivalent to the lower Cretaceous aquifers); and the Paleozoic aquifers. The Laney aquifer is exposed around the margins of the Green River Basin and the Washakie Basins (**fig. 65**). The Wasatch–Fort Union aquifer is the most widely exposed aquifer in southwestern Wyoming (**fig. 65**) and is at the land surface throughout most of the Great Divide Basin. Uplift has exposed the Mesaverde aquifer principally in the Rock Springs Uplift that separates the Washakie and the Great Divide Basins from the Green River Basin. The Dakota through the Nugget aquifers are exposed at the land surface only in small areas, and the Paleozoic aquifers are entirely in the subsurface.

The uppermost aquifer in the Wyoming part of the Upper Colorado River Basin aquifer system is the Laney aquifer. This aquifer consists of fractured sandstone beds assigned to the Laney Member of the Green River Formation. Although much of the Green River Formation is lacustrine clay, silt, or evaporite beds, all of which have minimal permeability, the sandstone beds of the uppermost Laney Member yield sufficient water for domestic and livestock-watering supplies. Water in the Laney aquifer is fresh to slightly saline. Locally, small yields can be obtained from wells completed in fractured lacustrine deposits of the Green River Formation.

The Wasatch Formation of Eocene and Paleocene age and the Fort Union Formation of Paleocene age compose the Wasatch–Fort Union aquifer. The lithology of the two formations is similar; the principal water-yielding beds are sandstones that are interbedded with shale, mudstone, and some coal beds. The upper part of the Wasatch Formation interfingers with shale and mudstone of the overlying Green River Formation around the margins of the Green River and the Washakie Basins. The Green River Formation is an effective confining unit in most places. Artesian pressure in the aquifer commonly is high enough to cause wells completed in the Wasatch Formation to flow. Locally, the Wasatch–Fort Union aquifer is very thick; for example, the aquifer is reported to be about 11,000 feet thick near Pinedale in Sublette County and about 7,000 feet thick near the center of the Great Divide Basin. Most of the freshwater in the Upper Colorado River Basin aquifer system is in the Wasatch–Fort Union aquifer, but the aquifer locally contains saline water where it is deeply buried.

Sandstone beds in the Mesaverde Group of Late Cretaceous age compose the Mesaverde aquifer (**fig. 66**). Shale beds form local confining units within the aquifer and the Lewis Shale locally overlies it in the Great Divide and the Washakie Basins. In most places, however, the Mesaverde aquifer and the overlying Wasatch–Fort Union aquifer are hydraulically connected. The Mesaverde aquifer is exposed at the land surface in a large area that surrounds the Rock Springs Uplift (**fig. 65**). The aquifer contains freshwater only where it is exposed at the land surface and for a short distance downdip; water in the deeply buried parts of the aquifer is saline or briny. A thick confining unit composed mostly of shale in several geologic formations underlies the Mesaverde aquifer and hydraulically separates it from deeper aquifers in Mesozoic rocks.

The Dakota through the Nugget aquifers consist of several sandstone formations separated by confining units (**fig. 66**). These aquifers are exposed at the land surface only locally in southwestern Wyoming and contain very saline water or brine in most places. A thick confining unit of Triassic and Permian rocks underlies these aquifers and hydraulically separates them from the deeper Paleozoic aquifers.

The principal aquifers in Paleozoic rocks are the Tensleep Sandstone of Pennsylvanian and Permian age and the Madison Limestone of Devonian and Mississippian age (**fig. 66**). Sandstone, limestone, and dolomite beds of Pennsylvanian to Cambrian age also are local aquifers. These aquifers are deeply buried and contain saline water almost everywhere, the Paleozoic aquifers are not extensively used for water supply in southwestern Wyoming.

Ground water in all the aquifers of the Upper Colorado River Basin aquifer system moves from aquifer recharge areas toward the centers of the structural basins (**fig. 67**). Discharge from the aquifers is by upward leakage to shallower aquifers and, ultimately, to major streams. The ground-water flow system is simple where the geologic structure consists of broad basins and uplifts but is complex where the aquifers have been intensely folded and faulted.

Water is less than 200 feet below the land surface in about three-fourths of the area of the aquifer system (**fig. 68**). Ground water is nearest the land surface near the major streams, which are discharge areas for the aquifers. In and near mountainous areas, depth to water ranges from 500 to 1,000 feet. Areas where water ranges from 200 to 500 feet below the land surface generally coincide with low plateaus. Where the topography is rugged, the depth to water is much more variable than can be shown by the generalized depth categories used to construct **figure 68**.

A map of the potentiometric surface of the Wasatch–Fort Union aquifer (**fig. 69**) shows that the regional movement of water in the eastern part of the aquifer is from recharge areas at basin margins toward the Great Divide Basin and southward into Colorado toward the center of the Washakie Basin. In the western part of the aquifer, water moves from recharge areas toward the Green River and its tributaries and toward the Flaming Gorge Reservoir. Where the aquifer is exposed at the land surface, much of the ground water moves along short flow paths from recharge areas to nearby small streams where it discharges. Local depressions on the potentiometric surface, such as the one in northeastern Sweetwater County, are the result of ground-water withdrawals.

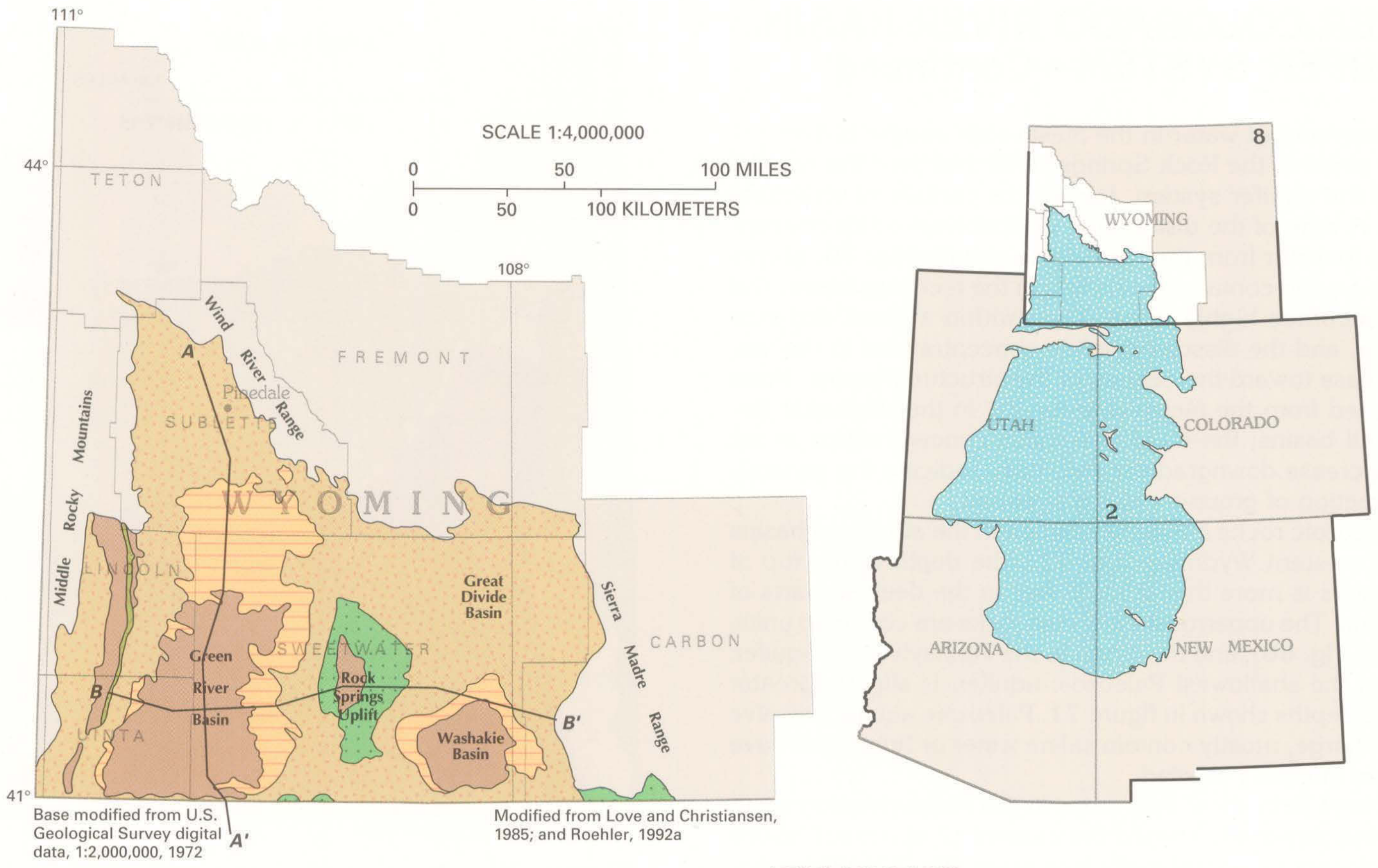


Figure 65. *The Upper Colorado River Basin aquifer system is in three structural basins and adjacent uplifted mountainous areas in southwestern Wyoming. The aquifer system consists of five aquifers, four of which are shown here: the fifth is completely buried.*

EXPLANATION

- Laney aquifer
- Wasatch–Fort Union aquifer
- Mesaverde aquifer
- Dakota through Nugget aquifers
- Confining unit
- Upper Colorado River Basin—Colorado Plateaus aquifer system
- A——A' Line of hydrogeologic section
- 8 Atlas segment number

Era	System and Series		Stratigraphic unit		Hydrogeologic unit: Taylor and others, 1986; Freethey, 1988a; Geldon, 1988a	Hydrogeologic unit: This report	Aquifer system
Cenozoic	Quaternary		Unnamed alluvium		Unnamed	Unnamed local aquifer	
	Tertiary	Miocene	Browns Park Formation				
		Oligocene	Bishop Conglomerate				
		Eocene	Bridger Formation			Confining unit	Upper Colorado River Basin aquifer system
			Green River Formation	Laney Member		Laney aquifer	
				Wilkins Peak Member; Tipton Shale Member; Lyman Member		Confining unit	
			Wasatch Formation		Wasatch–Fort Union aquifer	Wasatch–Fort Union aquifer	
		Paleocene	Fort Union Formation				
Mesozoic	Cretaceous		Mesaverde Group		Mesaverde aquifer	Mesaverde aquifer	
			Baxter Shale		Mancos confining unit	Confining unit	
			Frontier Formation				
			Aspen and Mowry Shales				
			Bear River Formation	Muddy Sandstone			
				Thermopolis Shale			
			Cloverly Formation		Dakota aquifer [1]	Dakota through Nugget aquifers	
	Jurassic		Morrison Formation		Morrison confining unit		
					Morrison aquifer		
			Sundance Formation		Curtis–Stump confining unit		
					Entrada–Preuss aquifer [1]		
			Gypsum Spring Formation		Carmel–Twin Creek confining unit		
	?		Nugget Sandstone		Navaho–Nugget aquifer		
	Triassic		Chugwater Formation		Confining unit	Confining unit	
			Dinwoody Formation				
Paleozoic	Permian		Phosphoria Formation				
	Pennsylvanian		Tensleep Sandstone		Pennsylvanian Sandstone aquifer	Pennsylvanian aquifer	Paleozoic aquifers
			Amsden Formation		Local aquifer	Unnamed	
					Confining unit		
	Mississippian				Local aquifer		
			Madison Limestone		Mississippian Carbonate–rock aquifer	Mississippian aquifer	
	Devonian		Darby Formation		Confining unit	Unnamed	
	Silurian				Local aquifer		
	Ordovician		Bighorn Dolomite				
	Cambrian		Gallatin Limestone				
			Gros Ventre Formation		Confining unit		
			Flathead Sandstone		Local aquifer		
Precambrian			Igneous and metamorphic rocks		Precambrian confining unit	Confining unit	

[1] Formations from which hydrogeologic names are derived may not be in the area mapped in figure 65

Figure 66. *The numerous sedimentary rock formations in southwestern Wyoming are grouped into five principal aquifers. The gray areas represent missing rocks.*

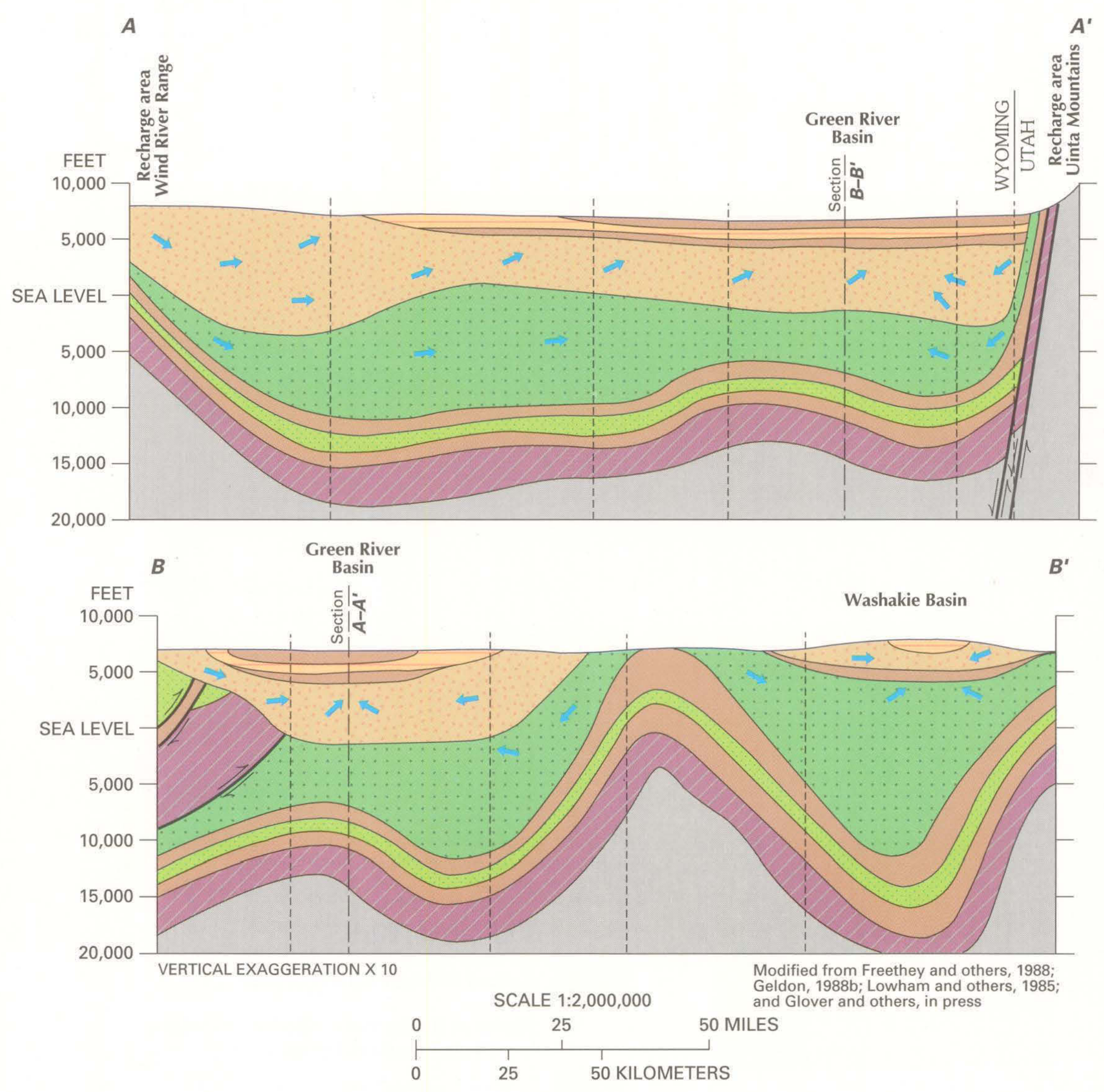


Figure 67. *The aquifers of the Upper Colorado River Basin aquifer system are, for the most part, in structural basins, such as the Green River and the Washakie. Ground water moves from aquifer recharge areas near the basin margins toward the centers of the basins. The lines of the sections are shown in figure 65.*

EXPLANATION

- Laney aquifer
- Wasatch–Fort Union aquifer
- Mesaverde aquifer
- Dakota through Nugget aquifers
- Paleozoic aquifers
- Confining unit
- Not a principal aquifer (crystalline rocks)
- Contact of hydrogeologic unit
- Bend in section
- Direction of ground-water movement
- Fault—Arrows show relative vertical movement

Figure 68. *Depth to water generally is greatest in the mountainous areas and least near streams. The water is at intermediate depths in plateau and mesa areas.*

