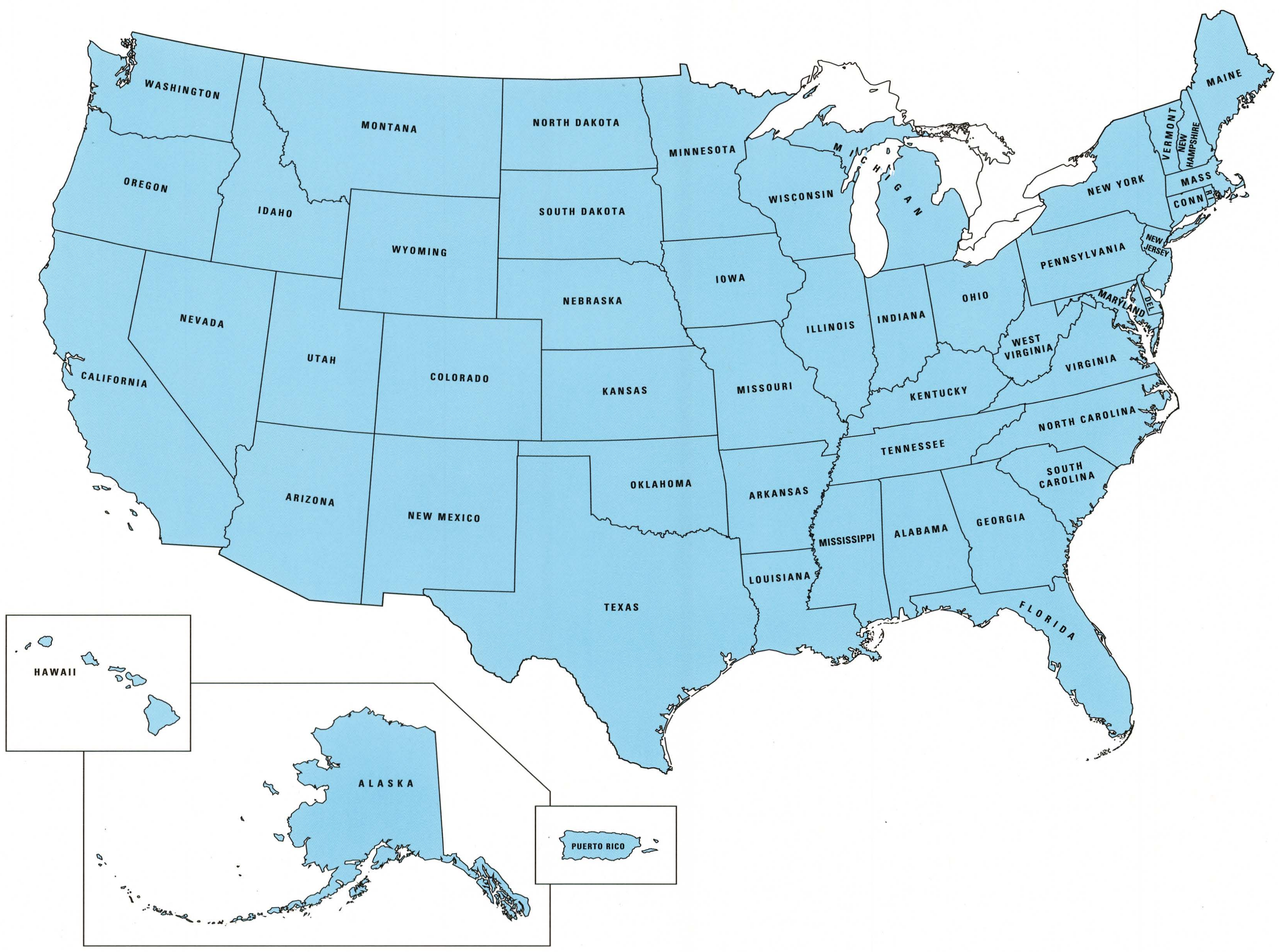
Ground Water Atlas of the United States

Introduction and National Summary

By James A. Miller



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Cartographic design and production by Gary D Latzke

INTRODUCTION

The Ground Water Atlas of the United States provides a summary of the most important information available for each principal aquifer, or rock unit that will yield usable quantities of water to wells, throughout the 50 States, Puerto Rico, and the U.S. Virgin Islands. The Atlas is an outgrowth of the Regional Aquifer-System Analysis (RASA) program of the U.S. Geological Survey (USGS), a program that investigated 24 of the most important aquifers and aquifer systems of the Nation and one in the Caribbean Islands (**fig. 1**). The objectives of the RASA program were to define the geologic and hydrologic frameworks of each aquifer system, to assess the geochemistry of the water in the system, to characterize the ground-water flow system, and to describe the effects of development on the flow system. Although the RASA studies did not cover the entire Nation, they compiled much of the data needed to make the National assessments of ground-water resources presented in the Ground Water Atlas of the United States. The Atlas, however, describes the location, extent, and geologic and hydrologic characteristics of all the important aquifers in the United States, including those not studied by the RASA program.

The Atlas is written so that it can be understood by readers who are not hydrologists. Simple language is used to explain technical terms. The principles that control the presence, movement, and chemical quality of ground water in different climatic, topographic, and geologic settings are clearly illustrated. The Atlas is, therefore, useful as a teaching tool for introductory courses in hydrology or hydrogeology at the college level and as an overview of ground-water conditions for consultants who need information about an individual aquifer. It also serves as an introduction to regional and National ground-water resources for lawmakers, personnel of local, State, or Federal agencies, or anyone who needs to understand ground-water occurrence, movement, and quality.

The purpose of the Ground Water Atlas of the United States is to summarize, in one publication with a common format, the most important ground-water information that has been collected over many years by the USGS, other Federal agencies, and State and local water management agencies. The purpose of this introductory chapter is to describe the content of the Atlas; to discuss the characteristics, use, and limitations of the maps and other types of illustrations used in the different chapters of the book; to summarize the locations of the principal aquifers on a Nationwide map; and to give an example of an aquifer in each principal hydrogeologic setting.

Introduction

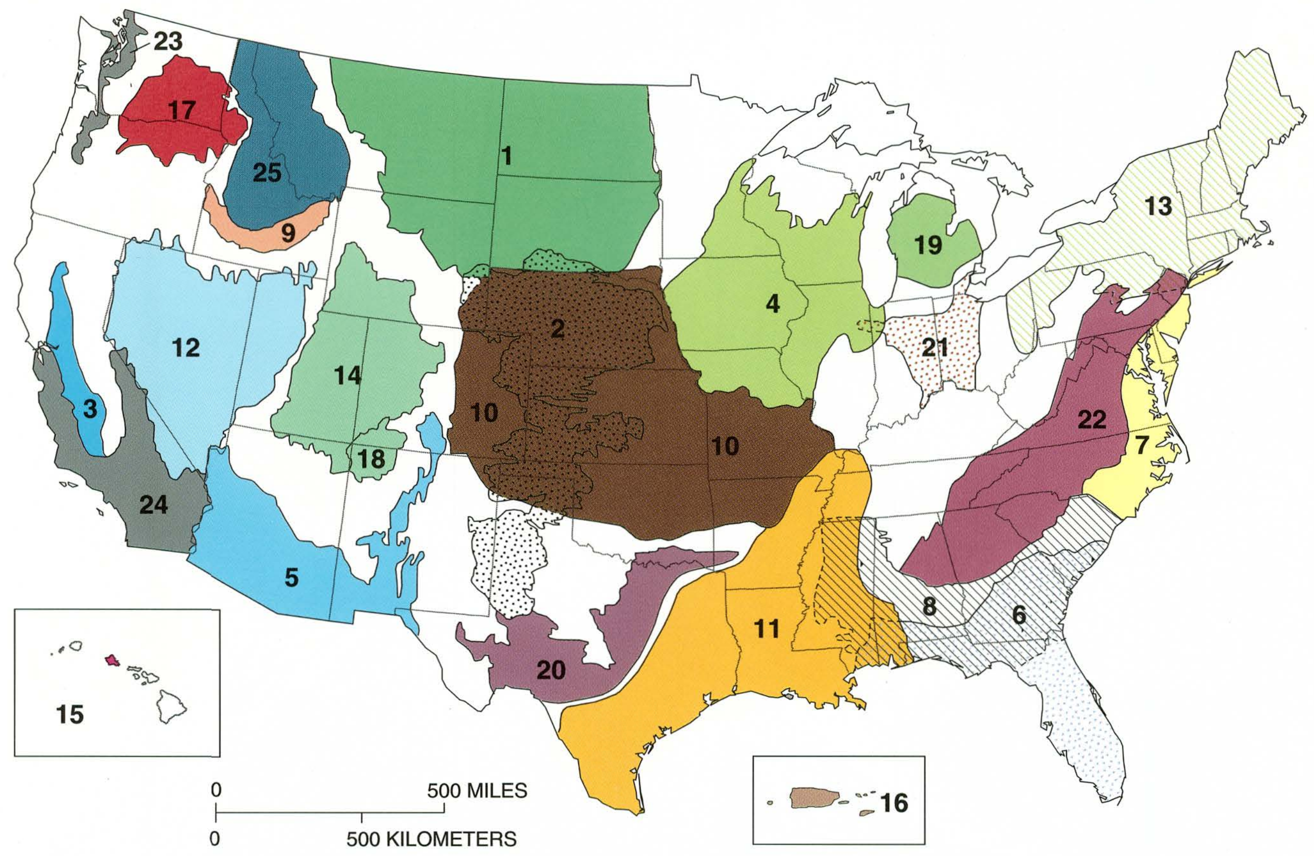


Figure 1. The Regional Aquifer-System Analysis program of the USGS studied 24 of the most important aquifers and aquifer systems in the United States, and one in the Caribbean Islands.

Modified from Sun and Johnston, 1994

EXPLANATION

Regional aquifer system study areas

1 Northern Great Plains
2 High Plains
3 Central Valley, California
4 Northern Midwest
5 Southwest alluvial basins
6 Floridan
7 Northern Atlantic Coastal Plain
8 Southeastern Coastal Plain
9 Snake River Plain
10 Central Midwest
11 Gulf Costal Plain
12 Great Basin
13 Northeast glacial aquifers
14 Upper Colorado River Basin
15 Oahu, Hawaii
16 Caribbean Islands
17 Columbia Plateau
18 San Juan Basin
19 Michigan Basin
20 Edwards–Trinity
21 Midwestern basins and arches
22 Appalachian valleys and Piedmont
23 Puget–Willamette Lowland
24 Southern California alluvial basins
25 Northern Rocky Mountain Intermontane Basins

Figure 2. The Ground Water Atlas of the United States consists of an introductory chapter and descriptive chapters that discuss the principal aquifers in 13 multi-State segments.

EXPLANATION

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

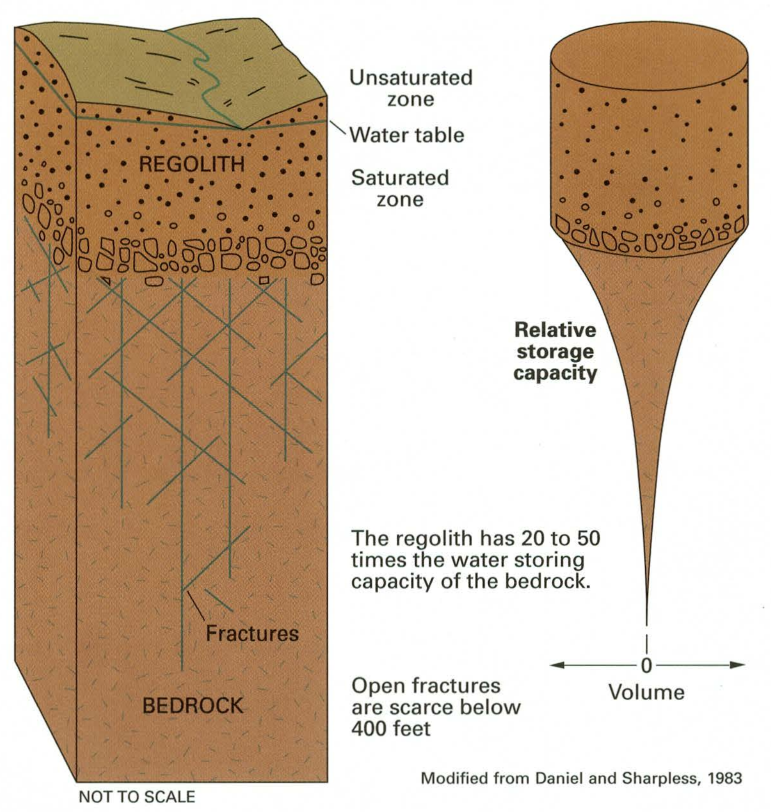


Figure 3. Diagrams that illustrate principles of ground-water occurrence and movement, such as this illustration from Atlas Chapter G, can be readily photographed or converted into overhead transparencies for use as teaching aids.

Modified from Daniel and Sharpless, 1983

ATLAS DESIGN

The Atlas consists of 14 chapters; this introductory chapter and 13 descriptive chapters which show the principal aquifers in regional areas called Segments that collectively cover the 50 States, Puerto Rico, and the U.S. Virgin Islands (**fig. 2**). The regional areas were delineated using two criteria: to keep each area at a size within which detail about each principal aquifer could be shown at a reasonable, uniform map scale; and to contain the most important regional aquifers or aquifer systems entirely within an area. Neither minor aquifers nor the minor features of the geology and hydrology of major aquifers are illustrated or described in the Atlas because of the scale of the maps. The 13 descriptive chapters have been published separately as Hydrologic Investigations Atlases 730–B through 730–N (**fig. 2**) and may be purchased by mail from the U. S. Geological Survey, Information Services, Box 25286, Federal Center, Denver CO 80225.