EXPLANATION

Approximate depth to water, in feet below land surface

200

500

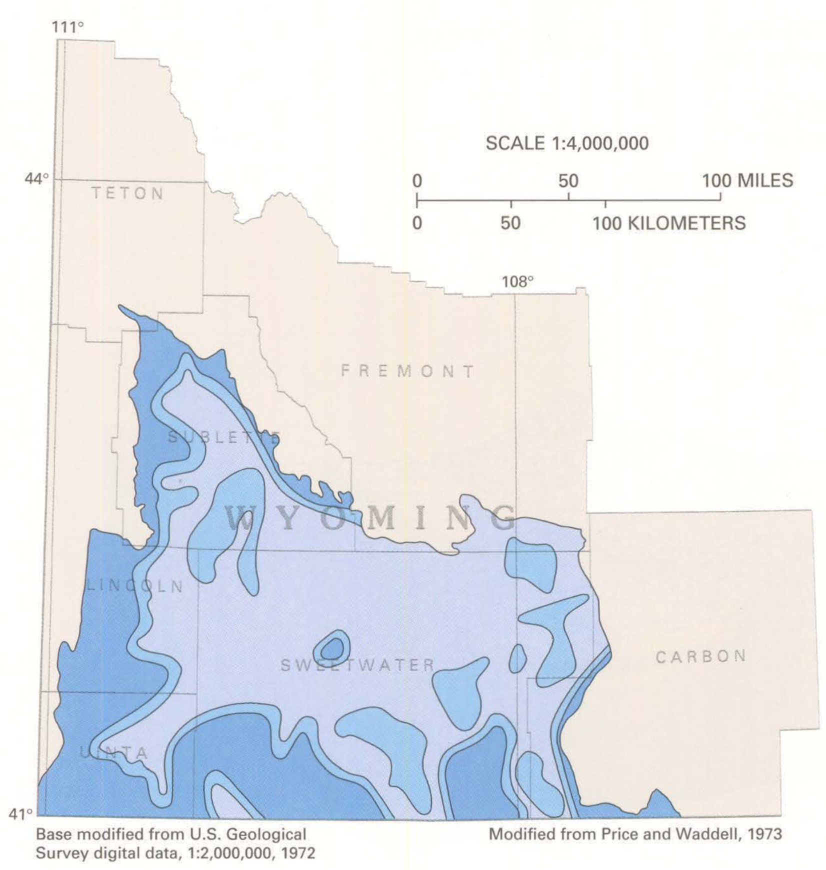
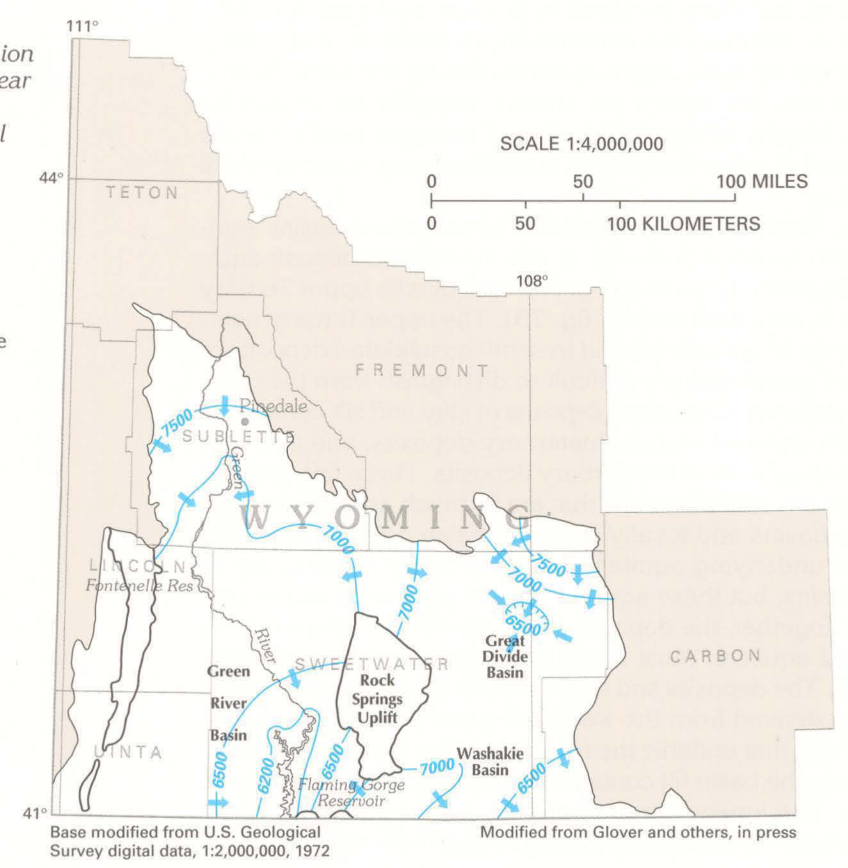


Figure 69. *Water in the Wasatch–Fort Union aquifer moves regionally from recharge areas near the northern and eastern limits of the aquifer toward large streams or the centers of structural basins.*

EXPLANATION

- 7000 — Potentiometric Contour—Shows altitude at which water level would have stood in tightly cased wells. Hachures indicate depression. Contour interval 300 and 500 feet. Datum is sea level
- Direction of ground-water movement
- Limit of Wasatch–Fort Union aquifer



UPPER COLORADO RIVER BASIN AQUIFER SYSTEM—Continued

Movement of water in the Mesaverde aquifer is from recharge areas at the Rock Springs Uplift and near the eastern limit of the aquifer system, toward the centers of structural basins. A map of the distribution of dissolved-solids concentrations in water from the Mesaverde aquifer (**fig. 70**) shows that the aquifer contains freshwater in the recharge areas. The water becomes highly mineralized within a short distance downdip, and the dissolved-solids concentrations in the water increase toward the centers of the structural basins. Brine is reported from the Mesaverde aquifer in the Washakie Basin. In all basins, the dissolved-solids concentrations in the water increase downgradient and, thus, indicate the generalized direction of ground-water movement.

Paleozoic rocks are deeply buried in the structural basins of southwestern Wyoming (**fig. 71**); the depth to the top of these rocks is more than 25,000 feet in the deepest parts of the basins. The uppermost Paleozoic rocks are confining units, however (**fig. 66**), and the depth to the Pennsylvanian aquifer, which is the shallowest Paleozoic aquifer, is slightly greater than the depths shown in **figure 71**. Paleozoic aquifers receive little recharge, mostly contain saline water or brine, and have not been intensely studied.

Sparse data show that water in the Pennsylvanian aquifer moves regionally toward the centers of structural basins from adjacent topographically high areas (**fig. 72**). Water discharges from this aquifer mostly by upward leakage to shallower aquifers. The water in the Pennsylvanian aquifer in the deepest parts of the Green River and the Washakie Basins is thought to move very slowly. Water in the Mississippian aquifer shows the same general trend of movement (**fig. 73**) as that in the Pennsylvanian aquifer. Much of the discharge from the Mississippian aquifer, however, appears to be by lateral movement of the water into adjacent structural basins to the southeast and northeast.

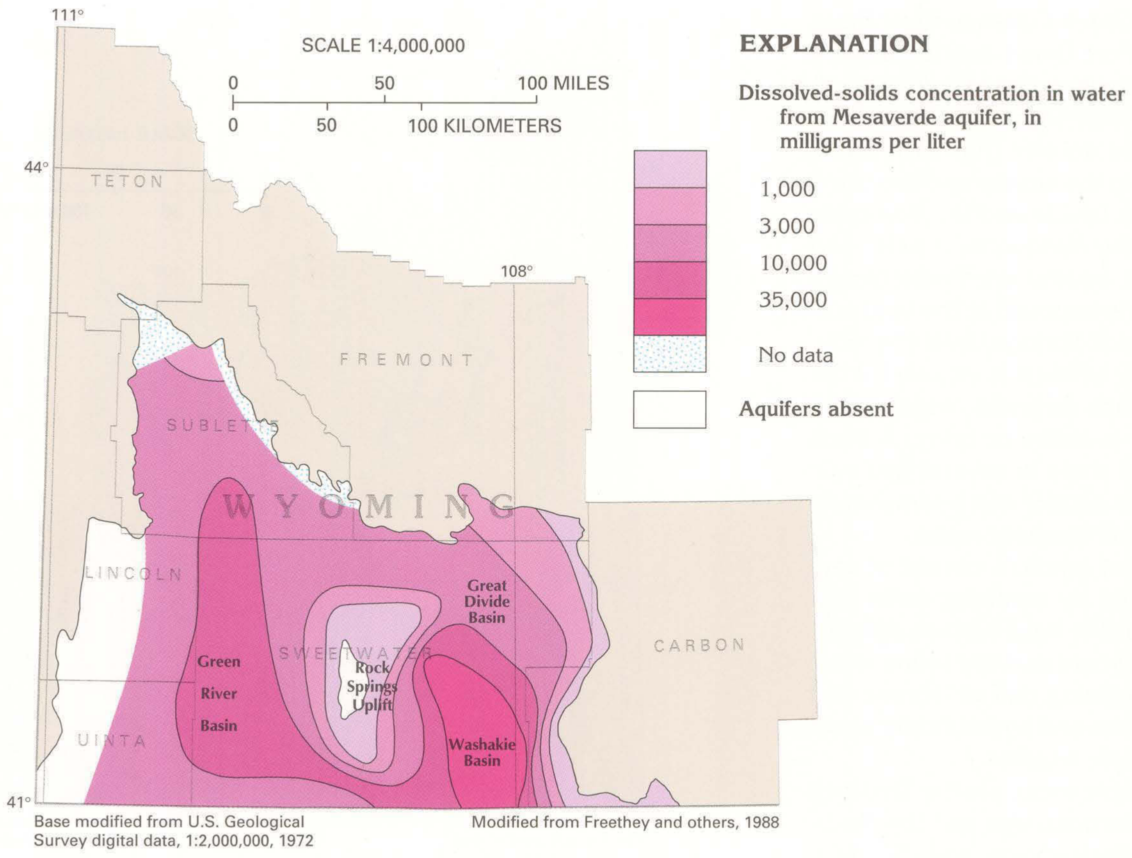


Figure 70. Dissolved-solids concentrations in water from the Mesaverde aquifer increase toward the centers of the structural basins. The general movement of ground water in the aquifer is from areas that have small dissolved-solids concentrations toward areas that have large concentrations.

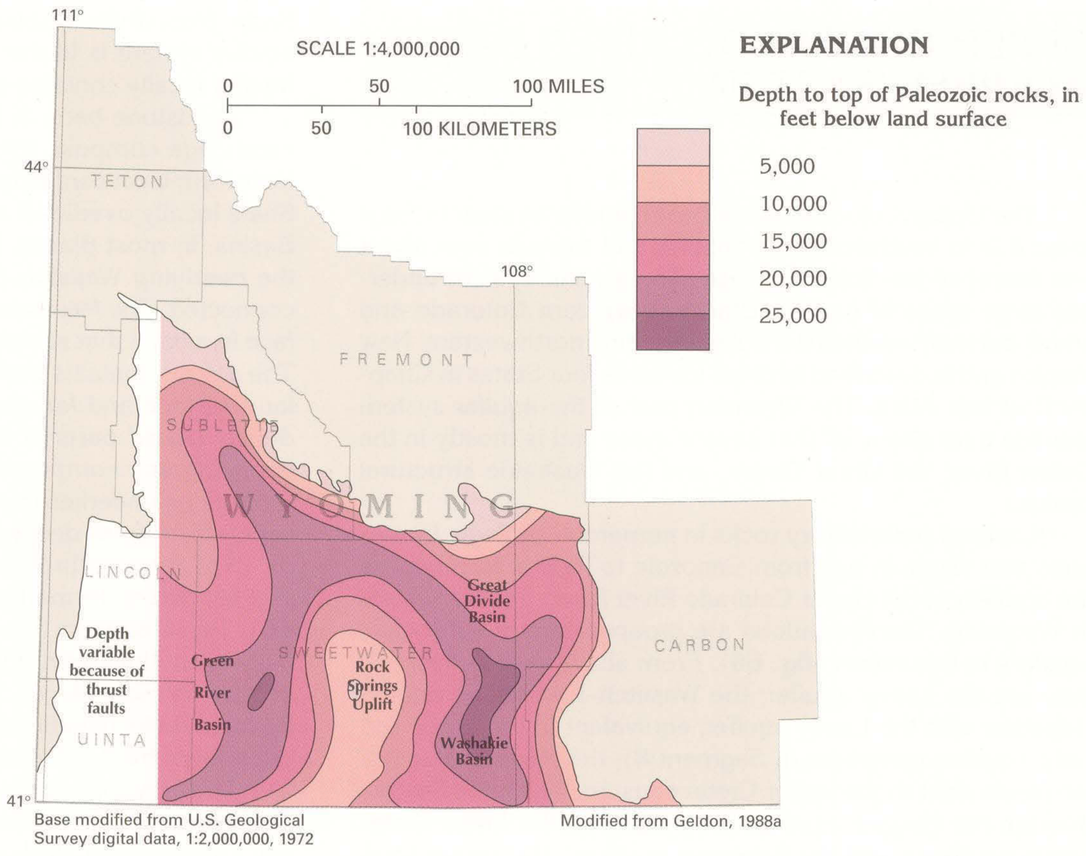


Figure 71. Paleozoic rocks are at shallow depths along the flanks of mountain ranges and in the Rock Springs Uplift but are buried to great depths in the structural basins.

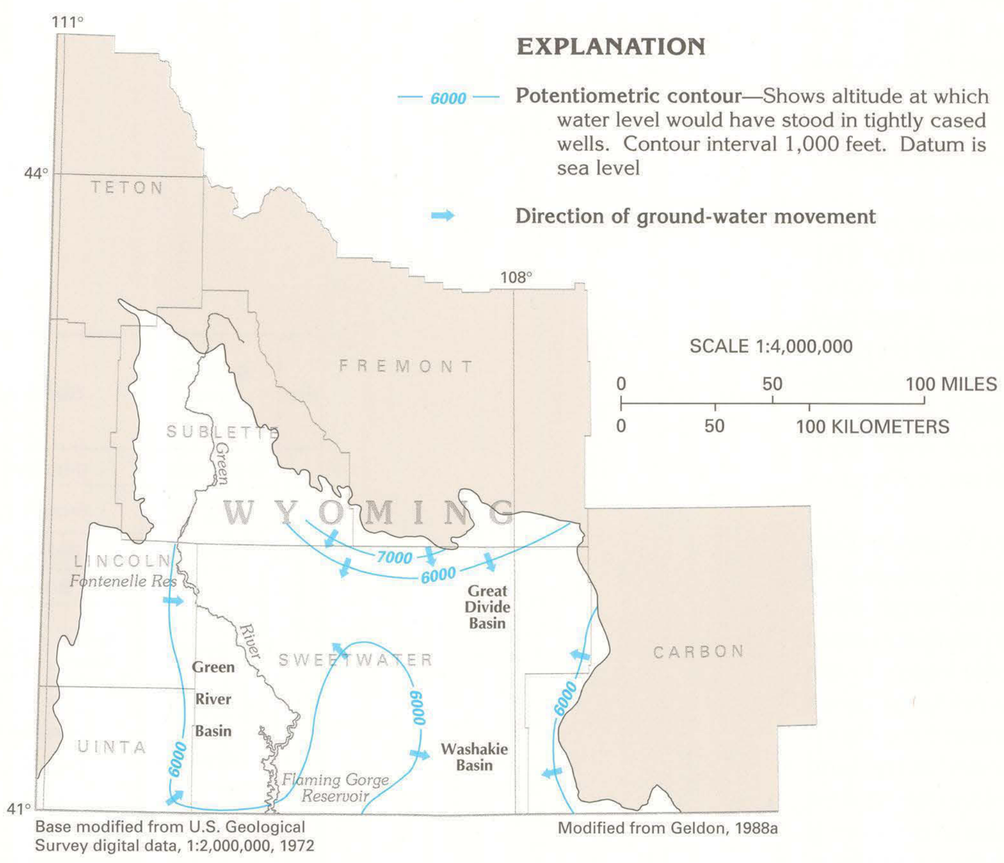


Figure 72. Regional movement of water in the Pennsylvanian aquifer is from recharge areas at high altitudes toward the centers of structural basins.