Maps are the primary types of illustrations in each Atlas chapter, but are supplemented by cross sections, block diagrams, charts, graphs, and photographs as needed to describe the geology and hydrology of each principal aquifer. Large-scale maps are necessary to describe some aquifers, such as the Biscayne aquifer of southeastern Florida (Atlas Chapter G) that extends over only a three-county area, but is the source of water for millions of people. In contrast, small-scale maps are needed for aquifers that extend over large areas, such as the High Plains aquifer that covers parts of eight States and four Atlas segments in the central part of the Nation. A set of five uniform map scales has been chosen so that the maps can be directly compared within a chapter and among different chapters.

Most of the illustrations in the Atlas use color to emphasize the information and to increase the clarity and understandability of the complex data or interpretive material that is presented. To help maintain consistency, each principal aquifer is assigned a unique color that is used to map the aquifer wherever it appears in the Atlas. Expanded, simplified figure captions describe the principal features of each illustration. Extensive reference lists are included in each chapter to assist readers who may require additional information. Photographs are frequently used to show special geologic or hydrologic conditions, or the results of aquifer development.

Each of the 13 descriptive chapters begins with an overview of climatic, geologic, and hydrologic conditions throughout the regional area covered by the chapter. The overview contains maps that show precipitation, runoff, physiography, geology, and ground-water withdrawals from each county in the regional area. The position and relation of each aquifer with respect to overlying, underlying, and laterally adjacent aquifers is shown by block diagrams and cross sections. The largest, and perhaps most important, illustration in each chapter is a map showing the shallowest principal aquifer throughout the regional area. Some chapters describe areas in the north-central and northeastern parts of the Nation, where productive surficial aquifers in glacial deposits of sand and gravel overlie bedrock aquifers. In these chapters, the surficial aquifers and the bedrock aquifers are shown on separate regional maps. Where aquifers are stacked atop other aquifers, the order of discussion is from shallowest to deepest.

A variety of illustrations is used to describe each principal aquifer in each regional area. Maps are used to show the location and extent of the aquifer, the thickness of the aquifer, the potentiometric surface of the aquifer (a surface that represents the level to which water will rise in wells completed in the aquifer), and the general chemical quality of the water that the aquifer contains. Where data are available, maps are used to show changes in aquifer water levels or the chemical quality of the water in the aquifer over time. Correlation charts list the geologic formations or parts of them that compose the aquifer, and show subdivisions that might exist in complex, layered aquifers or aquifer systems. Hydrogeologic sections show the relation of the aquifer to the geology of the area. Arrows are superimposed on the hydrogeologic sections and on the potentiometric-surface maps to show the direction of movement of water in the aquifer. Hydrographs are used to show the rise and fall of aquifer water levels in response to changes in the amount of precipitation or the rate of ground-water withdrawal. Pie diagrams are used to show the amount of water that is pumped for different uses or to illustrate the percentage of chemical constituents in the water. Special conditions caused by human activities are discussed and described; such conditions include land subsidence over large areas or sinkhole development caused by excessive ground-water withdrawals, waterlogging or salt buildup in the soil caused by extensive irrigation, and large water-level declines or saltwater intrusion caused by excessive pumping of ground water.

No new data were collected for the Atlas because the large amount of ground-water data available in the reports and files of the USGS and other agencies was sufficient for its preparation. Published illustrations and interpretations were merged, combined, modified, and simplified where necessary. The interpretive results and data bases of the RASA program were major sources of information for compilation of the Atlas. Where necessary, the results of some of the RASA studies were combined, or the RASA regional syntheses were supplemented by the results of smaller-scale studies. Maps and other types of illustrations were prepared from existing data for some aquifers for which no appropriate published illustrations were available.

Regional maps of the aquifers in most Atlas chapters show large to small areas that are designated either "minor aquifers," "not a principal aquifer," or "confining unit." Such areas are underlain either by low-permeability deposits and rocks, unsaturated materials, or aquifers that supply little water because they are of local extent, poorly permeable, or both. Permeability is the relative ease with which water will move through a rock unit; aquifers are more permeable than confining units. Within the areas mapped as principal aquifers, existing data are not uniformly distributed in space and time, because hydrologic investigations mostly have been conducted in areas where water supply or water quality problems existed, or where large quantities of ground water were withdrawn. Except for widely scattered places, long-term hydrologic records are rare because data is usually collected only during the course of a study or perhaps for a few years after the study has ended.

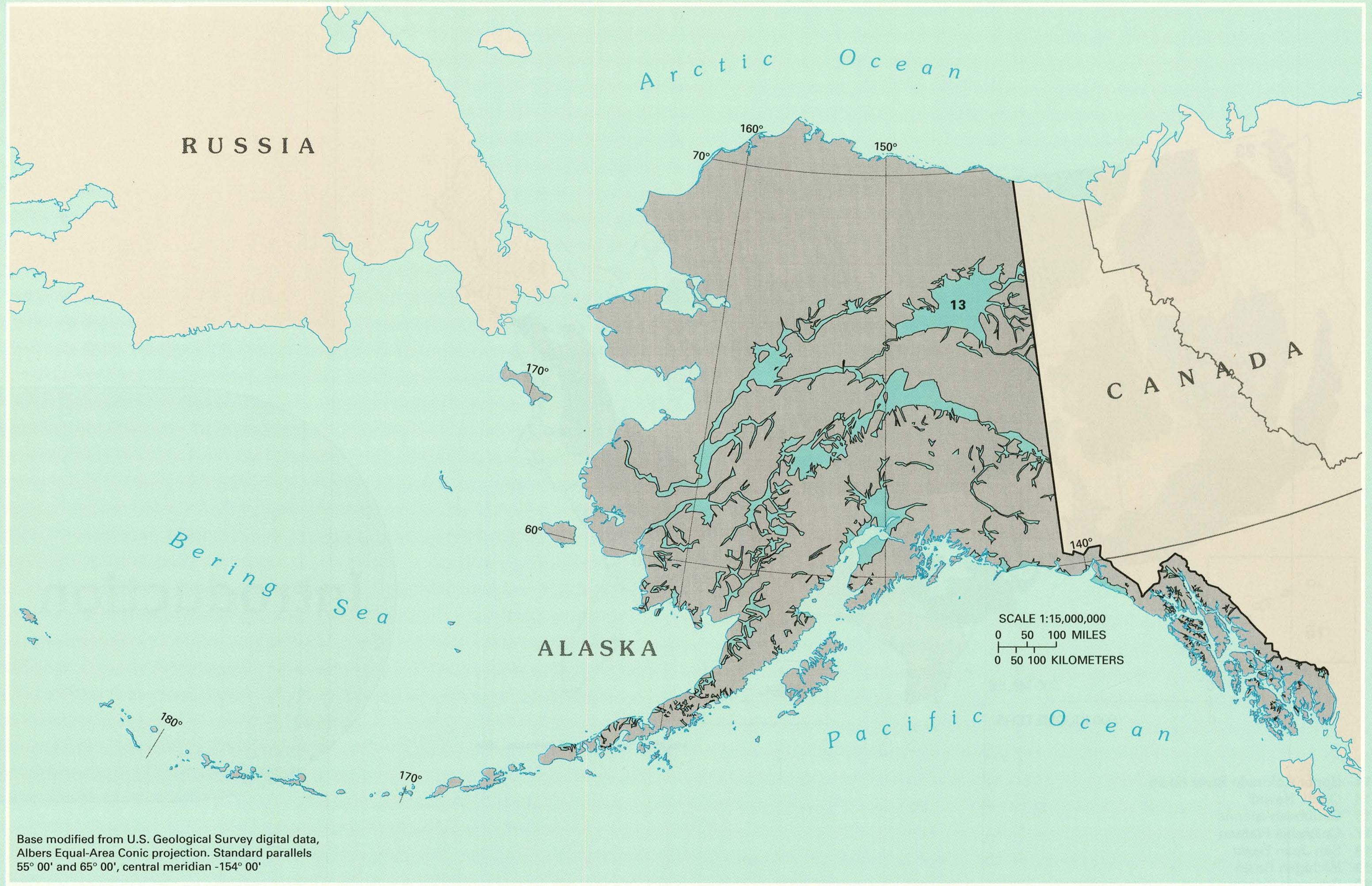
USE OF THE GROUND WATER ATLAS

The Atlas is designed to give an overview of the most important aspects of the geology, hydrology, ground-water flow system, general water quality, and use of the water withdrawn from the Nation's principal aquifers. The Atlas does not present a comprehensive description of all that is known about each principal aquifer or aquifer system. Because many of the aquifers and aquifer systems described extend over large areas, small-scale maps are required to show conditions throughout the entire aquifer. Accordingly, illustrations in the Atlas should not be used for local information or site-specific interpretations. The listed references should be consulted for detailed information about each principal aquifer or aquifer system.

Many Atlas chapters contain diagrams that illustrate basic concepts concerning the occurrence and movement of ground water. For example, some areas are underlain by fractured crystalline rock on which regolith, a combination of soil and weathered rock, has developed (**fig. 3**). The storage capacity of the regolith, which is characterized by intergranular porosity, or pore space between individual grains, is many times greater than that of the underlying crystalline rock, which is porous only where fractured. The cylinder-and-cone diagram on the right of **figure 3** summarizes the relative storage capacity of the physical situation shown on the left of the figure. Overhead transparencies or slide photographs can easily be made from such illustrations for classroom use in introductory hydrogeology courses.

The Atlas summarizes ground-water investigations that have been made over many years by a large number of hydrologists. It is, thus, a reference work that can be used by planners, consultants, teachers, and present and future hydrologists. It can also be consulted by hydrologists in other countries who wish to learn about the ground-water hydrology of the United States.

The Atlas accurately shows the principal aquifers of the United States and summarizes the significant characteristics of their flow systems and water quality. However, the scales of most of the maps used do not permit the descriptive chapters to be used to locate future water supplies, predict areas where overdrafting (withdrawals in excess of natural recharge), saltwater encroachment, or contamination are likely to occur, and so on. Studies such as these require maps and reports of much greater detail. Nevertheless, the Atlas shows significant features of the regional geology, permeability, and ground-water movement of the principal aquifers. Maps in the Atlas can also be used in conjunction with geologic and other types of maps for regional or national planning activities.



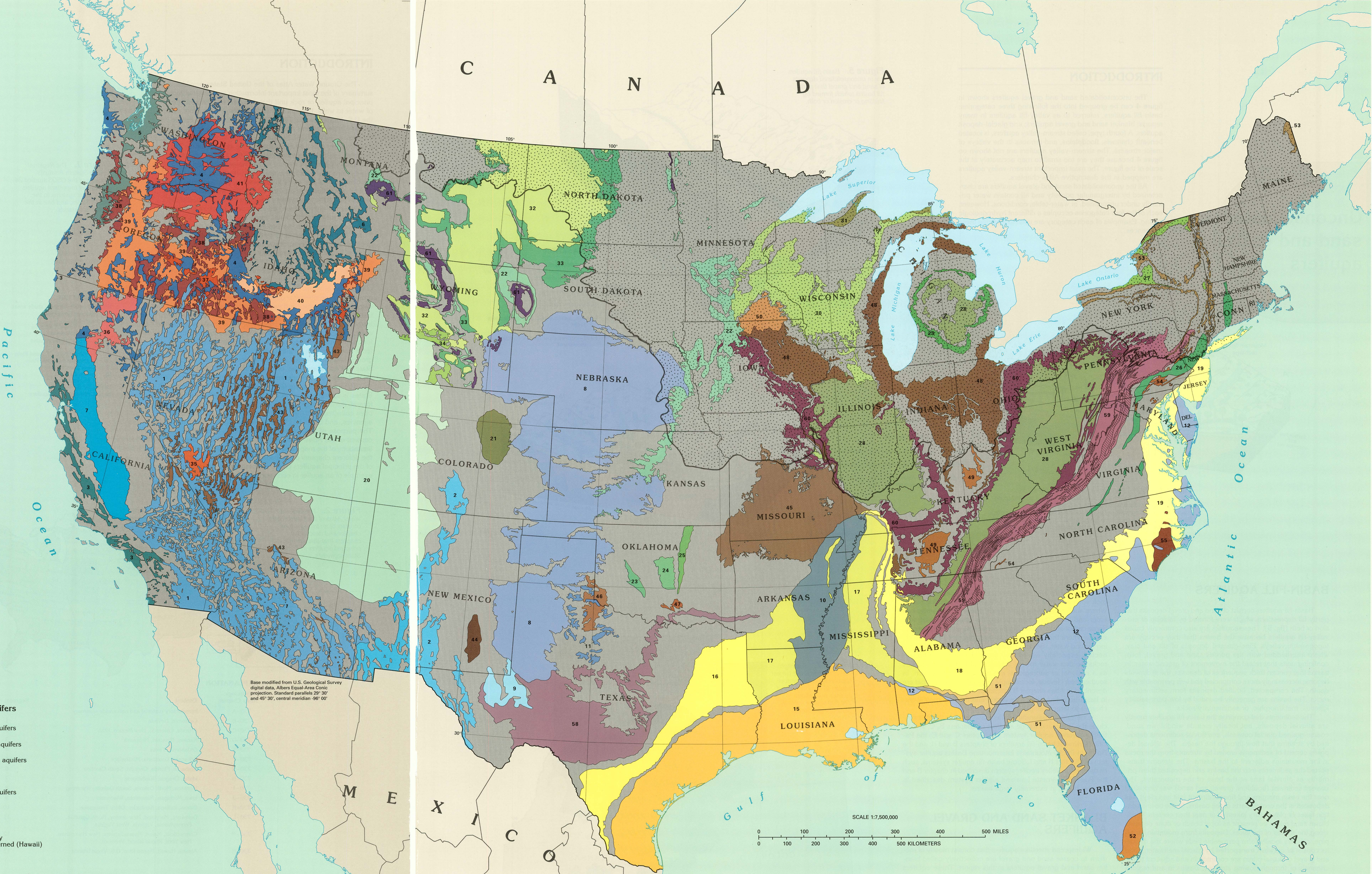


Figure 4. The principal aquifers of the United States and the Caribbean Islands are in six types of rocks and deposits. The colored areas show the extent of each principal aquifer at or near the land surface.