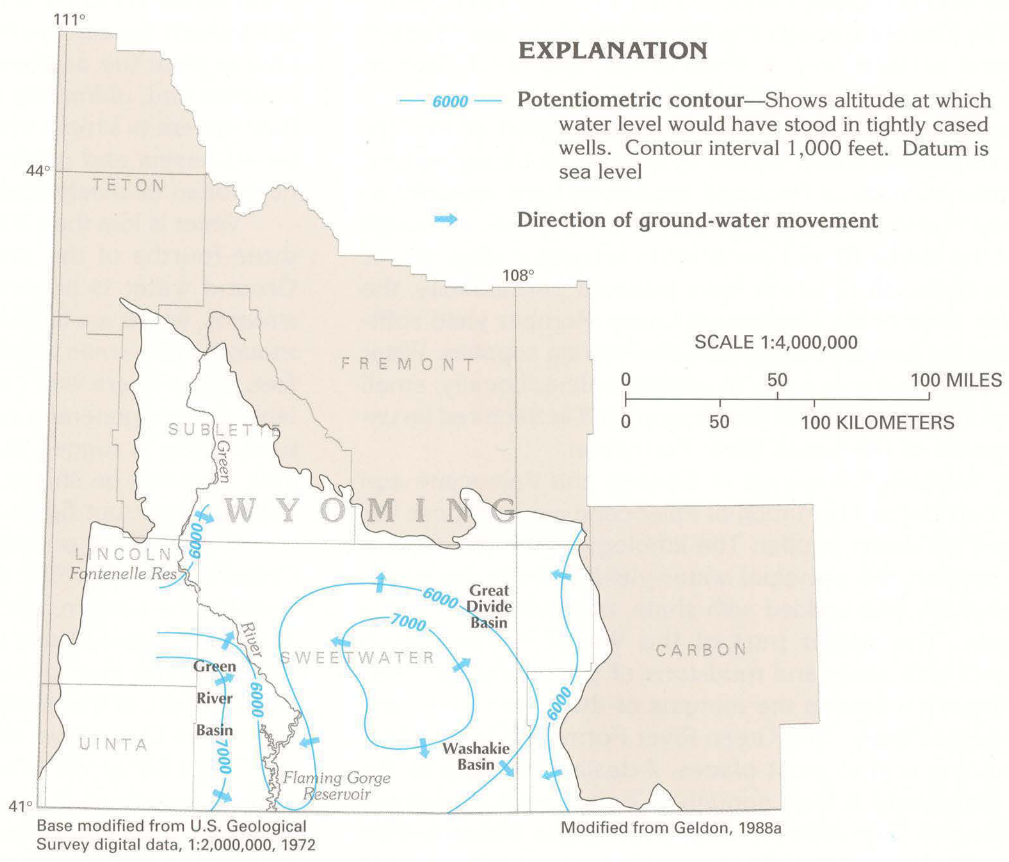


Figure 73. Water in the Mississippian aquifer moves regionally southeastward and northeastward from recharge areas and discharges to adjacent basins.

CENTRAL MIDWEST AQUIFER SYSTEM

The Central Midwest aquifer system in Segment 8 is only in small parts of southeastern South Dakota and southeastern Wyoming (**fig. 74**). The aquifer system extends southward and southwestward over parts of seven additional States (**fig. 42**) and is most extensive in Nebraska, Kansas, and Missouri, the States that compose Segment 3 of this Atlas. The aquifer system is discussed in detail in the chapter that describes that segment.

The Central Midwest regional aquifer system contains three subregional systems, only one of which, the Great Plains aquifer system, extends into Segment 8. The Great Plains aquifer system consists of two sandstone aquifers separated by a shale confining unit, all of which are in Lower Cretaceous rocks. The aquifer system is overlain by a thick sequence of Upper Cretaceous shale beds that are part of several geologic formations but which function together as a single confining unit, which is called the Great Plains confining system. The upper aquifer, which is called the Maha aquifer, consists chiefly of the Dakota, the Newcastle, or the Muddy Sandstones or equivalent rocks. The lower aquifer, which is called the Apishapa aquifer, consists mostly of the Cheyenne Sandstone or its equivalent, the Inyan Kara Group. The confining unit that separates the two aquifers is mostly the Skull Creek or the Thermopolis Shales or equivalent shale beds.

In southeastern South Dakota, water discharges upward from the Great Plains aquifer system to permeable beds in overlying unconsolidated deposits. The aquifer system contains water with dissolved-solids concentrations of 1,000 milligrams per liter or less in parts of Lincoln, Clay, and Union Counties, S. Dak. These small concentrations indicate a local ground-water flow system. Radiometric dates obtained from the water indicate that the aquifer system received some recharge during the Pleistocene Epoch when subglacial meltwater moved into the aquifer from areas of extremely high hydraulic head created by the weight of the glacial ice.

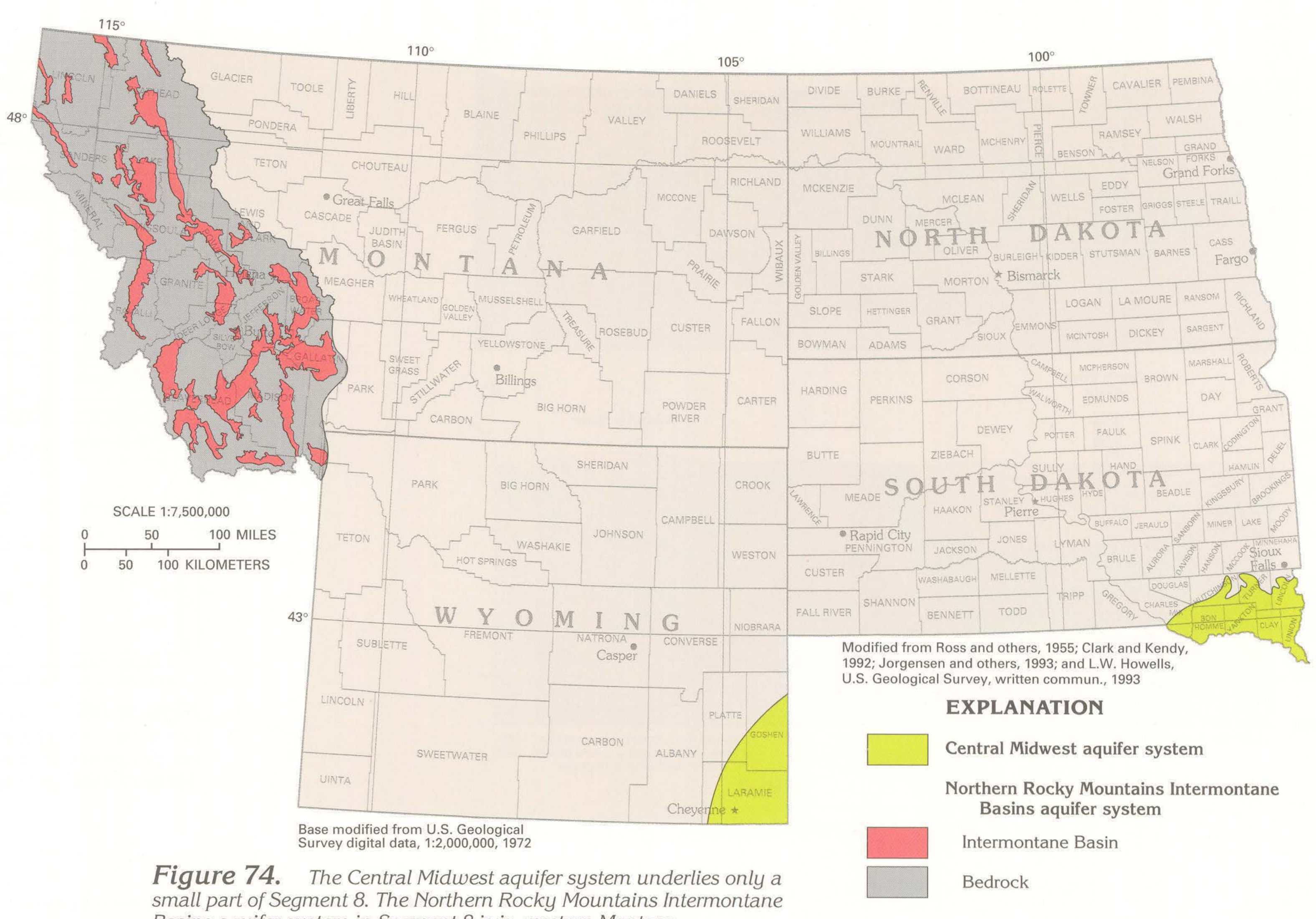


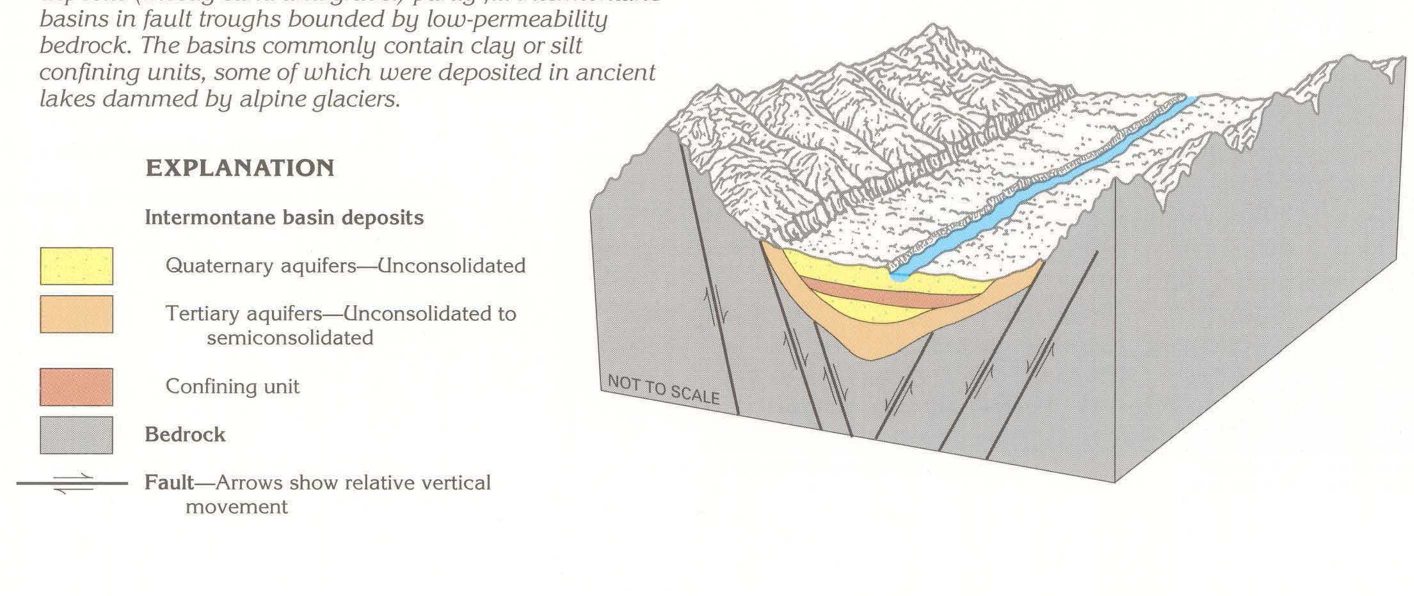
Figure 74. The Central Midwest aquifer system underlies only a small part of Segment 8. The Northern Rocky Mountains Intermontane Basins aquifer system in Segment 8 is in western Montana. Unconsolidated Quaternary deposits and upper Tertiary rocks are aquifers in narrow basins; less-permeable rocks underlie mountain ranges that separate the basins.

NORTHERN ROCKY MOUNTAINS INTERMONTANE BASINS AQUIFER SYSTEM

The part of the Northern Rocky Mountains Intermontane Basins aquifer system in Segment 8 is in western Montana (**fig. 74**). The part of the aquifer system that extends westward into Idaho is described in Segment 7 of this Atlas. Most of the basins that compose the aquifer system are not hydraulically connected, but share common hydrologic and geologic characteristics. Because the occurrence, movement, and quality of the water in these basins is controlled by the same hydrologic factors, the basins are treated together as an aquifer system. Results of detailed studies of example basins can be transferred to other basins with confidence that conditions will be similar.

The Northern Rocky Mountains Intermontane Basins aquifer system consists primarily of unconsolidated-deposit aquifers of Quaternary sand and gravel that overlie upper Tertiary aquifers in structural basins (**fig. 75**). The upper Tertiary aquifers consist of unconsolidated to semiconsolidated deposits of sand and gravel and are difficult to distinguish from the Quaternary deposits. Lacustrine deposits of clay and silt commonly are in the unconsolidated Quaternary deposits, and clay and silt beds locally are in the Tertiary deposits. These fine-grained materials are confining units that are as much as 600 feet thick in some basins and locally create artesian conditions for the water in underlying aquifers. Lower Tertiary aquifers are in some basins, but these aquifers are deeply buried and poorly known. Together, the deposits in the basins are referred to as "basin-fill aquifers." Most of the basins are bounded by faults (**fig. 75**). The deposits and rocks that fill the basins are mostly alluvium derived from the weathering and erosion of consolidated rocks that underlie the mountains that border the basins, but locally the basin fill contains materials deposited by alpine glaciers. The igneous, metamorphic, and sedimentary rocks that underlie the mountains generally yield little water to wells.

Figure 75. Unconsolidated to semiconsolidated deposits (mostly sand and gravel) partly fill intermontane basins in fault troughs bounded by low-permeability bedrock. The basins commonly contain clay or silt confining units, some of which were deposited in ancient lakes dammed by alpine glaciers.

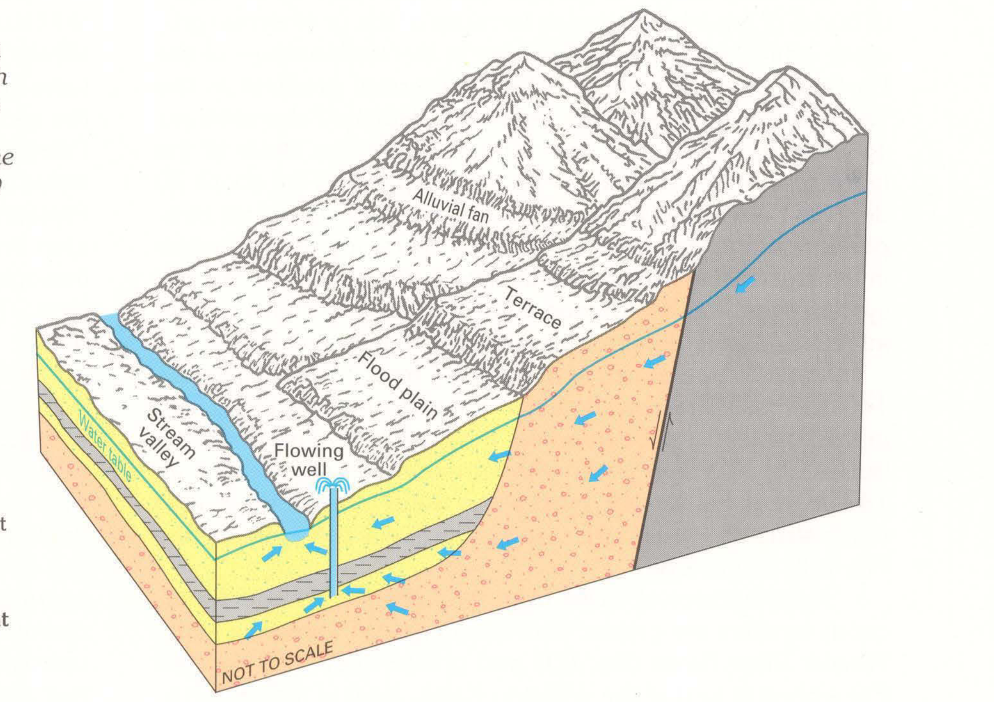


Recharge to the aquifer system is by precipitation that falls directly on basin floors and by snowmelt that runs off the surrounding mountains and is transported into the basins by tributary streams. The streams lose much of their water by infiltration into the basin-fill deposits. The basin-fill aquifers discharge primarily to streams that flow parallel to the long axes of the basins; some discharge is to springs and by withdrawals from wells. In small basins, the basin-fill deposits can be thin, and the basin, narrow (**fig. 76**). Withdrawals by wells located in such basins can capture some of the water that previously discharged to the stream. If withdrawals are great enough, then the hydraulic gradient can be reversed, and water can move from the stream to the aquifer and then to the pumping well.

Hydrologic conditions in large basins can be more complex because such basins commonly are filled with thick sequences of sediment that contain clay confining units (**fig. 77**). Coalescing alluvial fans comprise much of the valley fill near mountain fronts. The alluvium was deposited by streams that flowed into the basins from the surrounding mountains. Terraces formed where the alluvium has been dissected in places by streams that flow within the basins. Older semiconsolidated to unconsolidated deposits are near the basin margins, whereas the basin centers contain younger, mostly unconsolidated deposits. These younger deposits are mostly stream-valley alluvium but also contain glacial deposits, such as clayey glacial-lake deposits that form confining units (**fig. 77**). Water beneath the confining units is under artesian pressure, and wells completed in the deeper aquifers will flow at the land surface where the pressure is sufficiently high. Water above the confining units is under unconfined conditions. If the confining units are near the land surface, then the water table can be shallow enough so that the land surface becomes waterlogged.

Wells completed in the basin-fill aquifers of the Northern Rocky Mountains Intermontane Basins aquifer system locally yield as much as 3,500 gallons per minute but generally yield 50 gallons per minute or less. Yields adequate for domestic use and livestock-watering purposes can be obtained in most places from wells that are 200 feet deep or less. Deeper wells yield adequate volumes of water for irrigation, industrial purposes, and public supply. Several cities in western Montana obtain water supplies from the basin-fill aquifers.

Figure 77. *Large basins can contain thick sequences of basin fill, most of which is of Tertiary age. Confining units, such as the one shown here, create artesian conditions in the deeper aquifers, and some wells completed in these aquifers will flow at the land surface.*



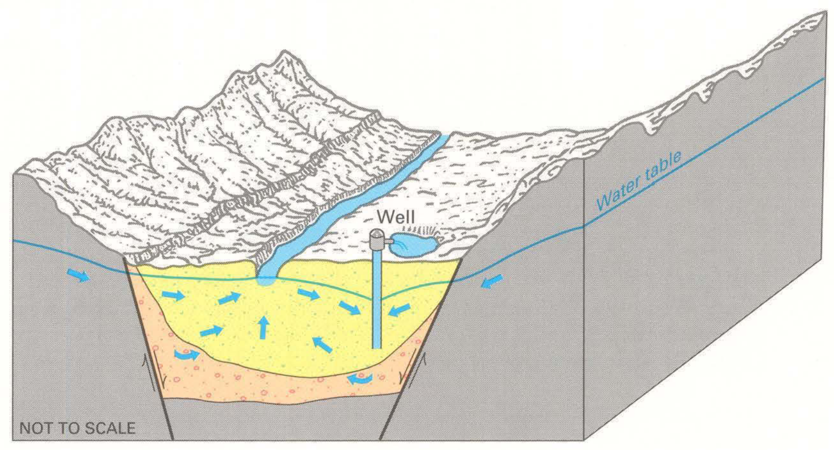
EXPLANATION

- Unconsolidated-deposit aquifers
- Upper Tertiary aquifers
- Glacial lake deposits—Confining unit
- Bedrock
- Direction of ground-water movement
- Fault—Arrows show relative vertical movement

Figure 76. *In small basins, wells drilled near streams can capture some of the streamflow if withdrawals from the wells are large.*

EXPLANATION

- Unconsolidated-deposit aquifers
- Upper Tertiary aquifers
- Bedrock
- Direction of ground-water movement
- Fault—Arrows show relative vertical movement



GEOTHERMAL WATER

Geothermal water, or ground water which has a temperature appreciably higher than that of the local average annual air temperature, is in all four States of Segment 8 (**fig. 78**). Although geothermal water is not extensively developed as a source of energy in the segment, the water is potentially useful for space heating, food processing, or other purposes. Where geothermal water is sufficiently hot, it can be used for space heating by pumping the water directly into pipes and radiators; heat pumps can be used to extract the heat from lower temperature water.

Some geothermal water contains large concentrations of dissolved minerals, such as sodium, calcium, sulfate, chloride, or iron. These ions have been dissolved from the minerals in the rocks that compose the geothermal reservoirs and vary as the mineral composition of the rocks varies. Concentrations of some constituents usually exceed those in the standards recommended for drinking water by the U.S. Environmental Protection Agency; thus, geothermal water that is withdrawn and used can become a disposal problem. In South Dakota, reinjection of geothermal water is required. In the area east of the Continental Divide in Segment 8, much of the geothermal water contains large concentrations of dissolved solids.

Large structural basins in parts of Montana, North Dakota, South Dakota, and Wyoming (**fig. 78**) are possible sources of low-temperature geothermal water, or water which has a temperature of less than 194 degrees Fahrenheit. Low-temperature geothermal water is reported from some deep wells in the Williston Basin and in shallow wells (less than 3,000 feet deep) in western North Dakota. Geothermal water discharges from numerous springs located mostly in the mountainous areas of Montana and Wyoming (**fig. 78**). The springs are connected by faults to deeply buried reservoirs that contain geothermal water, which moves upward along the fault zones to discharge at the land surface. A few areas in Montana and Wyoming are known to have low-temperature geothermal water of sufficient lateral extent to be favorable for development.

The concentration and variety of surface geothermal features in Yellowstone National Park (**fig. 78**) and the large size of some of these features make the Park one of the world's most impressive showplaces for naturally occurring hot water. More than 10,000 individual thermal features, including geysers, hot springs, mud volcanos, and fumaroles (steam vents), have been identified. Geysers are perhaps the best known and certainly the most spectacular features (**fig. 79**). They are a type of hot spring that periodically emits sudden, violent eruptions of steam and hot water. The periodic eruptions are thought to result from conditions like those shown in **figure 80**. A vertical tube extends downward from the vent of the geyser to saturated layers of hot rock. Chambers or side channels branch laterally off the tube and form reservoirs where cooler water is stored in porous rock. Rising steam bubbles at first condense in the cooler water (**fig. 80*A***), but soon concentrate at narrow parts of the vertical tube. The expanding steam builds up pressure, and small spurts of steam and hot water can discharge at the land surface as preliminary eruptions (**fig. 80*B***). At the same time, heat and pressure continue to increase in the water and steam column in the subsurface. Eventually, the preliminary eruptions remove enough water to cause a sudden relief of pressure in the vertical tube and side chambers; water in the tube and chambers suddenly flashes into steam, and a full-scale eruption takes place (**fig. 80*C***). The explosive release of pressure can cause a column of steam and hot water to rise 200 feet or more into the air. Occasionally, the eruptive force is great enough to break and eject some of the rocks through which the steam and hot water rise. After pressure is relieved by the eruption of the geyser, water begins to seep back into the vertical tube and side chambers (**fig. 80*D***) and the eruptive cycle begins again. The period between eruptions depends on several factors, including the volume of steam and water that is ejected and how rapidly ground water refills the tubes and chambers.

Much geothermal water discharges as hot springs that flow steadily instead of erupting at intervals. The hot spring water commonly contains large concentrations of silica (if the water has moved through such rocks as rhyolite, which is rich in silica) or calcium carbonate (if the water has moved through limestone or other calcite-rich rocks). The minerals precipitate as the spring water discharges at land surface. Thick deposits of travertine (a calcium carbonate mineral also called calcareous sinter), such as those shown in **figure 81**, or siliceous sinter (a silica mineral) can form large terracelike features near the spring vents. Iron oxide, manganese oxide, or coatings of sulfur, sulfide minerals, or algae can impart bright colors to the spring deposits.

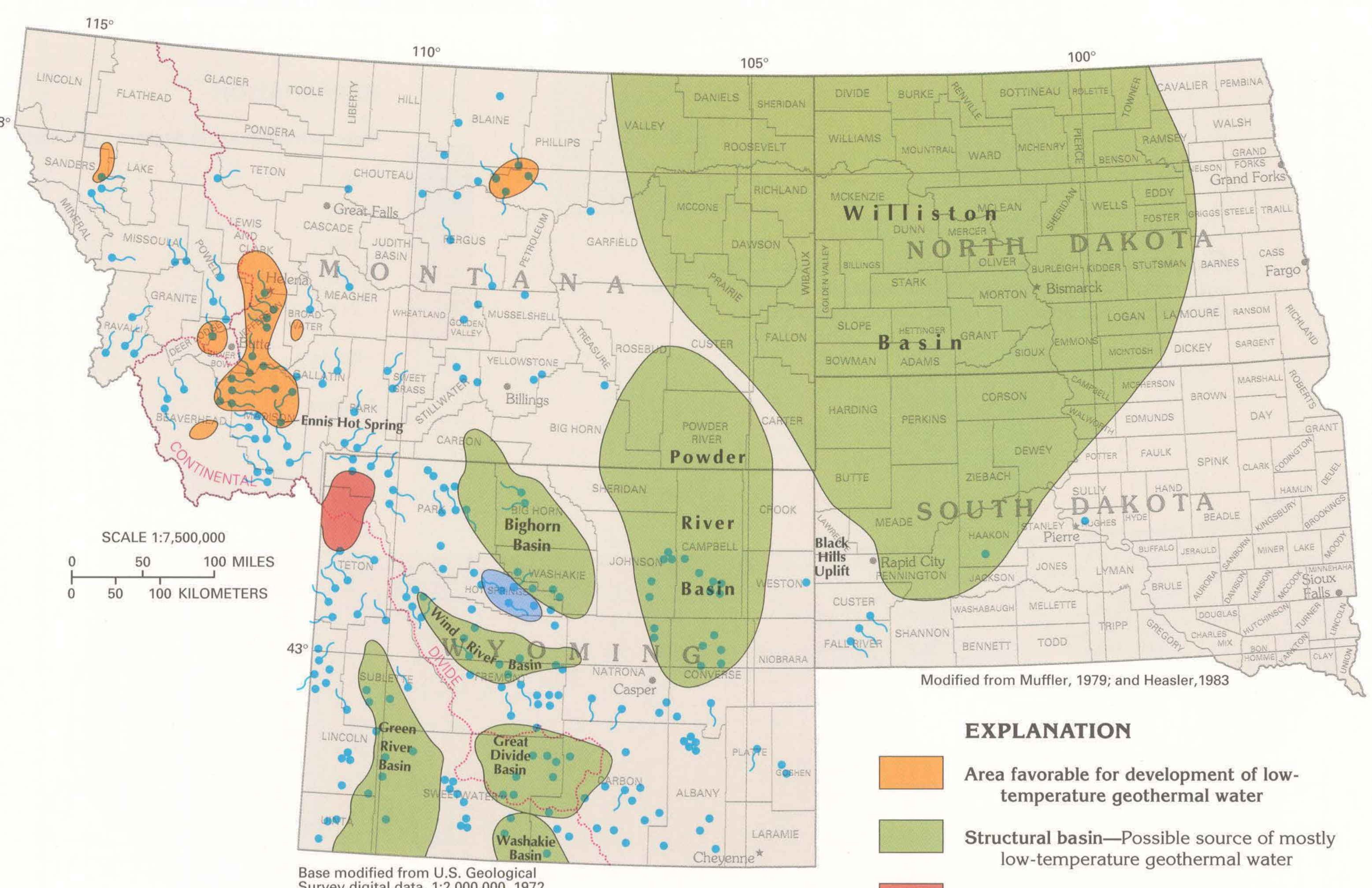


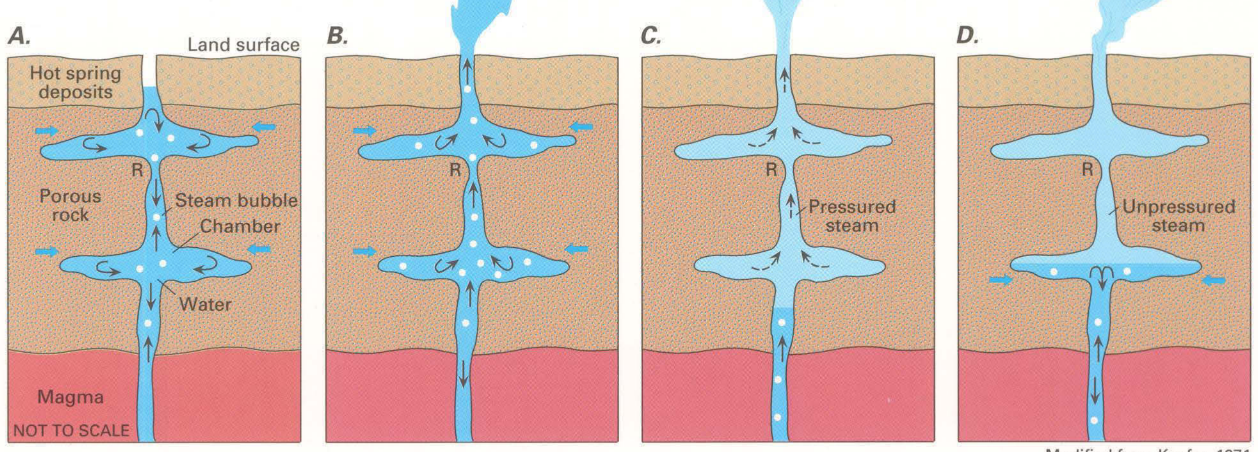
Figure 78. *Geothermal springs are mostly in the mountainous parts of Segment 8, but deep wells must be drilled to reach heated water in the major structural basins. Yellowstone National Park is one of the Nation's largest and best known areas of geothermal features.*

EXPLANATION

- Area favorable for development of low-temperature geothermal water
- Structural basin—Possible source of mostly low-temperature geothermal water
- Yellowstone National Park geothermal system
- Thermopolis hydrothermal system
- Geothermal spring
- Geothermal well

Figure 79. *An eruption of a geyser is a spectacular example of the sudden emergence of extremely hot geothermal water at the land surface. Much of the boiling water bursts into steam as pressure on the water is released.*

Figure 80. *Geysers erupt violently as steam and hot water are ejected under pressure. The solid arrows show the direction of water movement; dashed arrows show the movement of steam. Steam bubbles concentrate at the constrictions (**A**) and build up sufficient pressure to discharge as small eruptions (**B**), which relieve pressure and allow superheated water to flash suddenly into steam (**C**), which emerges as a full-scale eruption. Water begins to seep back into the emptied subsurface chambers and tubes (**D**) and the eruptive cycle begins anew.*



Recharge stage—Water heated by magma rises, mixes with cooler water in chambers in porous rock. Steam bubbles condense before reaching the surface.

Preliminary eruption stage—Pressure builds as steam bubbles clog at restriction (R). A little water spurts out at the surface.

Eruption stage—Enough water spurts out to cause steam to suddenly flash. The reduced pressure creates a chain reaction. Chambers empty suddenly and violently.

Recovery stage—Steam begins to condense in empty chambers and hot water from below begins to refill the system.

R.E. Davis, U.S. Geological Survey, 1989

Figure 81. *Thick deposits of travertine, which is a calcium carbonate mineral, can build up as the mineral precipitates from hot spring water.*

The temperature of ground water increases as the depth of burial of aquifers increases because of the geothermal gradient, which is a natural increase in the temperature of the Earth as depth increases. The geothermal gradient in the Williston Basin, for example, is about 2 degrees Fahrenheit per 100 feet of depth; thus, the temperature of the water at the bottom of a well that is 1,000 feet deep would be about 20 degrees Fahrenheit warmer than the average annual air temperature at the land surface. Maps of the temperature of water in the four deepest aquifers of the Northern Great Plains aquifer system (**figs. 82–85**) demonstrate that the water temperature increases as the depth of burial of the aquifers increases.

Water temperatures in the upper Cretaceous aquifers are 140 degrees Fahrenheit or less in the Williston Basin (**fig. 82**). In the Powder River Basin where the aquifers are more deeply buried, they contain water with temperatures of greater than 140 degrees Fahrenheit. Most of the water temperatures used to construct the map were measured in wells completed in the Fox Hills Sandstone.

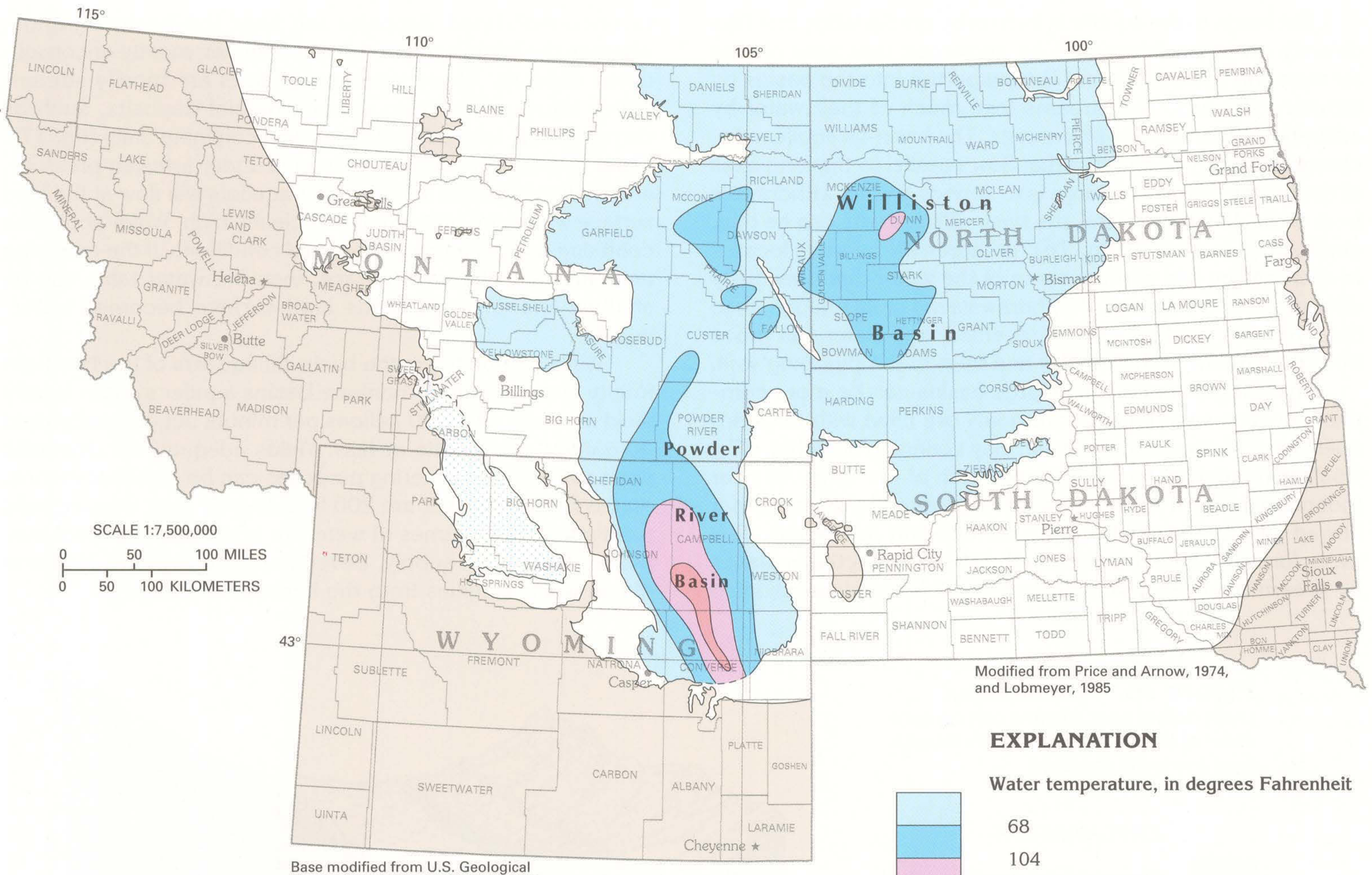
Temperatures of water from the underlying lower Cretaceous aquifers are greater than 212 degrees Fahrenheit in the Powder River Basin (**fig. 83**) and greater than 176 degrees Fahrenheit in part of the Williston Basin. Most of the temperatures used to construct the map were measured in wells completed in the Dakota Sandstone and are higher everywhere than those in the upper Cretaceous aquifers.