EXPLANATION

Unconsolidated sand and gravel aquifers

- 1 Basin and Range aquifers
- 2 Rio Grande aquifer system
- 3 California Coastal Basin aquifers
- 4 Pacific Northwest basin-fill aquifers
- 5 Puget–Willamette Lowland aquifer system
- 6 Northern Rocky Mountains Intermontane Basins aquifer system
- 7 Central Valley aquifer system
- 8 High Plains aquifer
- 9 Pecos River Basin alluvial aquifer
- 10 Mississippi River Valley alluvial aquifer
- 11 Seymour aquifer
- 12 Surficial aquifer system
- 13 Unconsolidated-deposit aquifers (Alaska)
- 14 South Coast aquifer (Puerto Rico)

Semiconsolidated sand aquifers

- 15 Coastal lowlands aquifer system
- 16 Texas coastal uplands aquifer system
- 17 Mississippi embayment aquifer system
- 18 Southeastern Coastal Plain aquifer system
- 19 Northern Atlantic Coastal Plain aquifer system

Sandstone aquifers

- 20 Colorado Plateaus aquifers
- 21 Denver Basin aquifer system
- 22 Lower Cretaceous aquifers
- 23 Rush Springs aquifer
- 24 Central Oklahoma aquifer
- 25 Ada–Vamoosa aquifer
- 26 Early Mesozoic basin aquifers
- 27 New York sandstone aquifers
- 28 Pennsylvanian aquifers
- 29 Mississippian aquifer of Michigan
- 30 Cambrian–Ordovician aquifer system
- 31 Jacobsville aquifer
- 32 Lower Tertiary aquifers
- 33 Upper Cretaceous aquifers
- 34 Upper Tertiary aquifers (Wyoming)

Basaltic and other volcanic-rock aquifers

- 35 Southern Nevada volcanic-rock aquifers
- 36 Northern California volcanic-rock aquifers
- 37 Pliocene and younger basaltic-rock aquifers
- 38 Miocene basaltic-rock aquifers
- 39 Volcanic- and sedimentary-rock aquifers
- 40 Snake River Plain aquifer system
- 41 Columbia Plateau aquifer system
- 42 Volcanic-rock aquifers—Overlain by sedimentary deposits where patterned (Hawaii)

Carbonate-rock aquifers

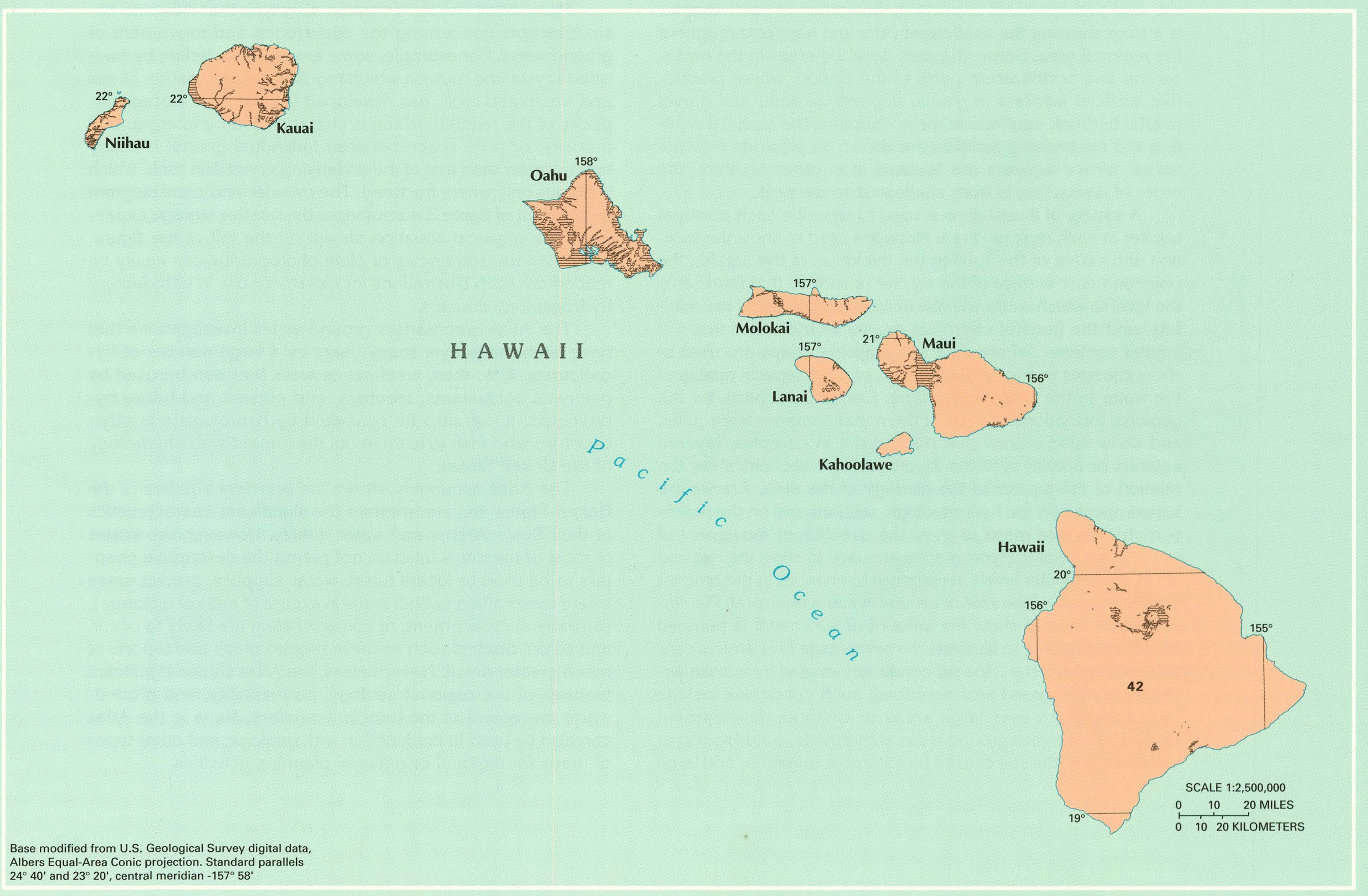
- 43 Basin and Range carbonate-rock aquifers
- 44 Roswell Basin aquifer system
- 45 Ozark Plateaus aquifer system
- 46 Blaine aquifer
- 47 Arbuckle–Simpson aquifer
- 48 Silurian–Devonian aquifers
- 49 Ordovician aquifers
- 50 Upper carbonate aquifer
- 51 Floridan aquifer system
- 52 Biscayne aquifer
- 53 New York and New England carbonate-rock aquifers
- 54 Piedmont and Blue Ridge carbonate-rock aquifers
- 55 Castle Hayne aquifer
- 56 North Coast Limestone aquifer system (Puerto Rico)
- 57 Kingshill aquifer (St. Croix)

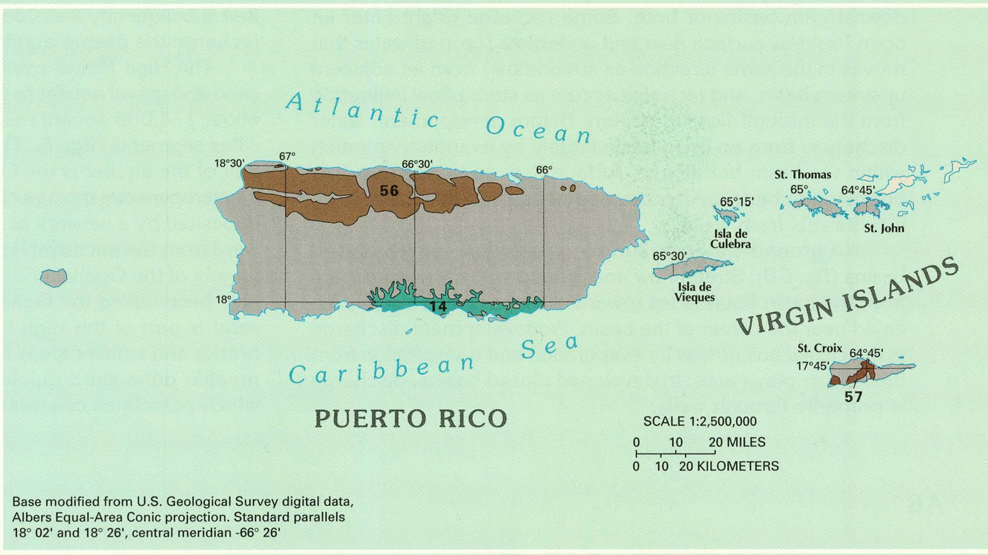
Sandstone and carbonate-rock aquifers

- 58 Edwards–Trinity aquifer system
- 59 Valley and Ridge aquifers—Carbonate-rock aquifers are patterned
- 60 Mississippian aquifers
- 61 Paleozoic aquifers

Glacial deposit aquifers overlie bedrock aquifers in many areas

Not a principal aquifer





NATIONWIDE MAP OF PRINCIPAL AQUIFERS

The distribution of the principal aquifers of the United States, Puerto Rico, and the U.S. Virgin Islands is shown in **figure 4**. The aquifers shown on the map are the shallowest principal aquifers; some are underlain by other productive aquifers, whereas others are overlain by minor aquifers. For example, the Mississippi River Valley alluvial aquifer overlies aquifers that are part of the Mississippi embayment aquifer system from southeastern Missouri to northeastern Louisiana, and also overlies aquifers that are part of the coastal lowlands aquifer system in east-central Louisiana. Local stream-valley alluvial aquifers that yield small to large amounts of water are in the valleys of many major streams that cross principal aquifers, but the stream-valley aquifers are not mapped on **figure 4** because of the map scale. Many of the principal aquifers are overlain by confining units and extend into the subsurface beyond the areas shown on the map.

The nationwide aquifer map was constructed by juxtaposing the regional maps of principal aquifers from the descriptive chapters. Regional maps for some chapters might show more detail than the nationwide map because minor aquifers that are important local sources of water were mapped in some States. On the nationwide map, however, such local aquifers are included in a category called "not a principal aquifer," along with confining units that might be mapped separately in some descriptive chapters. However, productive aquifers might underlie parts of the area mapped in this category: for example, the prolific Floridan aquifer system underlies the areas mapped as "not a principal aquifer" in the Coastal Plain of Florida, Georgia, and Alabama. Also included in this category are low-yielding aquifers that extend over large areas, such as those in the fractured crystalline rocks of the Appalachian and Blue Ridge region of the eastern United States.

Large areas of the eastern, northeastern, and north-central parts of the Nation are underlain by crystalline rocks. These igneous and metamorphic rocks are permeable only where they are fractured and generally yield only small amounts of water to wells. However, because these rocks extend over large areas, large volumes of ground water are withdrawn from them, and, in many places, they are the only reliable source of water supply. Accordingly, the crystalline rocks of northern Minnesota and northeastern Wisconsin, northeastern New York and the New England States, and the Piedmont and Blue Ridge Physiographic Provinces that extend from eastern Alabama to southeastern New York are mapped as aquifers in the Atlas chapters that describe those areas. Because the crystalline rocks have minimal permeability, they are not mapped as principal aquifers on **figure 4**.

In the north-central and northeastern parts of the conterminous United States, numerous local productive aquifers are in glacial deposits of sand and gravel. The map scale of the nationwide map is too small to allow individual aquifers in these glacial deposits to be shown. The general distribution of the glacial deposits is indicated by the dot patterned area on **figure 4**, and the locations of the principal bedrock aquifers that underlie them are mapped in the figure. These bedrock aquifers are used primarily where glacial-deposit aquifers are thin or yield little water.

The principal aquifers mapped in **figure 4** are in six types of permeable geologic materials: unconsolidated deposits of sand and gravel, semiconsolidated sand, sandstone, carbonate rocks, interbedded sandstone and carbonate rocks, and basalt and other types of volcanic rocks. Rocks and deposits with minimal permeability, that are not considered to be aquifers, consist of intrusive igneous rocks, metamorphic rocks, shale, siltstone, evaporite deposits, silt, and clay. There is, thus, a direct relation between permeability and type of geologic material. For this reason, the aquifers mapped in figure 4 are categorized according to their general geologic character. Each category is described and illustrated in the following sections of this report.

Unconsolidated sand and gravel aquifers

INTRODUCTION

The unconsolidated sand and gravel aquifers shown in **figure 4** can be grouped into the following three categories: basin-fill aquifers, referred to as valley-fill aquifers in many reports; blanket sand and gravel aquifers; and glacial-deposit aquifers. A fourth type, called stream-valley aquifers, is located beneath channels, floodplains, and terraces in the valleys of major streams. The stream-valley aquifers are not shown on **figure 4** because they are too small to map accurately at the scale of the figure. The most important stream-valley aquifers are mapped in the descriptive Atlas chapters.

All the unconsolidated sand and gravel aquifers are characterized by intergranular porosity and all contain water primarily under unconfined, or water-table, conditions. However, each of the four categories occupies a different hydrogeologic setting. Examples of each category are used to illustrate these differences.