Temperatures of water in the upper Paleozoic aquifers (**fig. 84**) are greater than 212 degrees Fahrenheit in most of the Powder River and the Bighorn Basins and in small areas of the Williston Basin. The temperatures used to construct the figure were measured in wells completed in the Pennsylvanian Tensleep Sandstone in the Bighorn Basin and in the Madison Limestone or equivalent rocks of Mississippian age elsewhere. The upper Paleozoic aquifers are considerably deeper, especially in the structural basins, than the overlying lower Cretaceous aquifers.

Water in the lower Paleozoic aquifers (**fig. 85**) in the Williston Basin shows a temperature-distribution pattern similar to that of the upper Paleozoic aquifers; that is, temperatures are lowest near the margins of the basin and greatest near the center of the basin. Temperatures in water from the lower Paleozoic aquifers are higher almost everywhere than those of water from shallower aquifers. Water temperatures in the lower Paleozoic aquifers (mostly Cambrian sandstones and Ordovician limestones) are greater than 176 degrees Fahrenheit throughout large parts of the Williston Basin and are greater than 212 degrees Fahrenheit in most of the deep parts of the basin.

One theory used to explain how geothermal water becomes heated in areas that are underlain by complex geologic structures is shown in **figure 86**. Precipitation that falls in highland areas recharges the aquifer system. Some of the water moves downward along faults and fracture zones to great depths. As the water descends, it becomes heated because of the geothermal gradient. At some depth, the heated water becomes lighter than the overlying water and then moves upward along faults to discharge as springflow. Some of the upward-moving water can be intercepted by wells. The water that discharges from the Ennis Hot Spring in Madison County, Mont., and the Thermopolis hydrothermal system in Hot Springs County, Wyo. (**fig. 78**), is thought to have been heated by deep circulation along fault systems.

Deeply circulating ground water also can become heated by cooling magma (molten igneous rock) at great depths in the crust of the Earth. The water warms as it descends, possibly along fault zones that overlie the magma chamber, until it absorbs enough heat to become lighter than overlying water. The warm water then rises to the surface. The mechanism for the circulation of the water is the same, regardless of whether the water becomes heated by the geothermal gradient or by the buried, cooling magma.

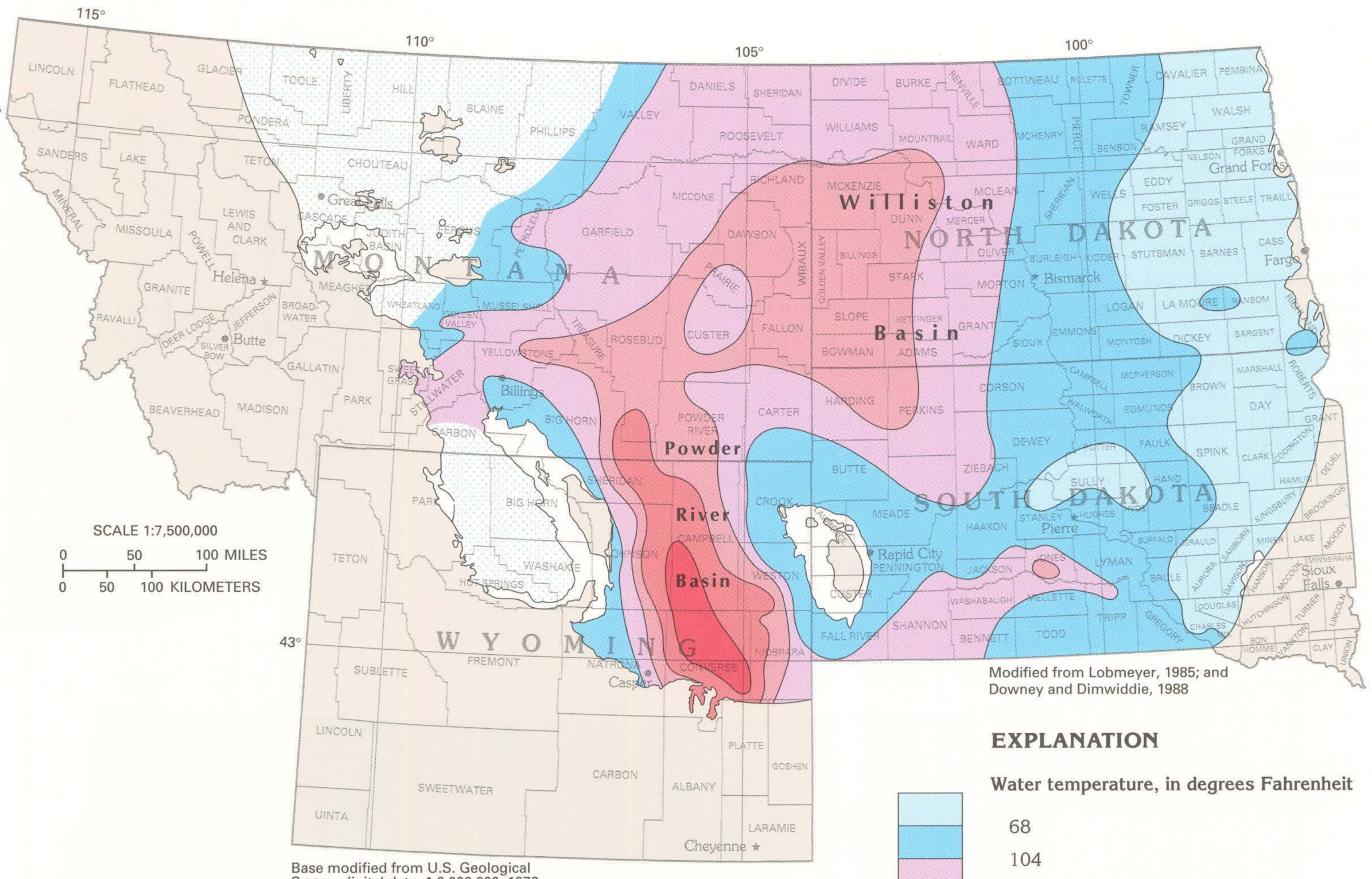


EXPLANATION

Water temperature, in degrees Fahrenheit

68
104
140
No data
Aquifers absent

Figure 82. The temperature of water in the upper Cretaceous aquifers of the Northern Great Plains aquifer system is less than 140 degrees Fahrenheit everywhere in the Williston Basin; in the Powder River Basin, water in these aquifers is slightly warmer.

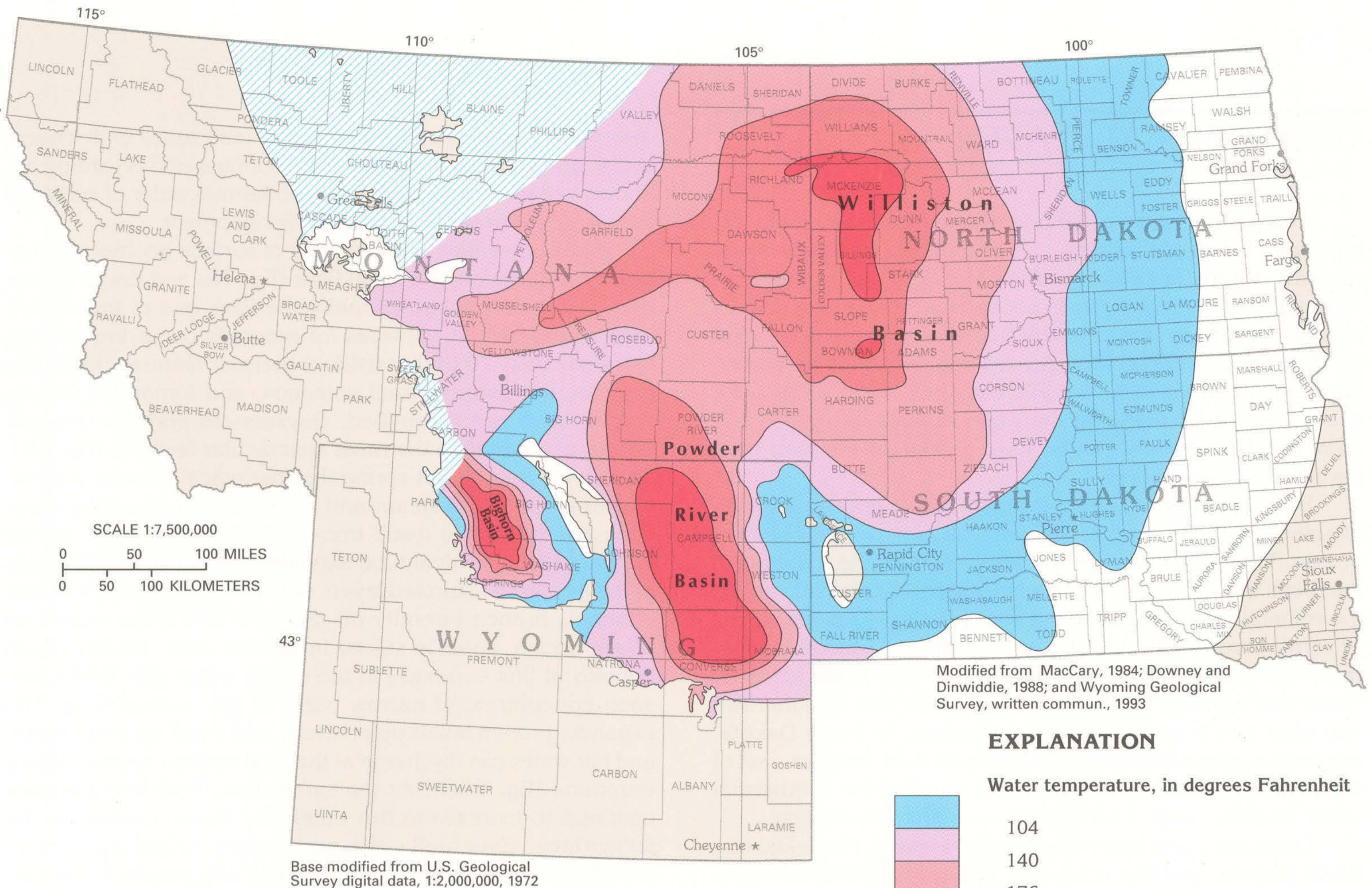


EXPLANATION

Water temperature, in degrees Fahrenheit

68
104
140
176
212
No data
Aquifers absent

Figure 83. Water everywhere in the lower Cretaceous aquifers of the Northern Great Plains aquifer system is warmer than that in the overlying upper Cretaceous aquifers.

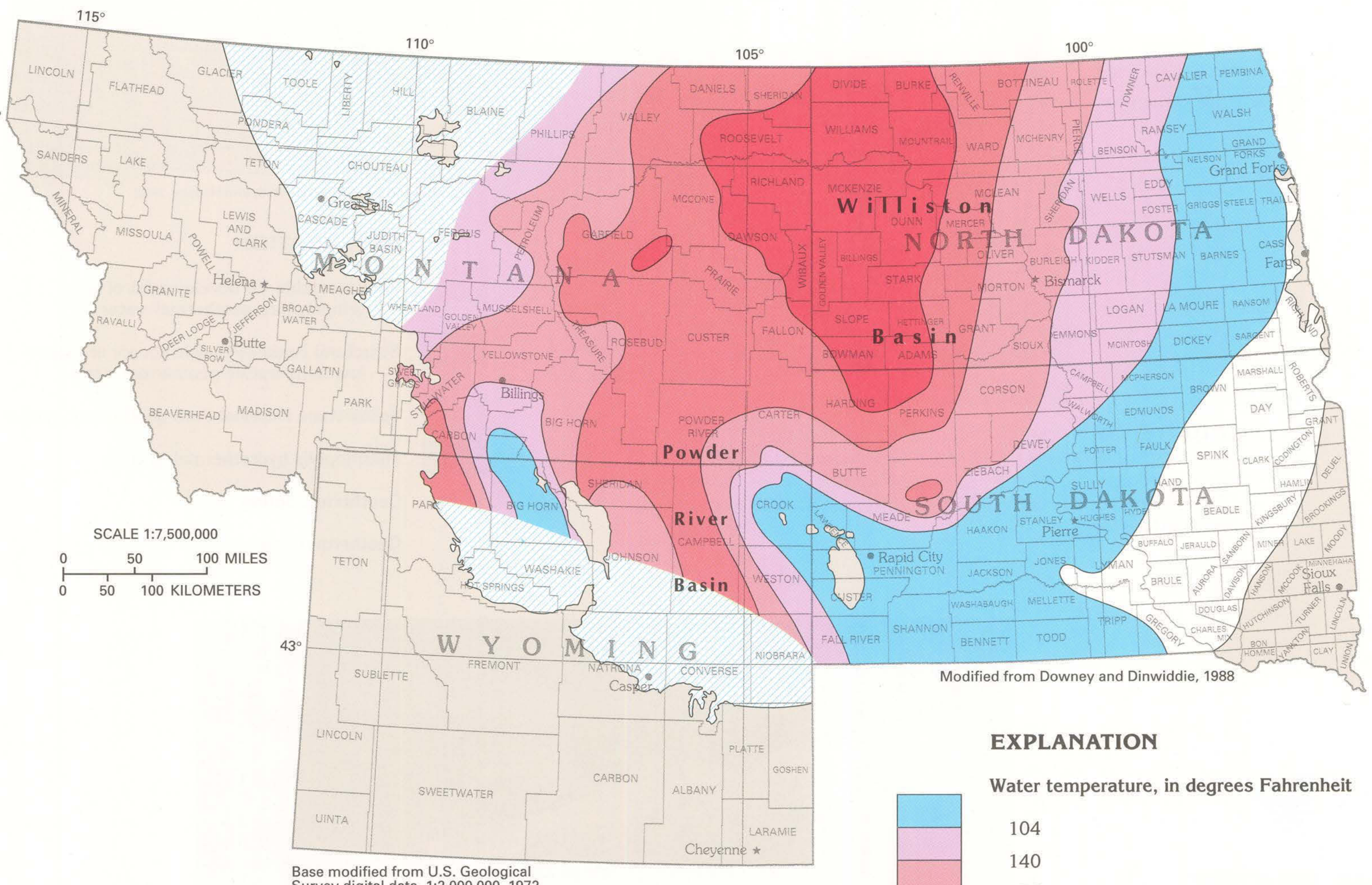


EXPLANATION

Water temperature, in degrees Fahrenheit

104
140
176
212
No Data
Aquifers absent

Figure 84. The temperature of water in the upper Paleozoic aquifers of the Northern Great Plains aquifer system is highest in the deep parts of the Bighorn, the Powder River, and the Williston Basins.



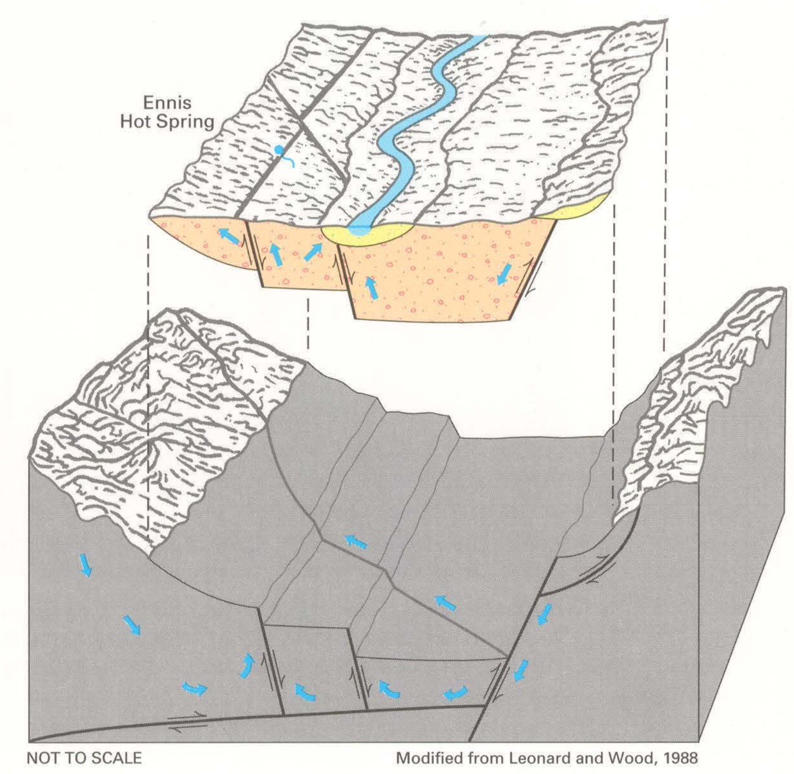
EXPLANATION

Water temperature, in degrees Fahrenheit

104
140
176
212
No data
Aquifers absent

Figure 85. The temperature of water in the lower Paleozoic aquifers of the Northern Great Plains aquifer system is greater than 212 degrees Fahrenheit in a large area in the deepest part of the Williston Basin.