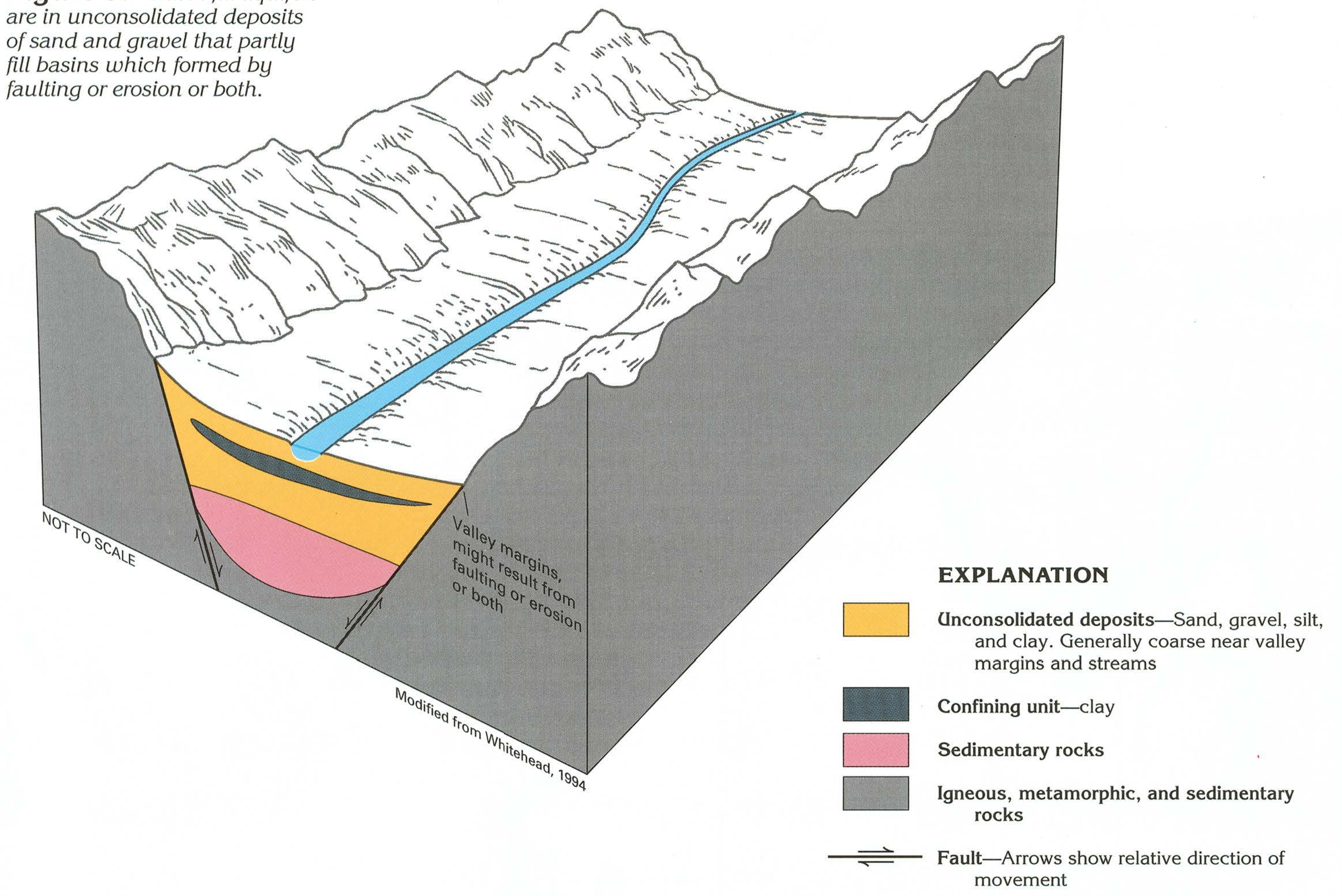


Figure 5. Basin-fill aquifers are in unconsolidated deposits of sand and gravel that partly fill basins which formed by faulting or erosion or both.

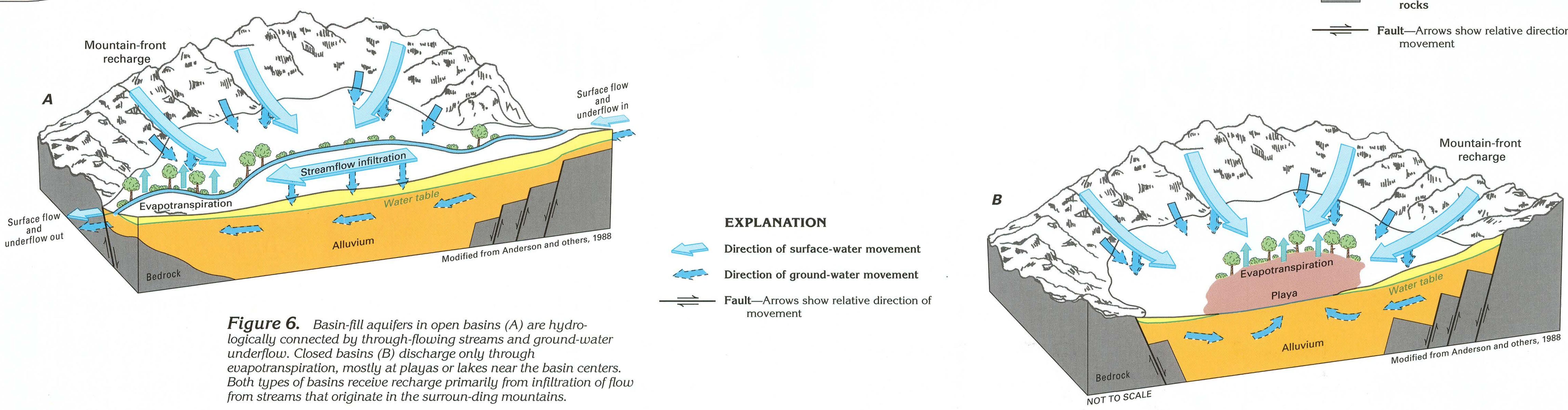


Figure 6. Basin-fill aquifers in open basins (A) are hydrologically connected by through-flowing streams and ground-water underflow. Closed basins (B) discharge only through evapotranspiration, mostly at playas or lakes near the basin centers. Both types of basins receive recharge primarily from infiltration of flow from streams that originate in the surroun-ding mountains.

BASIN-FILL AQUIFERS

Basin-fill aquifers consist of sand and gravel deposits that partly fill depressions which were formed by faulting or erosion or both (**fig. 5**). These aquifers are also commonly called valley-fill aquifers because the basins that they occupy are topographic valleys. Fine-grained deposits of silt and clay, where interbedded with the porous sand and gravel, form confining units that retard the movement of ground water. In basins that contain thick sequences of deposits, the sediments become increasingly more compacted and less permeable with depth. The compacted, lithified deposits form sedimentary rocks. The basins are generally bounded by low-permeability igneous, metamorphic, or sedimentary rocks.

The sediments that comprise the basin-fill aquifers mostly are alluvial deposits, but locally include windblown sand, coarse-grained glacial outwash, and fluvial sediments deposited by streams that flow through the basins. The alluvial deposits consist of sediments eroded by streams from the rocks in the mountains adjacent to the basins. The streams transported the sediments into the basins and deposited them primarily as alluvial fans at the base of the mountains. The coarser sediment (boulders, gravel, and sand) was deposited near the basin margins and finer sediment (silt and clay) was deposited in the central parts of the basins. Some basins contain lakes or playas (dry lakes) at or near their centers. Windblown sand might be present as local beach or dune deposits along the shores of the lakes. Deposits from mountain, or alpine, glaciers locally form permeable beds where the deposits consist of outwash transported by glacial meltwater. Sand and gravel of fluvial origin are common in and adjacent to the channels of through-flowing streams. Basins in arid regions might contain deposits of salt, anhydrite, gypsum, or borate, produced by evaporation of mineralized water, in their central parts.

The hydrogeologic setting of a typical basin generally is one of two types: open (**fig. 6*A***) or closed (**fig. 6*B***). Recharge to both types of basin is primarily by infiltration of streamflow that originates as precipitation which falls on the mountainous areas that surround the basins. This recharge, called mountain-front recharge, is intermittent because the streamflow that enters the valleys is intermittent. As the streams exit their bedrock channels and flow across the surface of the alluvial fans, the streamflow infiltrates the permeable deposits on the fans and moves downward to the water table. In basins which are located in arid climates, much of the infiltrating water is lost by evaporation or as transpiration by riparian vegetation (plants on or near stream banks).

Open basins contain through-flowing streams (**fig. 6*A***) and commonly are hydraulically connected to upstream or downstream basins or both. Some recharge might enter an open basin as surface flow and underflow (ground water that moves in the same direction as streamflow) from an adjacent upstream basin, and recharge occurs as streamflow infiltration from the through-flowing stream. Before development, water discharges from an open basin largely by evapotranspiration within the basin but also as surface flow and underflow into downstream basins. After development, most discharge is by withdrawals from wells.

No ground-water or surface-water flow leaves closed basins (**fig. 6*B***). Streamflow and ground-water movement are from the basin boundaries toward a lake or playa usually located near the center of the basin. Predevelopment discharge in the closed basins was by evaporation and transpiration from the lake or playa area; in developed closed basins, discharge is primarily through wells.

Some basins are bounded or underlain by permeable bedrock such as carbonate rocks or fractured crystalline rocks. Where such rocks surround a basin, some ground water can enter and leave the basin through the permeable bedrock. Some carbonate rocks are highly permeable and might be cavernous where they have been partially dissolved by circulating ground water. Several basins might be hydraulically connected, especially where they are underlain by carbonate rocks, so that water moves through and between the basins as a regional or subregional ground-water flow system. In southeastern Nevada, for example, major flow systems that are described in Atlas chapter B extend for as much as 250 miles in basin-bounding carbonate rocks, and the flow mostly discharges to large springs.

Examples of basin-fill aquifers discussed in the Atlas include the Basin and Range aquifers of chapters B, C, and H; the Rio Grande aquifer system of chapters C and E; the Pacific Northwest basin-fill aquifers of chapters B and H; and the Northern Rocky Mountains Intermontane Basins aquifer system of chapters H and I. Some basin-fill aquifer systems, such as the Central Valley aquifer system described in chapter B and the Puget-Williamette Lowland aquifer system described in chapter H, are in extremely large basins.

BLANKET SAND AND GRAVEL AQUIFERS

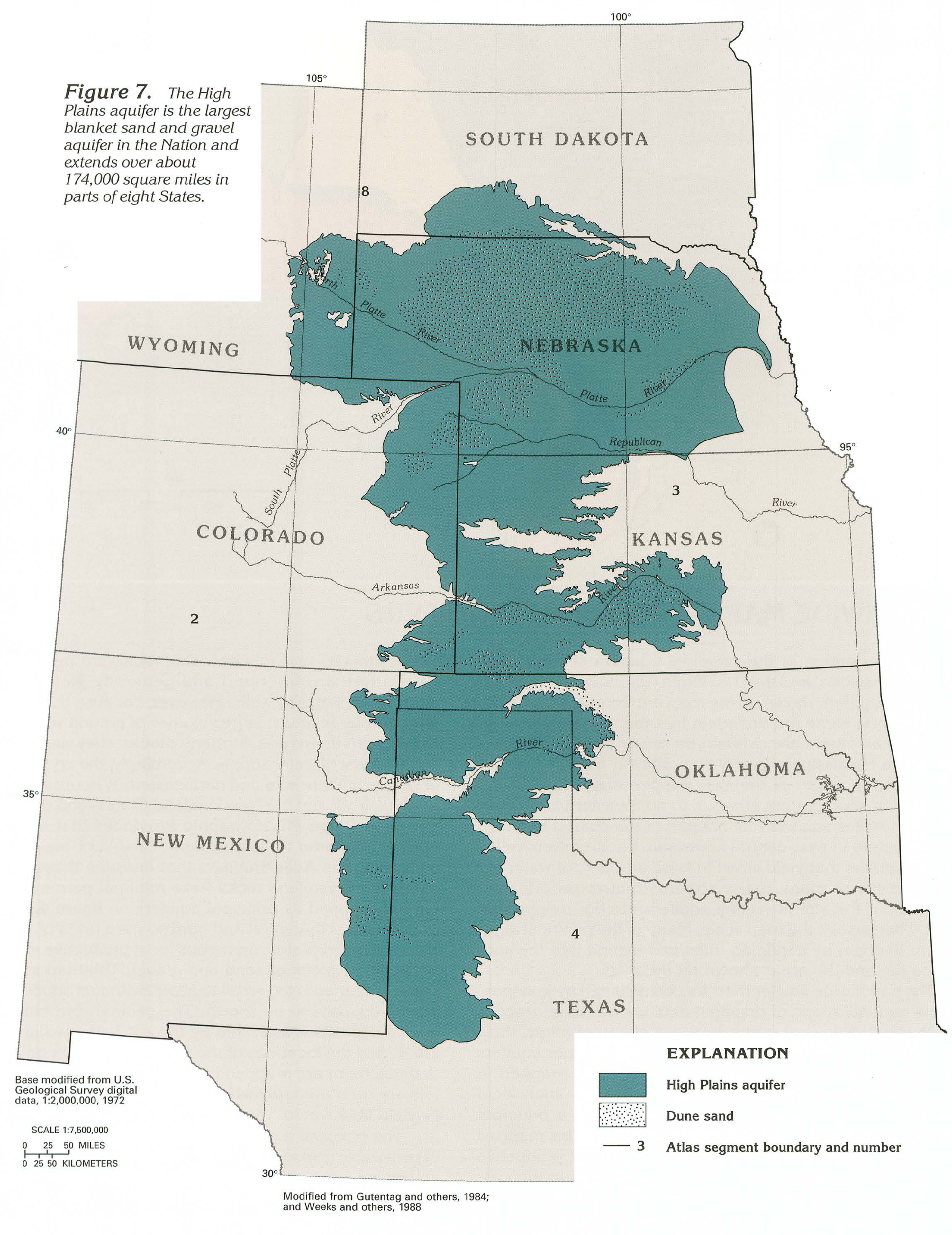
Widespread sheetlike aquifers that consist mostly of medium to coarse sand and gravel are collectively called blanket sand and gravel aquifers in this report. These aquifers mostly contain water under unconfined, or water-table, conditions but locally, confined conditions exist where the aquifers contain beds of low-permeability silt, clay, or marl. Where stream-valley alluvial aquifers, that also consist of sand and gravel, cross the blanket sand and gravel aquifers, the two types of aquifers are hydraulically connected and the stream-valley alluvial aquifers are not mapped separately.