Figure 86. Some geothermal water is thought to become heated because it circulates to great depths along faults.



EXPLANATION

Unconsolidated-deposit aquifers
Upper Tertiary aquifers
Bedrock
Direction of ground-water movement
Fault—Arrows show relative movement
Spring

GROUND-WATER PROBLEMS

The chemical quality of ground water is the most important ground-water problem in Segment 8. Highly mineralized water is present in shallow and deep aquifers in many parts of the four States. In most aquifers, the dissolved minerals in the water are from partial dissolution of aquifer minerals; in some, mineralized water has leaked into the aquifer from shallower or deeper aquifers.

Shallow aquifers can become contaminated where deeper aquifers that contain saline water discharge the water by upward leakage. In northeastern North Dakota, for example, aquifers in rocks of Cretaceous and Paleozoic age on the eastern flank of the Williston Basin contain highly mineralized water that is under artesian pressure. Where the bedrock aquifers are directly overlain by unconsolidated deposits, saline water can leak upward into permeable beds in the unconsolidated deposits. Some of the saline water discharges from the unconsolidated deposits to streams, and some flows into ponds and small lakes in depressions (**fig. 87**). Such ponds and lakes, which are common in Pembina, Walsh, and Grand Forks Counties, N. Dak. contain only salt-tolerant plants and aquatic life.

Seeps and ponds that contain saline water are numerous in Montana and present locally in Wyoming and North Dakota. Water in these seeps and ponds commonly contains dissolved-solids concentrations that range from 10,000 to 50,000 milligrams per liter. Most of the seeps form where unconsolidated deposits are underlain by almost impermeable bedrock (**fig. 88**). Recharge from precipitation enters closed depressions in the unconsolidated deposits and is unable to percolate downward into the bedrock. Evaporation is the only means by which the water can discharge; as a result, the water becomes increasingly mineralized with time. The saline water might collect as ponds in depressions on the land surface or can totally evaporate (**fig. 89**), thus leaving salt deposits where little or no vegetation will grow. The problem is intensified where the land is cultivated because plowing not only eliminates grasses and other natural vegetation that might transpire some of the precipitation, but loosens the soil and thus allows the precipitation to infiltrate rapidly into the unconsolidated deposits.

Locally, concentrations of fluoride greater than those recommended for drinking water by the U.S. Environmental Protection Agency are in water from some aquifers in Segment 8. Large fluoride concentrations have been reported in ground water in eastern North Dakota and South Dakota. Excessive concentrations of fluoride can cause mottling of tooth enamel in children.

Human activities can degrade the quality of ground water. For example, if uncased wells are drilled deep enough to penetrate an aquifer that contains saline water under artesian pressure, then the saline water can rise through the borehole and spread outward to contaminate shallower aquifers that contain freshwater (**fig. 90**). This type of contamination is possible only where the hydraulic head in the shallower aquifers is less than that in the aquifer that contains saline water. In areas where coal or metallic ores have been mined, precipitation that falls on, and percolates into, mine tailings or spoil piles where wastes have been stacked or ground water that moves laterally into the wastes can dissolve mineral material and carry contaminants into underlying and adjacent uncontaminated ground water (**fig. 91**). The mineralized ground water can move into wells or surface streams and ponds. Large concentrations of sulfate, iron and other metals, or radionuclides can result from the leaching of mine tailings. Other human activities that affect the quality of ground water include application of fertilizer and pesticides to cultivated land, disposal of human wastes in septic tanks, cesspools, or waste-treatment plants, disposal of liquid and solid wastes in landfills, storage of petroleum or other liquids in leaky underground tanks, and disposal of oil and gas production water or liquid industrial wastes by injection wells.

Declining water levels are a problem locally in unconfined and confined aquifers in all four States of Segment 8. In unconsolidated-deposit or consolidated-rock aquifers that contain water under unconfined conditions, large withdrawals from wells completed in the aquifers can reverse the prepumping direction of movement of ground water (**fig. 92**). Water that moves toward and discharges to streams under prepumping conditions can be intercepted by wells, particularly if large volumes of water are pumped from the wells. A cone of depression created by withdrawal from a single well, or several wells, can extend outward until it reaches a stream. Water from the stream can then move into the aquifer and toward the pumping well. If withdrawals are large enough, then streamflow can be decreased or completely diverted to the wells. Large withdrawals from pumping and flowing wells completed in the lower Cretaceous aquifers that are overlain by thick confining beds in eastern North and South Dakota have caused the hydraulic head in these aquifers to decline 200 feet or more over large areas.

John Bluemle, North Dakota Geological Survey, 1988

Figure 87. Saltwater lakes and ponds that result from upward leakage of saline water from bedrock aquifers are common in northeastern North Dakota.

Figure 88. Saline water can accumulate as ponds in depressions on the land surface of unconsolidated deposits that are underlain by almost impermeable bedrock. Evaporation causes a large increase in the dissolved-solids concentrations in the water.

EXPLANATION

- **Quaternary unconsolidated deposits**
- **Cultivated surface**—Plowed or fallow land
- **Bedrock**—Almost impermeable
- **Pond**—Contains saltwater

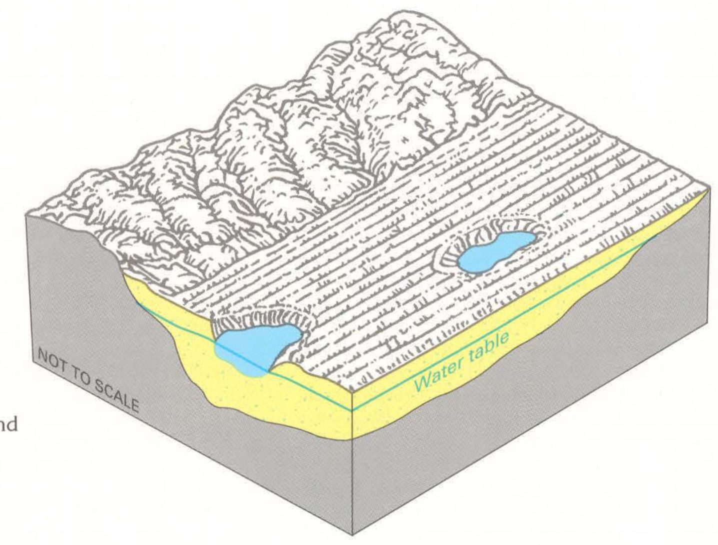


Figure 89. Where seeps of saltwater totally evaporate, salt deposits can cover large areas at the land surface. Such areas are unsuitable for pasture or cropland.

Figure 90. Uncased wells can provide conduits through which saline water in a deep aquifer with a high hydraulic head can move upward to contaminate shallower freshwater aquifers with smaller hydraulic heads.

EXPLANATION

- **Aquifer A**—Water contains small concentrations of dissolved solids
- **Aquifer B**—Water contains small concentrations of dissolved solids
- **Aquifer C**—Water contains large concentrations of dissolved solids
- **Confining unit**
- **Direction of ground-water movement**
- **Uncased drillhole**

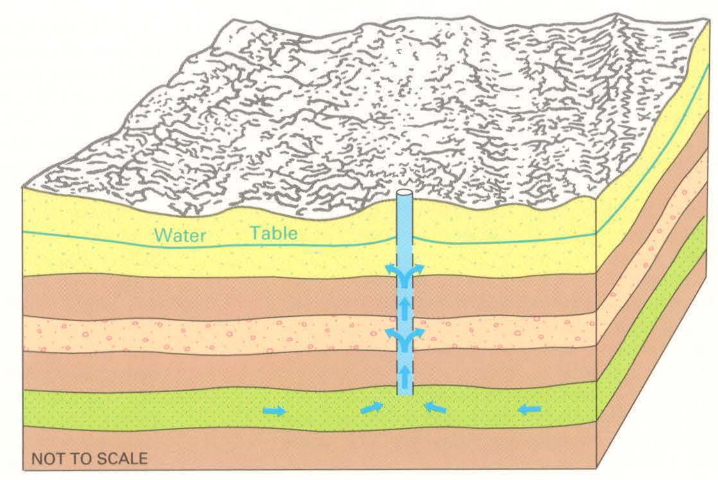
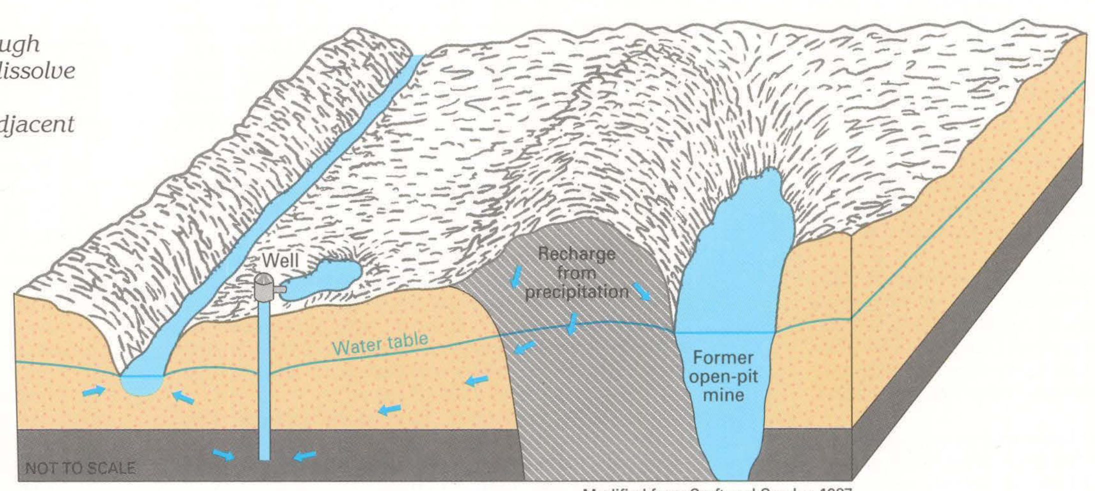


Figure 91. Water that percolates through mining wastes, such as tailings piles, can dissolve some of the minerals in the wastes and contaminate underlying ground water or adjacent ground and surface water.

EXPLANATION

- **Lower Tertiary aquifers**
- **Coal seam**
- **Tailings from open-pit mine**
- **Direction of ground-water movement**

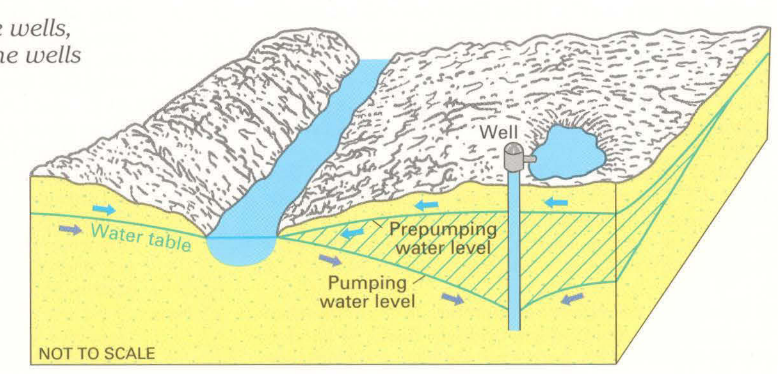


Modified from Croft and Crosby, 1987

Figure 92. Withdrawals from wells completed in unconsolidated-deposit aquifers can capture all or part of the flow of nearby streams. Water that formerly discharged to the stream has been diverted to the wells, and the stream loses water to the aquifer when the wells are pumped at large rates.

EXPLANATION

- **Unconsolidated-deposit aquifers**
- **Dewatered zone between prepumping and pumping water levels**
- **Direction of ground-water movement before pumping**
- **Direction of ground-water movement during pumping**



References

Regional summary

American Association of Petroleum Geologists, 1972, Geological highway map, Northern Rocky Mountains region; Idaho, Montana, and Wyoming: American Association of Petroleum Geologists Map 5, approximate scale 1:1,900,000, 1 sheet.

______1984, Geological highway map, Northern Great Plains region; Iowa, North Dakota, South Dakota, Nebraska, and Minnesota: American Association of Petroleum Geologists Map 12, approximate scale 1:1,900,000, 1 sheet.

Armstrong, C.A., 1983, Evaluation of the effects of Lake Audubon on ground- and surface-water levels in the Lake Nettie area, eastern McLean County, North Dakota: U.S. Geological Survey Water-Resources Investigations Report 83–4242, 41 p.

Bluemle, J.P., 1982, Bedrock geologic map of North Dakota: North Dakota Geological Survey Miscellaneous Map 21, scale 1:1,000,000, 1 sheet.

Cooley, M.E., 1986, Divisions of potential fracture permeability, based on distribution of structures and lineaments, *in* Sedimentary rocks of the Rocky Mountains–High Plains region, Western United States: U.S. Geological Survey Water-Resources Investigations Report 85–4091, scale 1:2,500,000, 2 sheets.

Columbia-North Pacific Technical Staff, 1971, Irrigation, Columbia-North Pacific Region, comprehensive framework study: Pacific Northwest River Basins Commission, Appendix IX, 343 p.

Downey, J.S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–G, 47 p.

Downey, J.S., and Dinwiddie, G.A., 1988, The regional aquifer system underlying the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming—Summary: U.S. Geological Survey Professional Paper 1402–A, 64 p.

Ellis, M.J., Adolphson, D.G., and West, R.E., 1969, Hydrology of a part of the Big Sioux drainage basin, eastern South Dakota: U.S. Geological Survey Hydrologic Investigations Atlas HA–311, 5 p.

Emmons, P.J., 1988, A digital simulation of the glacial-aquifer system in Sanborn and parts of Beadle, Miner, Hanson, Davison, and Jerauld Counties, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 87–4082, 59 p.

Fenneman, N.M., and Johnson, D.W., 1946, Physical divisions of the United States: U.S. Geological Survey, scale 1:7,000,000, 1 sheet.

Freethey, G.W., Kimball, B.A., Wilbery, D.E., and Hood, J.W., 1988, Hydrogeology, Upper Colorado River Basin, Colorado, Utah, Wyoming, and Arizona: U.S. Geological Survey Hydrologic Investigations Atlas HA–698, scales 1:2,500,000 and 1:5,000,000, 2 sheets.

Gebert, W.A., Graczyk, D.J., and Krug, W.R., 1987, Average annual runoff in the United States, 1951–80: U.S. Geological Survey Hydrologic Investigations Atlas HA–710, scale 1:7,500,000, 1 sheet.

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B., 1984, Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–B, 63 p.

Hamilton, L.J., 1985, Water resources of Aurora and Jerauld Counties, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 84–4030, 58 p.

Heath, R.C., 1984, Ground-water regions of the United States: U.S. Geological Survey Water-Supply Paper 2242, 78 p.

King, P.B., and Beikman, H.M., 1974, Geologic map of the United States: U.S. Geological Survey, scale 1:2,500,000, 3 sheets.

Leonard, R.B., Signor, D.C., Jorgensen, D.G., and Helgesen, J.O., 1984, Geohydrology and hydrochemistry of the Dakota aquifer, central United States, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5–6, 1982: National Water Well Association, p. 229–237.

Lines, G.C., and Glass, W.R., 1975, Water resources of the thrust belt of western Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–539, scales 1:500,000 and 1:250,000, 3 sheets.

Love, J.D., and Christiansen, A.C., 1985, Geologic map of Wyoming: U.S. Geological Survey, scale 1:500,000, 3 sheets.

Lowry, M.E., Head, W.J., Rankl, J.G., and Busby, J.F., 1986, Water resources of Weston County, Wyoming: U.S. Geological Survey Water-Resources Investigations Report 84–4079, 33 p.

Missouri River Basin Interagency Committee, 1969, Comprehensive framework study—Missouri River Basin, *in* Land resources availability and hydrologic analyses and projections: U.S. Government Printing Office, v. 6, appendixes, 75 p.

North Dakota State Water Commission, 1986, Map showing glacial drift aquifers in North Dakota and estimated potential yields: North Dakota State Water Commission, scale 1:1,000,000, 1 sheet.

Pacific Northwest River Basins Commission Columbia–North Pacific Technical Staff, 1971, Irrigation, Columbia–North Pacific Region, comprehensive framework study: Pacific Northwest River Basins Commission, App. IX, 343 p.

Perry, E.S., 1962, Montana in the geologic past: Montana Bureau of Mines and Geology Bulletin 26, 78 p.

Peterson, J.A., 1984, Stratigraphy and sedimentary facies of the Madison Limestone and associated rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–A, 34 p.

Ragsdale, J.O., 1982, Ground-water levels in Wyoming, 1971 through part of 1980: U.S. Geological Survey Open-File Report 82–859, 200 p.

Ross, C.P., Andrews, D.A., and Witkind, I.J., 1955, Geologic map of Montana: U.S. Geological Survey, scale 1:500,000, 2 sheets.

Solley, W.B., Pierce, R.R., and Perlman, H.A.,1993, Estimated use of water in the United States in 1990: U.S. Geological Survey Circular 1081, 76 p.

Sun, R.J., and Weeks, J.B., 1991, Bibliography of Regional Aquifer-System Analysis program of the U.S. Geological Survey, 1978–92: U.S. Geological Survey Water-Resources Investigations Report 91–4122, 92 p.

Thelin, G.P., and Heimes, F.J., 1987, Mapping irrigated cropland from Landsat data for determination of water use from the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–C, 38 p.

U.S. Geological Survey, 1970, The National atlas of the United States of America: U.S. Geological Survey, 417 p.

______1985, National water summary, 1984—Hydrologic events, selected water-quality trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 467 p.

______1986, National water summary, 1985—Hydrologic events and surface-water resources: U.S. Geological Survey Water-Supply Paper 2300, 506 p.

______1988, National water summary, 1986—Hydrologic events and groundwater quality: U.S. Geological Survey Water-Supply Paper 2325, 560 p.

Welder, G.E., 1968, Ground-water reconnaissance of the Green River Basin, southwestern Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–290, scales 1:62,500, 1:1,000,000, and 1:250,000, 2 sheets.

Principal aquifers

Bluemle, J.P., 1982, Bedrock geologic map of North Dakota: North Dakota Geological Survey Miscellaneous Map 21, scale 1:1,000,000, 1 sheet.

Bredehoeft, J.D., Neuzil, C.E., and Milly, P.C.D., 1983, Regional flow in the Dakota aquifer—A study of the role of confining layers: U.S. Geological Survey Water-Supply Paper 2237, 45 p.

Downey, J.S., 1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–G, 47 p.

Downey, J.S., and Dinwiddie, G.A., 1988, The regional aquifer system underlying the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming—Summary: U.S. Geological Survey Professional Paper 1402–A, 64 p.

Jorgensen, D.G., and Signor, D.C., eds., 1984, Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5–6, 1982: National Water Well Association, 247 p.

King, P.B., 1976, Precambrian geology of the United States, an explanatory text to accompany the Geologic Map of the United States: U.S. Geological Survey Professional Paper 902, 85 p.

King, P.B., and Beikman, H.M., 1974, Geologic map of the United States: U.S. Geological Survey, scale 1:2,500,000, 3 sheets.

______1976, The Paleozoic rocks, a discussion to accompany the Geologic Map of the United States: U.S. Geological Survey Professional Paper 903, 76 p.

______1978, The Cenozoic rocks, a discussion to accompany the Geologic Map of the United States: U.S. Geological Survey Professional Paper 904, 82 p.

Konizeski, R.L., McMurtrey, R.G., and Brietkrietz, Alex, 1962, Preliminary report on the geology and water resources of the southern part of the Deer Lodge Valley, Montana: Montana Bureau of Mines and Geology Bulletin 31, 24 p.

Love, J.D., and Christiansen, A.C., 1985, Geologic map of Wyoming, preliminary edition: U.S. Geological Survey, scale 1:500,000, 3 sheets.

Missouri River Basin Interagency Committee, 1969, Comprehensive framework study—Missouri River Basin, *in* Land resources availability and hydrologic analyses and projections: U.S. Government Printing Office, v. 6, appendixes, 75 p.

North Dakota State Water Commission, 1986, Map showing glacial drift aquifers in North Dakota and estimated potential yields: North Dakota State Water Commission, scale 1:1,000,000, 1 sheet.

Perry, E.S., 1962, Montana in the geologic past: Montana Bureau of Mines and Geology Bulletin 26, 78 p.

Reeder, M.O., 1978, Summary appraisals of the Nation's ground-water resources—Souris–Red–Rainy Region: U.S. Geological Survey Professional Paper 813–K, 25 p.

Ross, C.P., Andrews, C.A., and Witkind, I.J., 1955, Geologic map of Montana: U.S. Geological Survey, scale 1:500,000, 2 sheets.

Taylor, O.J., 1978, Summary appraisals of the Nation's ground-water resources—Missouri Basin region: U.S. Geological Survey Professional Paper 813–Q, 41 p.

U.S. Geological Survey, 1985, National water summary, 1984—Hydrologic events, selected water-quality trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 467 p.

High Plains Aquifer System

Babcock, H.M., and Bjorklund, L.J., 1956, Ground-water geology of parts of Laramie and Albany Counties, Wyoming, and Weld County, Colorado: U.S. Geological Survey Water-Supply Paper 1367, 61 p.

Bloyd, R.M., Jr., 1975, Summary appraisals of the Nation's ground-water resources—Upper Mississippi Region: U.S. Geological Survey Professional Paper 813–B, 22 p.

Cooley, M.E., and Crist, M.A., 1981, Stratigraphy and potentiometric surface of the Tertiary formations in southeastern Wyoming and an adjacent part of Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–1308, scale 1:168,960, 1 sheet.

Crist, M.A., 1977, Hydrologic evaluation of the Arikaree Formation near Lusk, Niobrara and Goshen Counties, Wyoming: U.S. Geological Survey Water-Resources Investigations Open-File Report 77–111, 23 p.

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B., 1984, Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–B, 63 p.

Gutentag, E.D., and Weeks, J.B., 1980, Water table in the High Plains aquifer in 1978 in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–642, scale 1:2,500,000.

King, P.B., and Beikman. H.M., 1974, Geologic map of the United States: U.S. Geological Survey, scale 1:2,500,000, 3 sheets.

Krothe, N.C., Oliver, J.W., and Weeks, J.B., 1982, Dissolved solids and sodium in water from the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–658, scale 1:2,500,000, 2 sheets.

Lines, G.C., 1976, Digital model to predict effects of pumping from the Arikaree aquifer in the Dwyer area, southeastern Wyoming: U.S. Geological Survey Water-Resources Investigations Open-File Report 8–76, 24 p.

Love, J.D., and Christiansen, A.C., 1985, Geologic map of Wyoming: U.S. Geological Survey, scale 1:500,000, 3 sheets.

Lowry, M.E., and Crist, M.A., 1967, Geology and ground-water resources of Laramie County, Wyoming: U.S. Geological Survey Water-Supply Paper 1834, 71 p.

Luckey, R.R., Gutentag, E.D., and Weeks, J.B., 1981, Water-level and saturated-thickness changes, predevelopment to 1980, in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–652, scale 1:2,500,000, 2 sheets.

Morris, D.A., and Babcock, H.M., 1960, Geology and ground-water resources of Platte County, Wyoming, *with a section on* Chemical quality of the water, by R.J. Langford: U.S. Geological Survey Water-Supply Paper 1490, 195 p.

Rapp, J.R., Visher, F.N., and Littleton, R.T., 1957, Geology and ground-water resources of Goshen County, Wyoming, *with a section on* Chemical quality of the ground water, by W.H. Durum: U.S. Geological Survey Water-Supply Paper 1379, 145 p.

Sun, R.J., and Weeks, J.B., 1991, Bibliography of Regional Aquifer-System Analysis program of the U.S. Geological Survey: U.S. Geological Survey Water-Resources Investigations Report 91–4122, 92 p.

Taylor, O.J., 1978, Summary appraisals of the Nation's ground-water resources—Missouri Basin region: U.S. Geological Survey Professional Paper 813–Q, 41 p.

U.S. Geological Survey 1985, National water summary, 1984—Hydrologic events, selected water-quality trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 467 p.

______1988, National water summary, 1986—Hydrologic events and ground-water quality: U.S. Geological Survey Water-Supply Paper 2325, 560 p.

Weeks, J.B., and Gutentag, E.D., 1981, Bedrock geology, altitude of the base, and 1980 saturated thickness of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–648, scale 1:2,500,000, 2 sheets.

Northern Great Plains aquifer system

Bloyd, R.M., Jr., 1975, Summary appraisals of the Nation's ground-water resources—Upper Mississippi Region: U.S. Geological Survey Professional Paper 813–B, 22 p.

Bluemle, J.P., 1982, Bedrock geologic map of North Dakota: North Dakota Geological Survey Miscellaneous Map 21, scale 1:1,000,000, 1 sheet.

Bredehoeft, J.D., Neuzil, C.E., and Milly, P.C.D., 1983, Regional flow in the Dakota aquifer—A study of the role of confining layers: U.S. Geological Survey Water-Supply Paper 2237, 45 p.

Brown, D.L., Blankennagel, R.K., MacCary, L.M., and Peterson, J.A., 1984, Correlation of paleostructure and sediment deposition in the Madison Limestone and associated rocks in parts of Montana, North Dakota, South Dakota, Wyoming, and Nebraska: U.S. Geological Survey Professional Paper 1273–B, 24 p.

Busby, J.F., Plummer, L.N., Lee, R.W., and Hanshaw, B.B., 1991, Geochemical evolution of water in the Madison aquifer in parts of Montana, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–F, 89 p.

Butler, R.D., 1984, Hydrogeology of the Dakota aquifer system, Williston Basin, North Dakota, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5–6, 1982: National Water Well Association, p. 99–108.

Case, H.L., III, 1984, Hydrology of Inyan Kara and Dakota—Newcastle aquifer system, South Dakota, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Thesis Conference on Geohydrology, October 5–6, 1982: National Water Well Association, p. 147–165.

Crosby, O.A., Armstrong, C.A., and Paulson, Q.F., 1978, Water resources of North Dakota, *in* U.S. Geological Survey and Bureau of Reclamation, Mineral and water resources of North Dakota: U.S. Government Printing Office, Committee on Printing, 93d Congress, 1st Session, 252 p.

Dinwiddie, G.A., and Downey, J.S., 1986, Northern Great Plains regional aquifer-system study, *in* Sun, R.J., ed., Regional aquifer system analysis program of the U.S. Geological Survey—Summary of projects, 1978–84: U.S. Geological Survey Circular 1002, p. 50–71.

Downey, J.S., 1982, Hydrodynamics of the Williston Basin in the Northern Great Plains, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5–6, 1982: National Water Well Association, p. 92–98.

______1984, Geohydrology of the Madison and associated aquifers in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–G, 47 p.

______1987, Regional bedrock aquifers of the Northern Great Plains, north-central United States, *in* McLean, J.S., and Johnson, A.I., eds., Regional aquifer systems of the United States—Aquifers of the western mountain area: American Water Resources Association Monograph 14, p. 5–13.

Downey, J.S., and Dinwiddie, G.A., 1988, The regional aquifer system underlying the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming—Summary: U.S. Geological Survey Professional Paper 1402–A, 64 p.

Dyer, C.F., and Goehring, A.J., 1965, Artesian-water supply of the Dakota Formation, southeastern South Dakota: U.S. Geological Survey Open-File Report, 49 p.

Feltis, R.D., 1977 Geology and water resources of the northern part of the Judith Basin, Montana: Montana Bureau of Mines and Geology Bulletin 101, 65 p.

______1980a, Dissolved-solids and ratio maps of water in the Madison Group, Montana: Butte, Montana, Bureau of Mines and Geology Hydrogeologic Map 3, scale 1:1,000,000, 1 sheet.

______1980b, Potentiometric surface map of water in the Madison Group, Montana: Montana Bureau of Mines and Geology Hydrogeologic Map 2, scale 1:1,000,000, 1 sheet.

______1980c, Water resources of the Judith Basin, central Montana: Montana Bureau of Mines and Geology Hydrogeologic Map 1, scale 1:1,000,000, 1 sheet.

______1982a, Map showing altitude of the top of the Dakota Formation and equivalent rocks, Montana: U.S. Geological Survey Water-Resources Investigations Report 82–4039, scale 1:1,000,000, 1 sheet.

______1982b, Map showing altitude of the top of the Eagle Sandstone, Montana: U.S. Geological Survey Water-Resources Investigations Report 82–4034, scale 1:1,000,000, 1 sheet.

______1982c, Map showing altitude of the top of the Fox Hills–lower Hell Creek aquifer, Montana: U.S. Geological Survey Water-Resources Investigations Report 82–4041, scale 1:1,000,000, 1 sheet.

______1982d, Map showing altitude of the top of the Judith River Formation, Montana: U.S. Geological Survey Water-Resources Investigations Report 82–4027, scale 1:1,000,000, 1 sheet.

______1982e, Map showing cumulative thickness of sandstone in the Dakota Formation and equivalent rocks, Montana: U.S. Geological Survey Water-Resources Investigations Report 82–4040, scale 1:1,000,000, 1 sheet.

Groff, S.L., 1958, A summary report on the ground-water situation in Montana: Montana Bureau of Mines and Geology Information Circular 26, 45 p.

Hanshaw, B.B., Busby, John and Lee, Roger, 1978, Geochemical aspects of the Madison aquifer system, *in* The economic geology of the Williston Basin, Montana, North Dakota, South Dakota, Saskatchewan, Manitoba—Williston Basin Conference, 24th, Billings, Mont.: Montana Geological Society, p. 385–389.

Helgesen, J.O., Jorgensen, D.G., Leonard, R.B., and Signor, D.C., 1984, Regional study of the Dakota aquifer (Darton's Dakota revisited), *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5–6, 1982: National Water Well Association, p. 69–73.

Hopkins, W.B., 1978, Deep aquifers of eastern Montana, *in* The economic geology of the Williston Basin, Montana, North Dakota, South Dakota, Saskatchewan, Manitoba—Williston Basin Conference, 24th, Billings, Mont.: Montana Geological Society, p. 392–403.

Jorgensen, D.G., Downey, Joe, Dutton, A.R., and Maclay, R.W., 1988, Region 16, Central Nonglaciated Plains, Chapter 19 *of* Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology, v. O–2 of The Geology of North America: Geological Society of America, p. 141–156.

King, P.B., and Beikman, H.M., 1974, Geologic map of the United States: U.S. Geological Survey, scale 1:2,500,000, 3 sheets.

Krothe, N.C., and Kempton, J.P., 1988, Region 14, Central Glaciated Plains, Chapter 17 *of* Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology, v. O–2 of The Geology of North America: Geological Society of America, p. 129–132.

Lennox, D.H., Maathuis, H., and Pederson, D., 1988, Region 13, Western Glaciated Plains, Chapter 16 *of* Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology, v. O–2 of The Geology of North America: Geological Society of America, p. 115–128.

Leonard, R.B., Signor, D.C., Jorgensen, D.G., and Helgesen, J.O., 1984, Geohydrology and hydrochemistry of the Dakota aquifer, central United States, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5–6, 1982: National Water Well Association, p. 229–237.

Lobmeyer, D.H., 1985, Freshwater heads and ground-water temperatures in aquifers of the Northern Great Plains of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402–D, 11 p.

Love, J.D., and Christiansen, A.C., 1985, Geologic map of Wyoming: U.S. Geological Survey, scale 1:500,000, 3 sheets.

Love, J.D., Christiansen, A.C., and Ver Ploeg, A.J., 1993, Stratigraphic chart showing Phanerozoic nomenclature for the State of Wyoming: Geological Survey of Wyoming Map Series 41, 1 sheet.

McLean, J.S., and Johnson, A.I., eds., 1988, Regional aquifer systems of the United States—Aquifers of the western mountain area: American Water Resources Association Monograph 14, 229 p.

Missouri River Basin Interagency Committee, 1967, The Missouri River Basin comprehensive framework study—Ground water in the Missouri River Basin: Missouri River Basin Interagency Committee, scale 1:2,500,000, 12 sheets.

______1969, Comprehensive framework study—Missouri River Basin, *in* Land resources availability and hydrologic analyses and projections: U.S. Government Printing Office, v. 6, 75 p.

Montana Bureau of Mines and Geology, 1978, Ground water of the Fort Union coal region, eastern Montana: Montana Bureau of Mines and Geology Special Publication 80, 47 p.

Montana Water Resources Board, 1969, Ground water in Montana, a comprehensive water and related land resources plan for the State of Montana: Montana Water Resources Board Inventory Series Report no. 16, 145 p.

Neuzil, C.E., Bredehoeft, J.D., and Wolff, R.G., 1982, Leakage and fracture permeability in the Cretaceous shales confining the Dakota aquifer in South Dakota, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5–6, 1982: National Water Well Association, p. 113–120.