The blanket sand and gravel aquifers largely consist of alluvial deposits. However, some of these aquifers, such as the High Plains aquifer, include large areas of windblown sand, whereas others, such as the surficial aquifer system of the southeastern United States, contain some alluvial deposits but are largely comprised of beach and shallow marine sands.

Except for the Seymour aquifer in north Texas, which is underlain by low-permeability rocks, the blanket sand and gravel aquifers partly overlie, and are hydraulically connected to, other aquifers. Where they are in contact with aquifers in older rocks, the blanket sand and gravel aquifers store water that subsequently leaks downward under natural conditions to recharge the deeper aquifers.

The High Plains aquifer is the most widespread blanket sand and gravel aquifer in the Nation. This aquifer extends over about 174,000 square miles in parts of eight States and four Atlas segments (**fig. 7**). The principal water-yielding geologic unit of the aquifer is the Ogallala Formation of Miocene age, a heterogeneous mixture of clay, silt, sand, and gravel that was deposited by a network of braided streams which flowed eastward from the ancestral Rocky Mountains. Because it consists largely of the Ogallala Formation, the High Plains aquifer has also been called the Ogallala aquifer in many reports. Dune sand is part of the High Plains aquifer in large areas of Nebraska and smaller areas in the other States (**fig. 7**). This permeable dune sand quickly absorbs precipitation, some of which percolates downward to the water table of the aquifer.

Figure 7. The High Plains aquifer is the largest blanket sand and gravel aquifer in the Nation and extends over about 174,000 square miles in parts of eight States.



BLANKET SAND AND GRAVEL AQUIFERS—Continued

The High Plains aquifer is the most intensively pumped aquifer in the United States. During 1990, about 15 billion gallons per day, or about 17 million acre-feet per year, of water was withdrawn from the aquifer. An acre-foot is the volume of water that will cover one acre of land to a depth of one foot, or 43,560 cubic feet of water. Most of this water (almost 16 million acre-feet) was withdrawn for irrigation (**fig. 8**). Withdrawals during 1978 were much greater, with irrigation withdrawals amounting to almost 23 million acre-feet. Average annual withdrawals of water from the aquifer are much larger (2 to 35 times larger) than natural recharge to the aquifer. By 1980, withdrawals had resulted in water-level declines of more than 100 feet in parts of the aquifer in southwestern Kansas and the Texas panhandle (**fig. 9**). Declines were greatest in Texas, Kansas, and Oklahoma. Water levels rose locally in the aquifer, particularly in Nebraska, in response to increased recharge where surface water that was applied for irrigation infiltrated the aquifer.

The saturated thickness of the High Plains aquifer is the vertical distance between the water table and the base of the aquifer. In 1992, the saturated thickness of the aquifer ranged from 0 where the sediments that comprise the aquifer are unsaturated to about 1,000 feet in parts of Nebraska and averaged about 190 feet. Ground-water development has caused changes in the saturated thickness of the aquifer, because this thickness changes as aquifer water levels change. Between predevelopment conditions and 1980, the saturated thickness of the aquifer decreased in many places (**fig. 10**), but locally increased in Texas and Nebraska. The areas of increase are the result of increased recharge to the aquifer by one or more of the following factors: greater than normal precipitation; decreased withdrawals; or downward leakage of surface-water irrigation and water from unlined canals and reservoirs. Decreases in saturated thickness of 10 percent or more result in a decrease in well yields and an increase in pumping costs because the pumps must lift the water from greater depths.

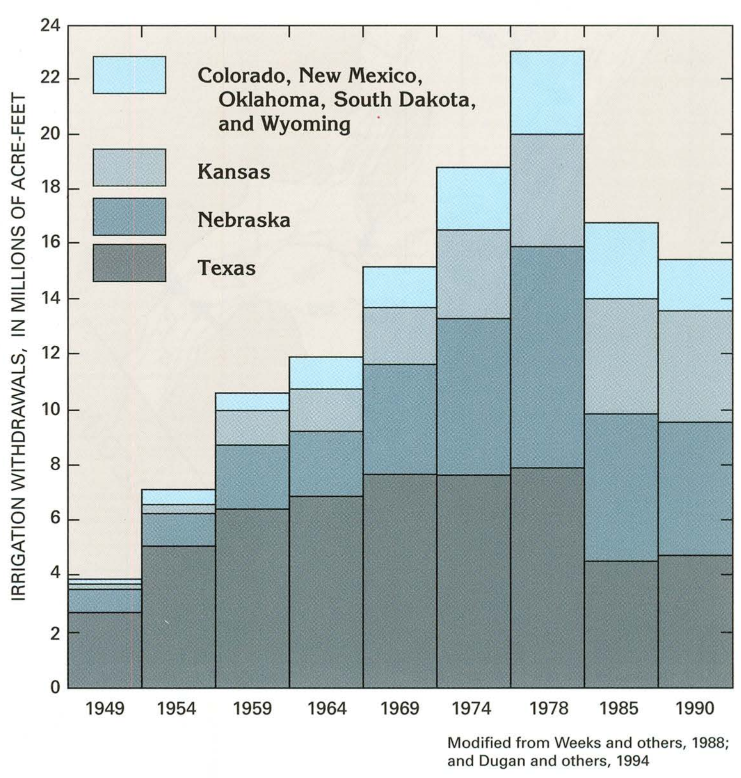


Figure 8. *Ground-water withdrawals from the High Plains aquifer for irrigation account for most of the discharge from the aquifer. Irrigation withdrawals have been largest in Texas and Nebraska.*

Water in the High Plains aquifer generally is unconfined. Locally, clay beds confine the water, but regionally, water-table conditions prevail. The configuration of the 1980 water-table surface of the aquifer (**fig. 11**) generally conforms to the configuration of the land surface. Regional movement of water in the aquifer is from west to east; locally, the water moves toward major streams. The water-table contours bend upstream where they cross the North Platte, the Republican, and the Canadian Rivers (**fig. 11**), indicating that water moves from the aquifer to the rivers. By contrast, the contours are either straight or bend downstream where they cross the Arkansas River, indicating that the Arkansas is a losing stream and water from the river recharges the aquifer.

Significant parts of the High Plains aquifer in Kansas, Colorado, and New Mexico are unsaturated, as shown in **figure 11**. In these areas, the water table is discontinuous and only local supplies of water can be obtained from filled channels that have been eroded into bedrock.

Other blanket sand and gravel aquifers include the Seymour aquifer of Texas (fig. 4) which, like the High Plains aquifer, was deposited by braided, eastward flowing streams but has been dissected into separate pods by erosion; the Mississippi River Valley alluvial aquifer, which consists of sand and gravel deposited by the Mississippi River as it meandered over an extremely wide floodplain; and the Pecos River Basin alluvial aquifer, which is mostly stream-deposited sand and gravel, but locally contains dune sands.

GLACIAL-DEPOSIT AQUIFERS

Large areas of the north-central and northeastern United States are covered with sediments that were deposited during several advances and retreats of continental glaciers. The massive ice sheets planed off and incorporated soil and rock fragments during advances and redistributed these materials as ice-contact or meltwater deposits or both during retreats. Thick sequences of glacial materials were deposited in former river valleys cut into bedrock, whereas thinner sequences were deposited on the hills between the valleys. The glacial ice and meltwater derived from the ice laid down several types of deposits, which are collectively called glacial drift. Till, which consists of unsorted and unstratified material that ranges in size from boulders to clay, was deposited directly by the ice. Outwash, which is mostly stratified sand and gravel, and glacial-lake deposits consisting mostly of clay, silt, and fine sand, were deposited by meltwater. Ice-contact deposits consisting of local bodies of sand and gravel were deposited at the face of the ice sheet or in cracks in the ice. The glacial sand and gravel deposits form numerous local but highly productive aquifers in the area shown in **figure 4**. These glacial-deposit aquifers overlie bedrock aquifers in many places. Holocene alluvium that forms productive aquifers in many river valleys in the glaciated areas is derived from reworked glacial deposits and is not distinguished from the glacial deposits in the Atlas. Likewise, sand and gravel deposited by mountain, or alpine, glaciers in Alaska, the northern Rocky Mountains, and the Puget Sound area form local aquifers that are mapped together with alluvial sand and gravel with which they commonly are connected.

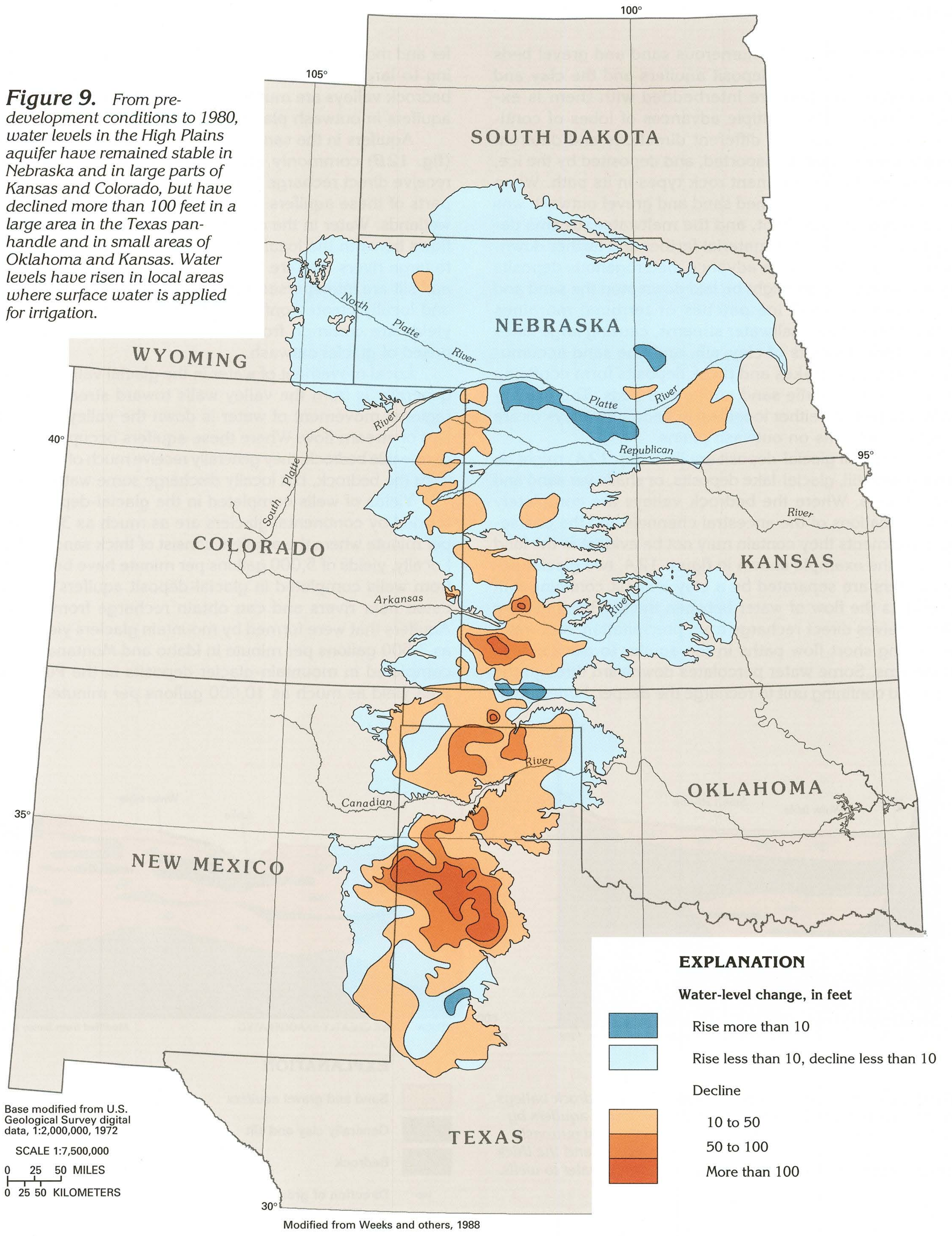


Figure 9. *From predevelopment conditions to 1980, water levels in the High Plains aquifer have remained stable in Nebraska and in large parts of Kansas and Colorado, but have declined more than 100 feet in a large area in the Texas panhandle and in small areas of Oklahoma and Kansas. Water levels have risen in local areas where surface water is applied for irrigation.*

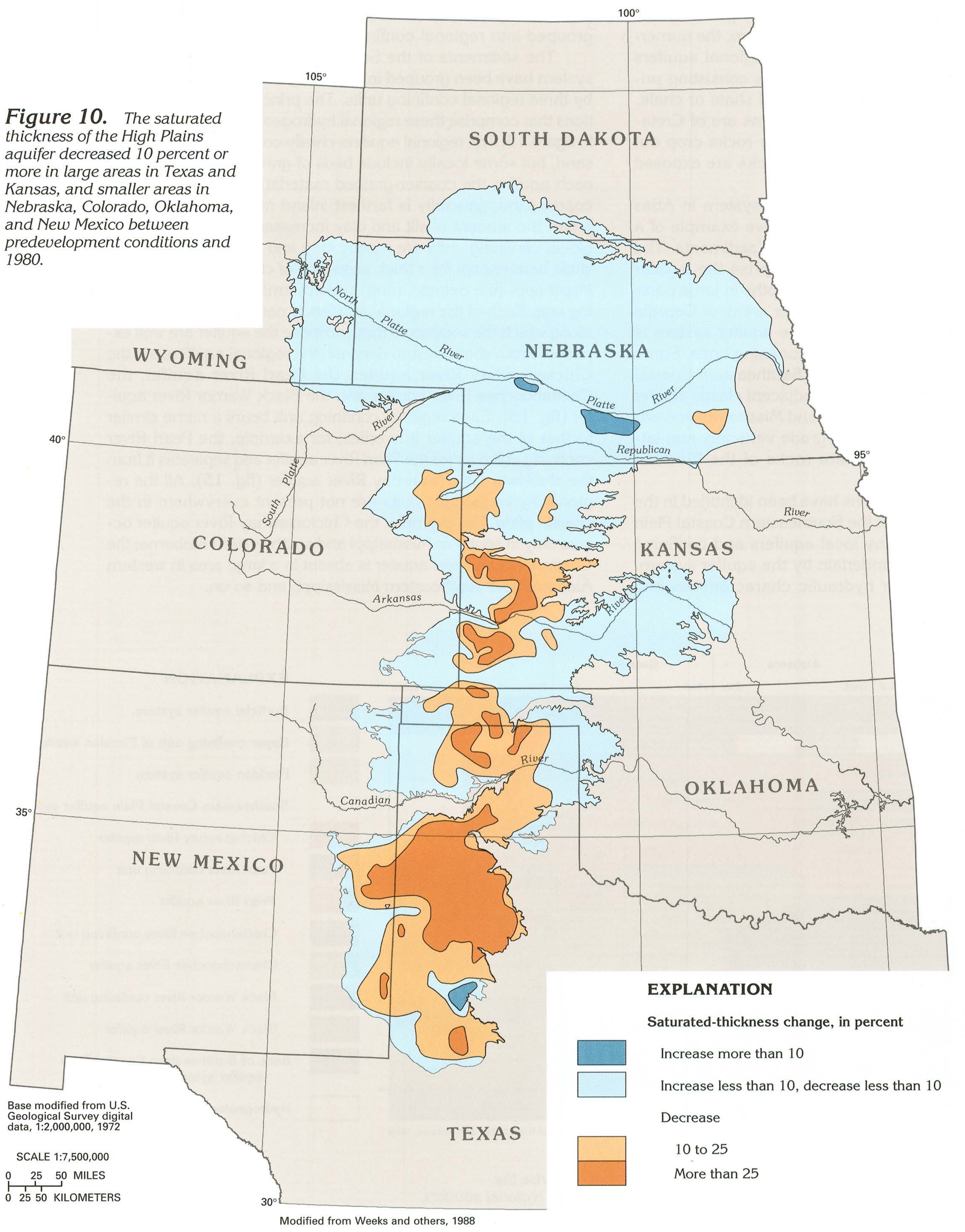


Figure 10. *The saturated thickness of the High Plains aquifer decreased 10 percent or more in large areas in Texas and Kansas, and smaller areas in Nebraska, Colorado, Oklahoma, and New Mexico between predevelopment conditions and 1980.*

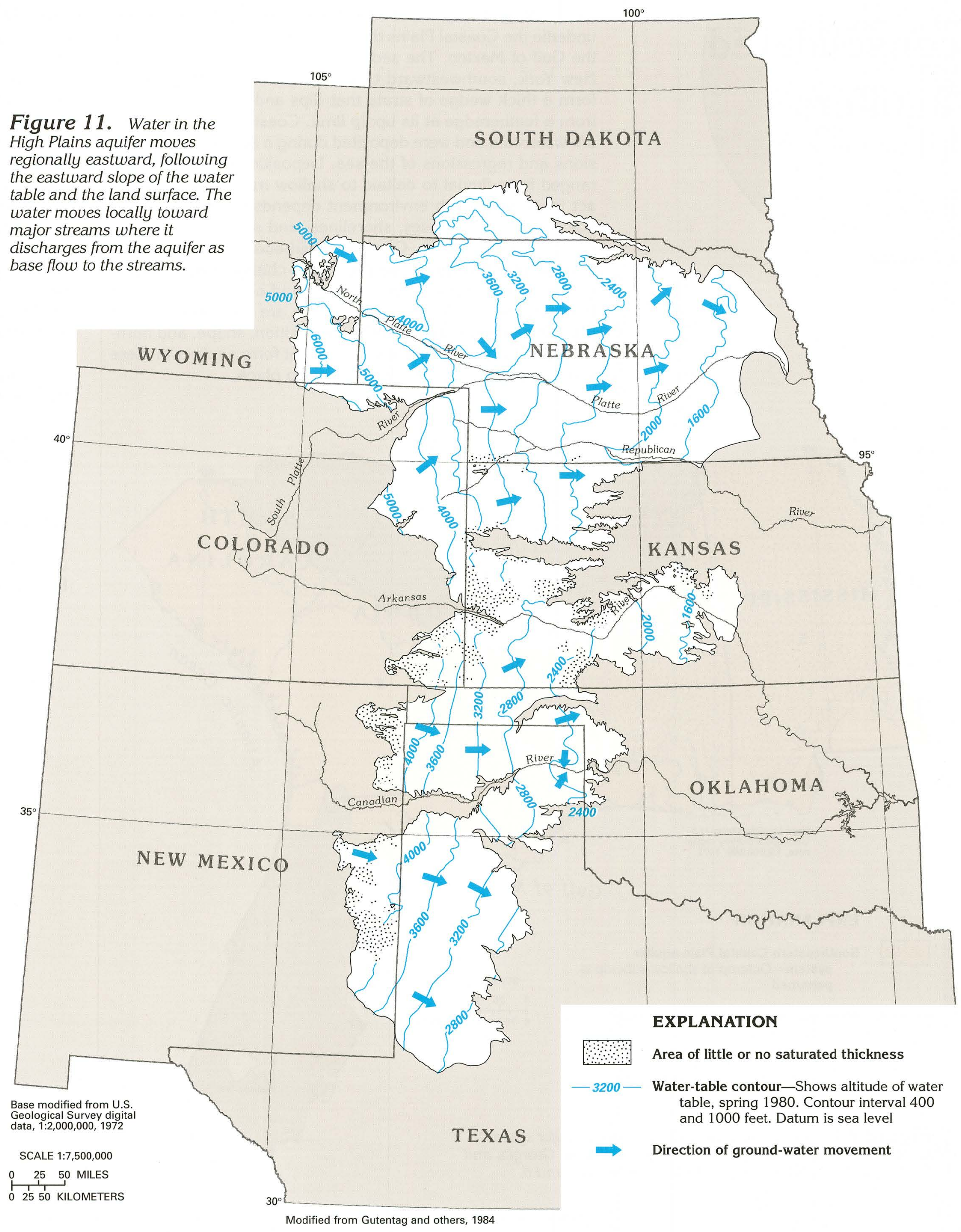


Figure 11. *Water in the High Plains aquifer moves regionally eastward, following the eastward slope of the water table and the land surface. The water moves locally toward major streams where it discharges from the aquifer as base flow to the streams.*

GLACIAL-DEPOSIT AQUIFERS—
Continued

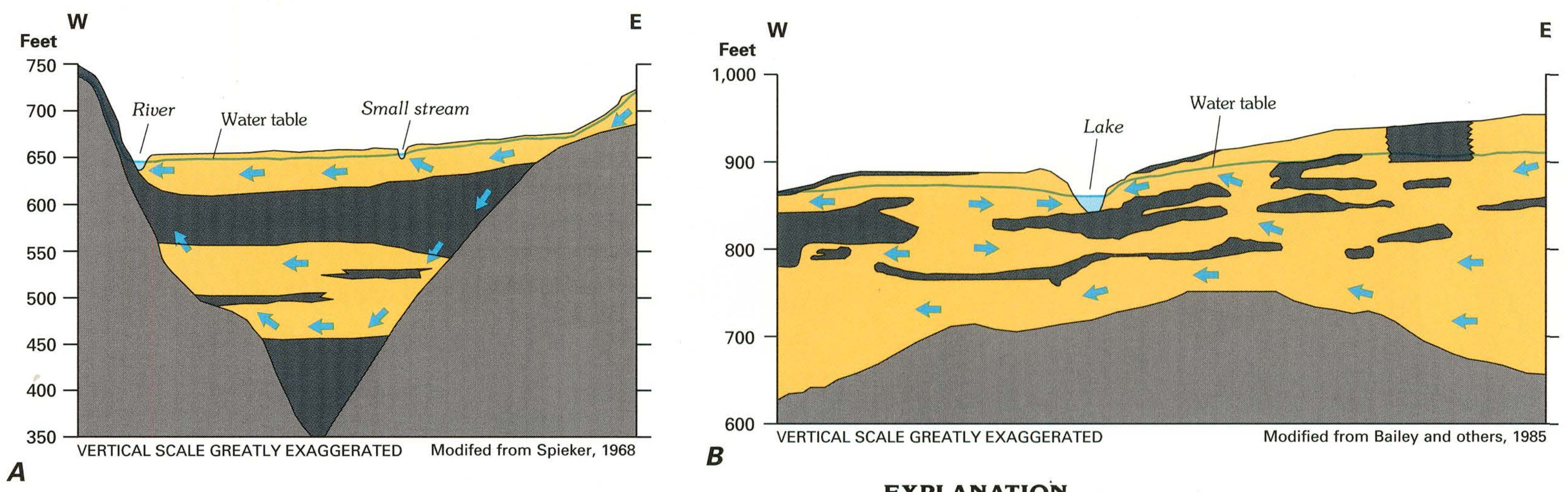
The distribution of the numerous sand and gravel beds that make up the glacial-deposit aquifers and the clay and silt confining units that are interbedded with them is extremely complex. The multiple advances of lobes of continental ice originated from different directions and different materials were eroded, transported, and deposited by the ice, depending on the predominant rock types in its path. When the ice melted, coarse-grained sand and gravel outwash was deposited near the ice front, and the meltwater streams deposited successively finer material farther and farther downstream. During the next ice advance, heterogenous deposits of poorly permeable till might be laid down atop the sand and gravel outwash. Small ice patches or terminal moraines dammed some of the meltwater streams, causing large lakes to form. Thick deposits of clay, silt, and fine sand accumulated in some of the lakes and these deposits form confining units where they overlie sand and gravel beds. The glacial-deposit aquifers are either localized in bedrock valleys or are in sheetlike deposits on outwash plains.

The valley-fill glacial-deposit aquifers (**fig. 12*A***) might be buried beneath till, glacial-lake deposits, or shallower sand and gravel aquifers. Where the bedrock valleys are completely filled, the locations of the ancestral channels and the coarse-grained sediments they contain may not be evident at the land surface. In the example shown in **figure 12*A***, two glacial-deposit aquifers are separated by a clay and silt confining unit that restricts the flow of water between them. The shallower aquifer receives direct recharge from precipitation, and water moves along short flow paths in the aquifer to discharge at local streams. Some water percolates downward through the fine-grained confining unit to recharge the deeper, buried aquifer and moves along more lengthy flow paths before discharging to larger streams. Valley-fill glacial-deposit aquifers in bedrock valleys are much more common than glacial-deposit aquifers in outwash plains.

Aquifers in the sand and gravel of glacial outwash plains (**fig. 12*B***) commonly are exposed at the land surface and receive direct recharge from precipitation. Water in the upper parts of these aquifers discharges to local streams, lakes, or wetlands. Water in the deeper parts of the aquifers, however, flows beneath the local surface-water bodies and discharges to large rivers that are regional drains. Lenslike beds of clay and silt are interspersed with the permeable sand and gravel, and locally create confined conditions in the aquifers. Large yields are common from wells completed in aquifers composed of glacial outwash.

Local movement of water in the glacial valley-fill aquifers generally is from the valley walls toward streams (**fig. 13**); regional movement of water is down the valley in the direction of stream flow. Where these aquifers occupy channels in permeable bedrock, they generally receive much of their recharge from the bedrock, but locally discharge some water to it.

Yields of wells completed in the glacial-deposit aquifers formed by continental glaciers are as much as 3,000 gallons per minute where the aquifers consist of thick sand and gravel. Locally, yields of 5,000 gallons per minute have been obtained from wells completed in glacial-deposit aquifers that are located near rivers and can obtain recharge from the rivers. Aquifers that were formed by mountain glaciers yield as much as 3,500 gallons per minute in Idaho and Montana, and wells completed in mountain-glacier deposits in the Puget Sound area yield as much as 10,000 gallons per minute.