Paulson, Q.F., 1983, Guide to North Dakota's ground-water resources: U.S. Geological Survey Water-Supply Paper 2236, 25 p. (Reprinted 1986)

Peter, K.D., 1982, Hydrochemistry of lower Cretaceous sandstone aquifers, Northern Great Plains, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5-6, 1982: National Water Well Association, p. 197–208.

Peterson, J.A., 1984, Stratigraphy and sedimentary facies of the Madison Limestone and associated rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming: U.S.Geological Survey Professional Paper 1273–A, 34 p.

Ross, C.P., Andrews, D.A., and Witkind, I.J., 1955, Geologic map of Montana: U.S. Geological Survey, scale 1:5,000,000, 2 sheets.

Schoon, R.A., 1984, Overview of South Dakota's Dakota aquifer, *in* Jorgensen, D.G. and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5–6, 1982: National Water Well Association, p. 38–40.

Stephenson, D.A., Fleming, A.H., and Mickelson, D.M., 1988, Glacial deposits, Chapter 35 *of* Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology, v. O–2 of The Geology of North America: Geological Society of America, p. 301–314.

Swenson, F.A., 1955, Geology and ground-water resources of the Missouri River valley in northeastern Montana: U.S. Geological Survey Water-Supply Paper 1263, 128 p.

Swenson, F.A., Miller, W.R., Hodson, W.G., and Visher, F.N., 1975, Water in the Madison Group, Powder River Basin, Wyoming and Montana: U.S. Geological Survey Open-File Report 75–660, 26 p.

Taylor, O.J., 1978, Summary appraisals of the Nation's ground-water resources, Missouri Basin region: U.S. Geological Survey Professional Paper 813–Q, 41 p.

Thayer, P.A., 1983, Relationship of porosity and permeability to petrology of the Madison Limestone in rock cores from three test wells in Montana and Wyoming: U.S. Geological Survey Professional Paper 1273–C, 29 p.

Wartman, B.L., 1984, Geology and hydrology of the Inyan Kara Formation (lower Cretaceous), North Dakota, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5–6, 1982: National Water Well Association, p. 22–25.

Weeks, J.B., and Sun, R.J., 1987, Regional aquifer-system analysis program of the U.S. Geological Survey—Bibliography, 1978–86: U.S. Geological Survey Water-Resources Investigations Report 87–4138, 81 p.

Winter, T.C., Benson, R.D., Engberg, R.A., Wiche, G.J., Emerson, D.G., Crosby, O.A., and Miller, J.E., 1984, Synopsis of ground-water and surface-water resources of North Dakota: U.S. Geological Survey Open-File Re-port 84–732, 127 p.

Upper Colorado River Basin aquifer system

Bradley, W.M., 1964, Geology of Green River Formation and associated Eocene rocks in southwestern Wyoming and adjacent parts of Colorado and Utah: U.S. Geological Survey Professional Paper 496–A, 86 p.

Driver, N.E., and others, 1984, Hydrology of area 53, Northern Great Plains and Rocky Mountain Coal Provinces, Colorado, Wyoming, and Utah: U.S. Geological Survey Water-Resources Investigations Open-File Report 83–765, 87 p.

Freethey, G.W., 1988a, Lithologic and hydrologic properties of Mesozoic rocks in the Upper Colorado River Basin, *in* McLean, J.S., and Johnson, A.I., eds., Regional aquifer systems of the United States—Aquifers of the western mountain area: American Water-Resources Association Monograph 14, p. 81–99.

______1988b, Upper Colorado River Basin regional aquifer-system analysis—Mesozoic rocks in Colorado, Utah, and Wyoming, Arizona, and New Mexico, *in* McLean, J.S., and Johnson, A.I., eds, Regional aquifer systems of the United States—Aquifers of the western mountain area: American Water-Resources Association Monograph 14, p. 57–70.

Freethey, G.W., Kimball, B.A., Wilberg, D.E., and Hood, J.W., 1988, General hydrogeology of the aquifers of Mesozoic age, Upper Colorado River Basin—excluding the San Juan Basin—in Colorado, Utah, Wyoming, and Arizona: U.S. Geological Survey Hydrologic Investigations Atlas HA–698, scale 1:2,500,000, 2 sheets.

Geldon, A.L., 1988a, Hydrostratigraphic characterization of Paleozoic formations in the Upper Colorado River Basin, Arizona, Colorado, New Mexico, Utah, and Wyoming, *in* McLean, J.S., and Johnson, A.I., eds., Regional aquifer systems of the United States—Aquifers of the western mountain area: American Water-Resources Association Monograph 14, p. 135–159.

______1988b, Porosity and permeability of the Paleozoic rocks in the Upper Colorado River Basin, Arizona, Colorado, New Mexico, Utah, and Wyoming, *in* McLean, J.S., and Johnson, A.I., eds., Regional aquifer systems of the United States—Aquifers of the western mountain area: American Water-Resources Association Monograph 14, p. 171–190.

Glover, K.C., Naftz, D.L., and Martin, L.J., in press, Geohydrology of Tertiary rocks in parts of the Upper Colorado River Basin, Colorado, Utah, Wyoming, and Arizona: U.S. Geological Survey Professional Paper 1411–D.

Kuhn, Gerhard, Daddow, P.B., Craig, G.S., Jr., and others, 1983, Hydrology of area 54, Northern Great Plains and Rocky Mountain Coal Province, Colorado and Wyoming: U.S. Geological Survey Water-Resources Investigations Open-File Report 83–146, 95 p.

Linder-Lundsford, J.B., Kimball, B.A., Chafin, D.T., and Bryant, C.G., 1989, Hydrogeology of aquifers of Paleozoic age, Upper Colorado River Basin—excluding the San Juan Basin—in Colorado, Utah, Wyoming, and Arizona: U.S. Geological Survey Hydrologic Investigations Atlas HA–702, scale 1:2,500,000, 2 sheets.

Love, J.D., and Christiansen, A.C., 1985, Geologic map of Wyoming: U.S. Geological Survey, scale 1:500,000, 3 sheets.

Lowham, H.W., Peterson, D.A., Larson, L.R., Zimmerman, E.A., Ringen, B.H., and Mora, K.L., 1985, Hydrology of area 52—Rocky Mountain Coal Province, Wyoming, Colorado, Idaho, and Utah: U.S. Geological Survey Water-Resources Investigations Open-File Report 83–761, 96 p.

Price, Don, and Arnow, Ted, 1974, Summary appraisals of the Nation's ground-water-resources—Upper Colorado region: U.S. Geological Survey Professional Paper 813–C, 40 p.

Price, Don, and Waddell, K.M., 1973, Selected hydrologic data in the Upper Colorado River Basin: U.S. Geological Survey Hydrologic Investigations Atlas HA–477, scale 1:2,500,000, 2 sheets.

Roehler, H.W., 1990, Stratigraphy of the Mesaverde Group in the central and eastern Greater Green River Basin, Wyoming, Colorado, and Utah: U.S. Geological Survey Professional Paper 1508, 52 p.

______1992a, Introduction to Greater Green River Basin geology, physiography, and history of investigations: U.S. Geological Survey Professional Paper 1506–A, 14 p.

______1992b, Correlation, composition, areal distribution, and thickness of Eocene stratigraphic units, Greater Green River Basin, Wyoming, Colorado, and Utah: U.S. Geological Survey Professional Paper 1506–E, 49 p.

Taylor, O.J., compiler, 1987, Oil shale, water resources, and valuable minerals of the Piceance Basin, Colorado—The challenge and choices of development: U.S. Geological Survey Professional Paper 1310, 143 p.

Taylor, O.J., Freethey, G.W., and Glover, K.C., 1986, Upper Colorado River Basin regional aquifer-system study, *in* Sun, R.J., ed., Regional aquifer-system analysis program of the U.S. Geological Survey—Summary of projects, 1978–84: U.S. Geological Survey Circular 1002, p. 223–233.

Taylor, O.J., and Hood, J.W., 1988, Region 3, Colorado Plateau and Wyoming Basin, Chapter 6 of Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology: v. 0–2 of The Geology of North America: Geological Society of America, p. 51–58.

Taylor, O.J., and Hood, J.W., and Zimmerman, E.A., 1983, Plan of study for the regional aquifer system analysis of the Upper Colorado River Basin in Colorado, Utah, Wyoming, and Arizona: U.S. Geological Survey Water-Resources Investigations Report 83–4184, 23 p.

______1986, Hydrogeologic framework of the Upper Colorado River Basin—excluding the San Juan Basin—Colorado, Utah, Idaho, Wyoming, and Arizona: U.S. Geological Survey Hydrologic Investigations Atlas HA–687, scale 1:3,000,000, 2 sheets.

Weigel, J.F., 1987, Selected hydrologic and physical properties of Mesozoic formations in the Upper Colorado River Basin in Arizona, Colorado, Utah, and Wyoming—excluding the San Juan Basin: U.S. Geological Survey Water-Resources Investigations Report 86–4170, 68 p.

Welder, G.E., 1968, Ground-water reconnaissance of the Green River Basin, southwestern Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–290, scales 1:62,500, 1:1,000,000, and 1:250,000, 2 sheets.

Central Midwest aquifer system

Bredehoeft, J.D., Neuzil, C.E., and Milly, P.C.D., 1983, Regional flow in the Dakota aquifer—A study of the role of confining layers: U.S. Geological Survey Water-Supply Paper 2237, 45 p.

Dyer, C.F., and Goehring, A.J., 1965, Artesian-water supply of the Dakota Formation, southeastern South Dakota: U.S. Geological Survey Open-File Report, 49 p.

Helgesen, J.O., Jorgensen, D.G., Leonard, R.B., and Signor, D.C., 1984, Regional study of the Dakota aquifer (Darton's Dakota revisited), *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5–6, 1982: National Water Well Association, p. 69–73.

Jorgensen, D.G., Leonard, R.B., and Signor, D.L., and Helgesen, J.O., 1986a, Central Midwest regional aquifer-system study, *in* Sun, R.J., ed., Regional aquifer-system analysis program of the U.S. Geological Survey—Summary of projects, 1978–84: U.S. Geological Survey Circular 1002, p. 132–140.

______1986b, Equivalent freshwater head and dissolved-solids concentration of water in rocks of Cambrian, Ordovician, and Mississippian age in the northern mid-continent, U.S.A.:U.S. Geological Survey Miscellaneous Field Studies Map MF–1835–B, scale 1:1,000,000, 2 sheets.

Jorgensen, D.G., Helgesen, J.O., and Imes, J.L., 1993, Regional aquifers in Kansas, Nebraska, and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming—Geohydrologic framework: U.S. Geological Survey Professional Paper 1414–B, 72 p.

King, P.B., and Beikman, H.M., 1974, Geologic map of the United States: U.S. Geological Survey, 3 sheets, scale 1:2,500,000.

Leonard, R.B., Signor, D.C., Jorgensen, D.G., and Helgesen, J.O., 1984, Geohydrology and hydrochemistry of the Dakota aquifer, central United States, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5–6, 1982: National Water Well Association, p. 229–237.

Neuzil, C.E., Bredehoeft, J.D., and Wolff, R.G., 1984, Leakage and fracture permeability in the Cretaceous shales confining the Dakota aquifer in South Dakota, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5-6, 1982: National Water Well Association, p. 113-120.

Swenson, F.A., 1968, New theory of recharge to the artesian basin of the Dakotas: Geological Society of America Bulletin, v. 79, p. 163–182.

Taylor, O.J., 1978, Summary appraisals of the Nation's ground-water resources—Missouri Basin region: U.S. Geological Survey Professional Paper 813–Q, 41 p.

Weeks, J.B., and Gutentag, E.D., 1981, Bedrock geology, altitude of base, and 1980 saturated thickness of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–648, scale 1:2,500,000, 2 sheets.

Northern Rocky Mountains Intermontane Basins aquifer system

Bloyd, R.M., Jr., 1975, Summary appraisals of the Nation's ground-water resources—Upper Mississippi region: U.S. Geological Survey Professional Paper 813–B, 22 p.

Clark, D.W., and Kendy, Eloise, 1992, Plan of study for the Regional Aquifer-System Analysis of the Northern Rocky Mountains Intermontane Basins, Montana and Idaho: U.S. Geological Survey Water-Resources Investigations Report 92–4116, 16 p.

Cox, E.R., 1975, Water resources of northwestern Wyoming: U.S. Geological Survey Open-File Report 75–409, 31 p.

Davis, G.H., 1988, Western alluvial valleys and the High Plains, Chapter 34 of Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology: v. 0–2 of The Geology of North America: Geological Society of America, p. 283–300.

Foxworthy, B.L., Summary appraisals of the Nation's ground-water resources—Pacific Northwest region: U.S. Geological Survey Professional Paper 813–S, 39 p.

Foxworthy, B.L., Hanneman, D.L., Coffin, D.L., and Halstead, E.C., 1988, Region 1, Western mountain ranges, Chapter 4 of Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology: v. 0–2 of The Geology of North America: Geological Society of America, p. 25–35.

McLean, J.S., and Johnson, A.I., eds., 1988, Regional aquifer systems of the United States—Aquifers of the western mountain area: American Water Resources Association Monograph 14, 229 p.

Muffler, L.J.P., 1982, Occurrence and characteristics of ground water in Montana, the Rocky Mountain region: Montana Bureau of Mines and Geology Open-File Report MBMG 99, v. 2, 132 p.

Pacific Northwest River Basins Commission Columbia–North Pacific Technical Staff, 1970a, Water resources—Columbia–North Pacific Region comprehensive framework study: Pacific Northwest River Basins Commission, App. V, v. 1, 543 p.

______1970b, Water resources—Columbia–North Pacific Region comprehensive framework study: Pacific Northwest River Basins Commission, App. V, v. 2, p. 545–1,022.

Perry, E.S., 1962, Montana in the geologic past: Montana Bureau of Mines and Geology Bulletin 26, 78 p.

Rosenshein, J.S., 1988, Region 18, Alluvial valleys, Chapter 21 *of* Back, William, Rosenshein, J.S., and Seaber, P.R., eds., Hydrogeology, v. O–2 of The Geology of North America: Geological Society of America, p. 165–175.

Ross, C.P., Andrews, D.A., and Witkind,I.J., 1955, Geologic map of Montana: U.S. Geological Survey, scale 1:500,000, 2 sheets.

Taylor, O.J., 1978, Summary appraisals of the Nation's ground-water resources—Missouri Basin region: U.S. Geological Survey Professional Paper 813–Q, 41 p.

U.S. Geological Survey, 1968, Committee on Interior and Insular Affairs, Mineral and water-resources of Montana: U.S. Government Printing Office, Document 98, U.S. Congress, 90th, 2d session, 116 p.

Geothermal water

Downey, J.S., and Dinwiddie, G.A., 1988, The regional aquifer system underlying the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming—Summary: U.S. Geological Survey Professional Paper 1402–A, 64 p.

Heasler, H.P., 1983, Geothermal resources of Wyoming: Department of Geology and Geophysics, University of Wyoming, Laramie, Wyoming, scale 1:500,000, 1 sheet.

Keefer, W.R., 1971, The geologic story of Yellowstone National Park: U.S. Geological Survey Bulletin 1347, 92 p.

Leonard, R.B., and Wood, W.A., 1988, Evaluation of a hydrothermal anomaly near Ennis, Montana: U.S. Geological Survey Professional Paper 1044–K, 53 p.

Lobmeyer, D.H., 1985, Freshwater heads and ground-water temperatures in aquifers of the Northern Great Plains of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402–D, 11 p.

MacCary, L.M., 1984, Apparent water resistivity, porosity, and water temperature of the Madison Limestone and underlying rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273–D, 14 p.

Muffler, L.J.P., ed., 1979, Assessment of geothermal resources of the United States: U.S. Geological Survey Circular 790, 163 p.

Price, Don, and Arnow, Ted, 1974, Summary appraisals of the Nation's ground-water resources—Upper Colorado region: U.S. Geological Survey Professional Paper 813–C, 40 p.

Ground-water problems

Croft, M.G., and Crosby, O.A., 1987, Hydrology of area 46—Northern Great Plains and Rocky Mountains Coal Provinces, North Dakota: U.S. Geological Survey Water-Resources Investigations Open-File Report 84–467, 80 p.

Craigg, S.D., and Thamke, J.N., 1992, Overview of possible effects of brine disposal on shallow ground-water resources in the East Poplar oil field, Fort Peck Indian Reservation, northeastern Montana [abs.]: American Water Resources Association, Montana Section Meeting, Helena, Mont., September 17–18, 1992, unpaginated.

______1993, Hydrogeologic aspects of brine disposal in the East Poplar oil field, Fort Peck Indian Reservation, northeastern Montana [abs.]: Geological Society of America, Cordilleran and Rocky Mountain Section Meeting, Reno, Nev., May 19–21, 1993, Abstracts with Programs, P. A25.

Miller, M.R., Bergantino, R.N., Bermel, W.M., and Schmidt, F.A., 1980, Regional assessment of the saline seeps in Montana: Montana Bureau of Mines and Geology Hydrogeologic Map 7, scales 1:65,500 and 1:7,500,000, 1 sheet.