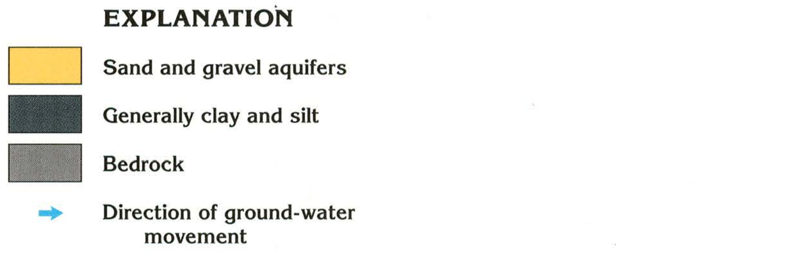
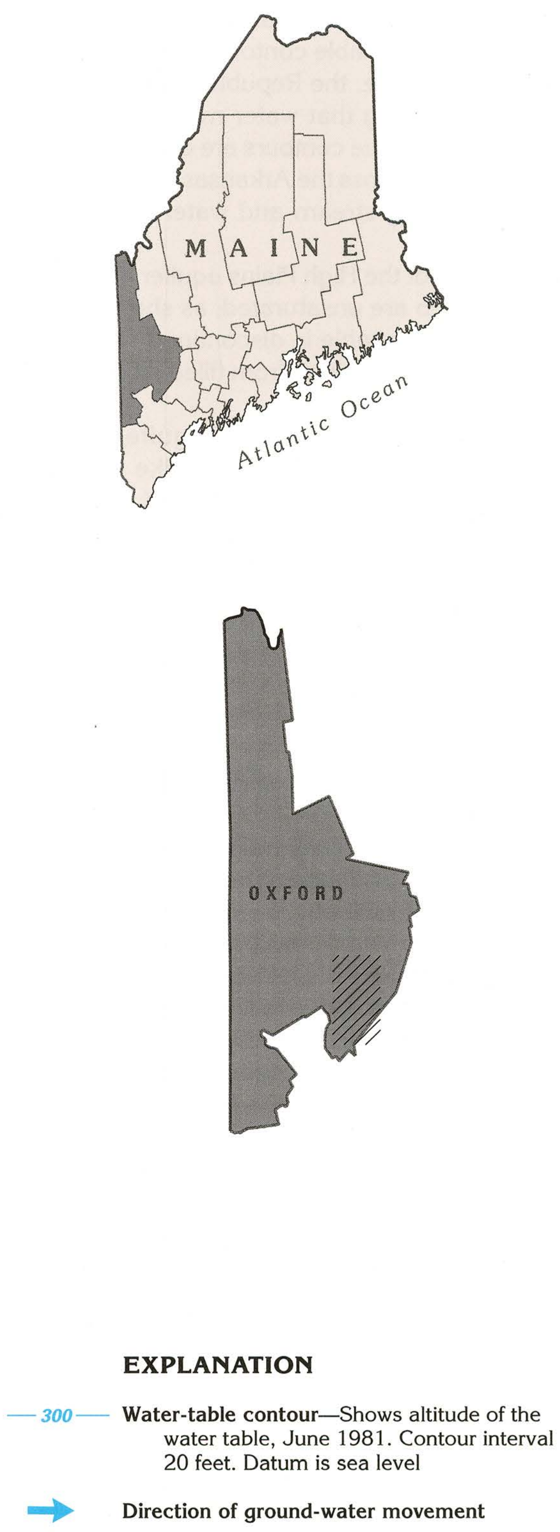
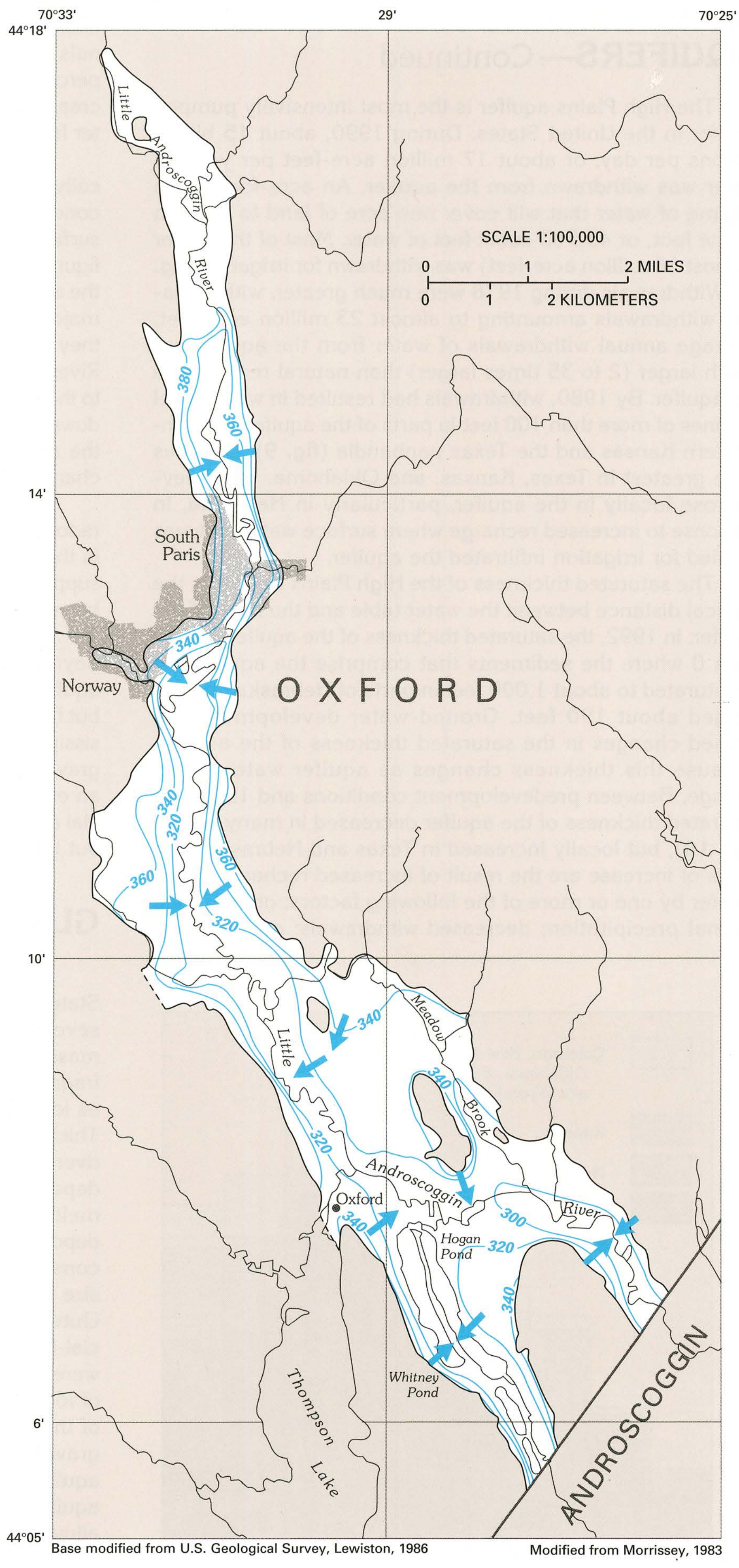


Figure 12. *Most glacial-deposit aquifers are in bedrock valleys (A) and might be hydraulically separated from deeper aquifers by clay and silt confining units. Sand and gravel in glacial outwash plains (B) receive recharge directly from precipitation, and the thick sequences of sand and gravel yield large volumes of water to wells.*

Figure 13. *Water in valley-fill glacial-deposit aquifers such as the one in the Little Androscoggin River valley in southwestern Maine moves toward the river from the valley sides and then moves down-valley, parallel to the direction of streamflow.*





Semiconsolidated sand aquifers

SEMICONSOLIDATED SAND AQUIFERS

Sediments that primarily consist of semiconsolidated sand, silt, and clay, interbedded with some carbonate rocks, underlie the Coastal Plains that border the Atlantic Ocean and the Gulf of Mexico. The sediments extend from Long Island, New York, southwestward to the Rio Grande, and generally form a thick wedge of strata that dips and thickens seaward from a featheredge at its updip limit. Coastal Plain sediments are water-laid and were deposited during a series of transgressions and regressions of the sea. Depositional environments ranged from fluvial to deltaic to shallow marine, and the exact location of each environment depends upon the relative position of land masses, shorelines, and streams at a given point in geologic time. Complex interbedding and variations in lithology result from the constantly-changing depositional environments. Some beds are thick and continuous for tens to hundreds of miles, whereas others are traceable only for short distances. Consequently, the position, shape, and number of the bodies of sand and gravel that form aquifers in these sediments varies greatly from place to place.

The semiconsolidated sand aquifers have been grouped into five aquifer systems (**fig. 4**) which interfinger with and grade into each other. Within each aquifer system, the numerous local aquifers have been grouped into regional aquifers that are separated by regional confining units consisting primarily of silt and clay, but locally are beds of shale or chalk. The rocks that comprise these aquifer systems are of Cretaceous and Tertiary age. In general, the older rocks crop out farthest inland, and successively younger rocks are exposed coastward.

The Southeastern Coastal Plain aquifer system in Atlas Segments 5 and 6 (**fig. 14**) is a representative example of a complex aquifer system in semiconsolidated sediments. The predominantly clastic sediments that comprise the aquifer system crop out or are buried at shallow depths in large parts of Mississippi and Alabama, and in smaller areas of Georgia and South Carolina; toward the coast, the aquifer system is covered either by shallower aquifers or confining units. Some of the aquifers and confining units of the Southeastern Coastal Plain aquifer system grade laterally into adjacent clastic aquifer systems in North Carolina, Tennessee, and Mississippi and adjacent States to the west; some also grade vertically and laterally southeastward into carbonate rocks of the Floridan aquifer system.

Numerous geologic formations have been identified in the complexly interbedded rocks of the Southeastern Coastal Plain aquifer system. Likewise, many local aquifers and confining units are present in the area underlain by the aquifer system. Based on similarities in their hydraulic characteristics and water levels, sequences of local aquifers can be grouped into regional aquifers; sequences of local confining units can be grouped into regional confining units in the same manner.

The sediments of the Southeastern Coastal Plain aquifer system have been grouped into four regional aquifers separated by three regional confining units. The principal geologic formations that comprise these regional hydrogeologic units are shown in **figure 15**. The regional aquifers chiefly consist of coarse to fine sand, but some locally include beds of gravel and limestone. In each aquifer, the coarser-grained material, such as gravel and coarse sand, generally is farthest inland near sediment source areas; the amount of silt and clay increases coastward. The regional confining units are mostly clay and mudstone with local shale beds except for a thick sequence of chalk in Alabama and Mississippi (the Selma Group) which forms an effective confining unit. Each of the regional aquifers is named for a major river along which the sediments that comprise the aquifer are well exposed. From shallowest to deepest, the regional aquifers are the Chickasawhay River aquifer, the Pearl River aquifer, the Chattahoochee River aquifer, and the Black Warrior River aquifer (**fig. 15**). Each regional confining unit bears a name similar to that of the aquifer it overlies; for example, the Pearl River confining unit overlies the Pearl River aquifer and separates it from the shallower Chickasawhay River aquifer (**fig. 15**). All the regional hydrogeologic units are not present everywhere in the coastal plain. For example, the Chickasawhay River aquifer occurs only in southern Mississippi and southwestern Alabama; the Chattahoochee River aquifer is absent in a large area in western Alabama and southeastern Mississippi, and so on.

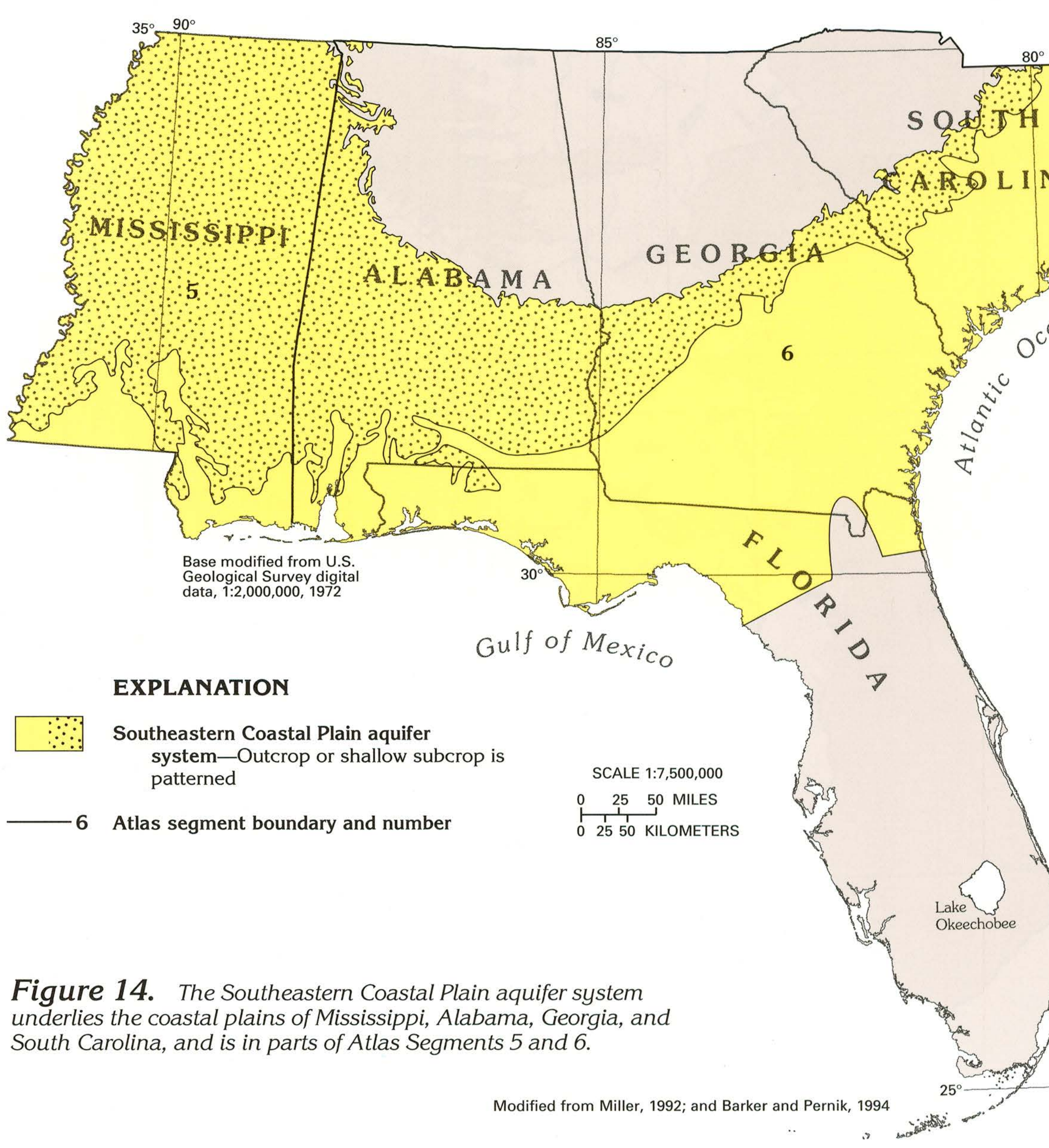


Figure 14. *The Southeastern Coastal Plain aquifer system underlies the coastal plains of Mississippi, Alabama, Georgia, and South Carolina, and is in parts of Atlas Segments 5 and 6.*

Modified from Miller, 1992; and Barker and Pernik, 1994

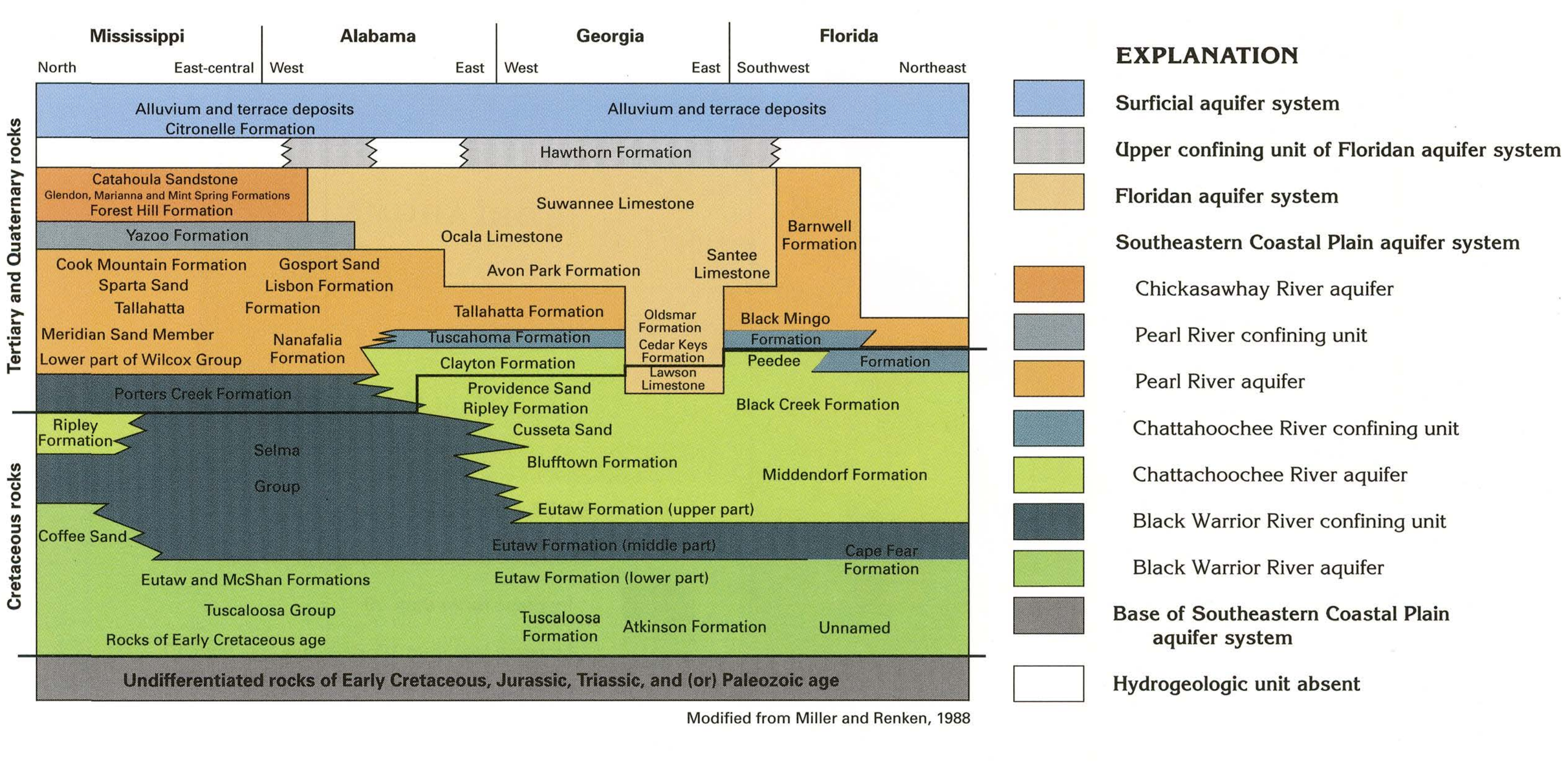


Figure 15. *The large number of geologic formations that comprise the Southeastern Coastal Plain aquifer system can be grouped into four regional aquifers, each named for a major river that crosses the aquifer outcrop area, and three regional confining units. The chart does not show exact correlations of the geologic units.*

SEMICONSOLIDATED SAND AQUIFERS— Continued

Recharge to the regional aquifers is from precipitation that falls on inland, topographically high aquifer outcrop areas. A map of the potentiometric surface of the Pearl River aquifer (**fig. 16**) shows that in outcrop areas, where unconfined conditions exist, the water moves from high altitudes toward streams. As the water moves coastward, down the hydraulic gradient (slope of the potentiometric surface), it becomes confined and the potentiometric surface becomes smoother, in contrast to its highly irregular shape in updip areas. Water in the aquifer moves along short flow paths in and near outcrop areas and along longer, regional flow paths in downgradient areas. The Pearl River aquifer grades into carbonate rocks of the Floridan aquifer system in southern Alabama, southern Georgia and southeastern South Carolina (**fig. 15**), and into clastic beds of the Mississippi embayment aquifer system in southwestern Mississippi.

The potentiometric surface of the Chattahoochee River aquifer (**fig. 17**) resembles that of the Pearl River aquifer. The contours are irregular in outcrop areas, reflecting the influence of incised streams between high-altitude recharge areas. In the confined part of the aquifer, water moves along gentler hydraulic gradients and generally down the dip of the beds. The downdip limit of this aquifer in Mississippi, Alabama, and Georgia is the area in which the sands that comprise the aquifer change to clays.

Although movement of water in the outcrop areas of the Black Warrior aquifer is similar to that of the shallower aquifers in the aquifer system, water in the confined parts of the aquifer moves differently. As shown by the flow-direction arrows in **figure 18**, important components of flow in the deep, confined parts of the aquifer are parallel to the outcrop belt of the aquifer in Mississippi and are coast-parallel in South Carolina. The water also moves along extremely long flow paths toward deeply entrenched regional drains such as the Tombigbee, the Alabama, and the Chattahoochee Rivers once it enters the confined parts of the aquifer. The downdip limit of ground-water movement in the Black Warrior River aquifer is defined as the point at which the aquifer contains water having dissolved-solids concentrations of 10,000 milligrams per liter. Although permeable sediments equivalent to this aquifer extend to the Gulf and Atlantic Coasts, little ground-water movement is thought to occur downdip of the 10,000 milligrams per liter dissolved-solids line. Coastal plain aquifers commonly contain unflushed saline water in their deep, downdip parts.

The general movement of water in the southeastern Coastal Plain is summarized in **figure 19**, which represents conditions in southeastern Georgia. The figure shows the relation between the Southeastern Coastal Plain aquifer system and the carbonate rocks of the Floridan aquifer system. Water enters the Pearl River aquifer where it crops out adjacent to the crystalline rocks that form the base of the Southeastern Coastal Plain aquifer system. Some of the water moves coastward in the clastic sediments of the Pearl River aquifer and laterally into the Floridan aquifer system where sands change to limestone; some water moves downward into the Chattahoochee River aquifer from the Pearl River aquifer where the two are in contact. The Black Warrior River aquifer is recharged in this area only by downward leakage across the confining unit that completely overlies it. Where the Chattahoochee River and the Black Warrior River aquifers are confined, water moves laterally through the aquifers. Near the coast, flow is blocked either by an increase in the amount of clay in the aquifer (Chattahoochee River aquifer) or by stagnant saline water (Black Warrior River aquifer). The flow becomes predominantly vertical as the water leaks upward to shallower aquifers or to the ocean. Water leaks downward from the Floridan aquifer system to the Southeastern Coastal Plain aquifer system, or leaks in the opposite (upward) direction, depending on the direction of decreasing hydraulic head between the two aquifer systems. The horizontal flow arrow shown in the Black Warrior River aquifer near the right side of the figure represents the coast-parallel direction of flow in this aquifer.

Other semiconsolidated sand aquifers are grouped into extensive aquifer systems as shown in **figure 4**. The Northern Atlantic Coastal Plain aquifer system extends from North Carolina through Long Island, New York, and locally contains as many as 10 aquifers. The Mississippi Embayment aquifer system consists of six aquifers, five of which are equivalent to aquifers in the Texas coastal uplands aquifer system to the west. The coastal lowlands aquifer system contains five thick, extensive permeable zones.

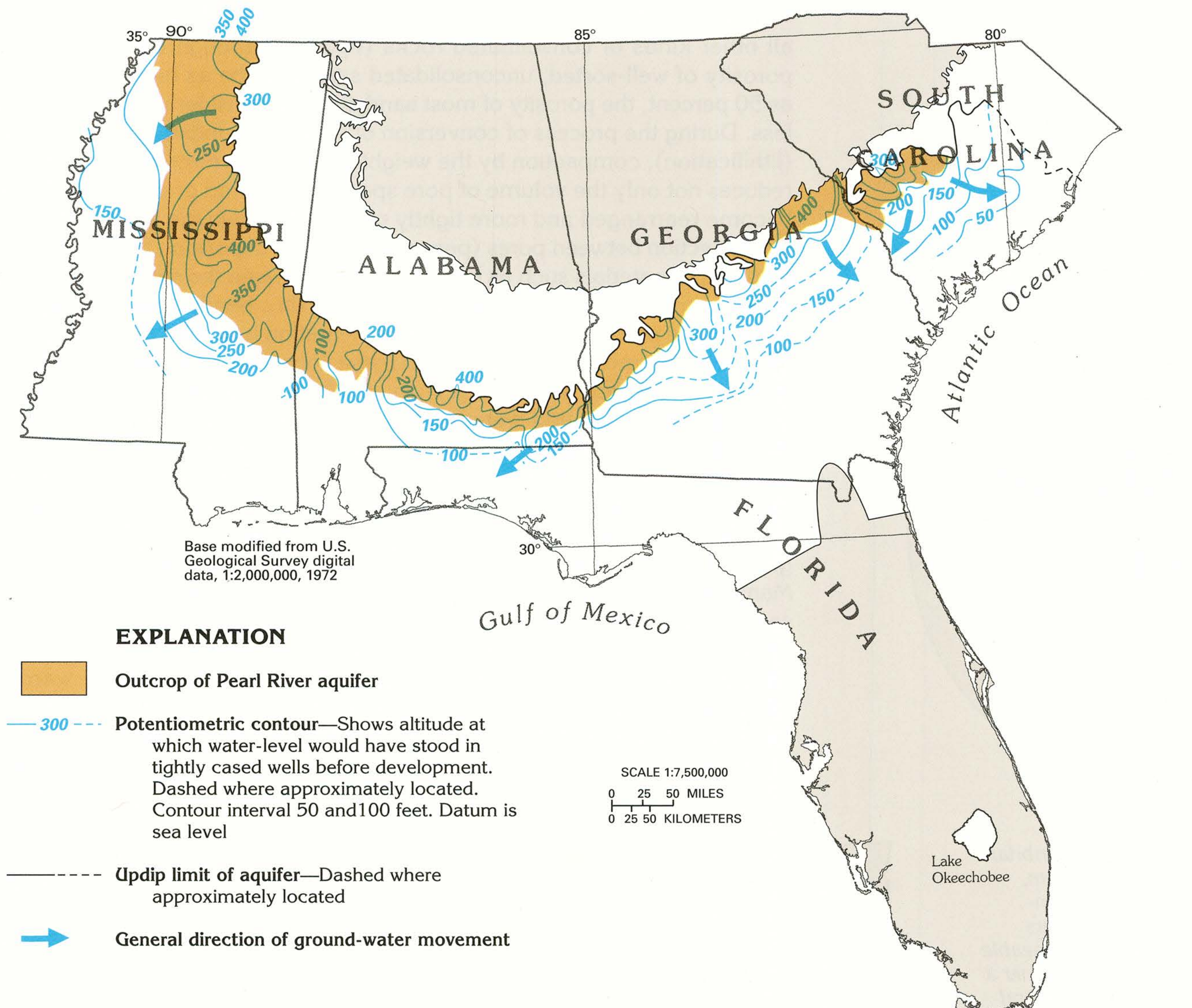


Figure 16. Water enters the Pearl River aquifer in topographically high outcrop areas and mostly moves toward major streams, where it discharges. Some water moves down the hydraulic gradient of the aquifer to become part of a deep, regional, confined ground-water flow system.

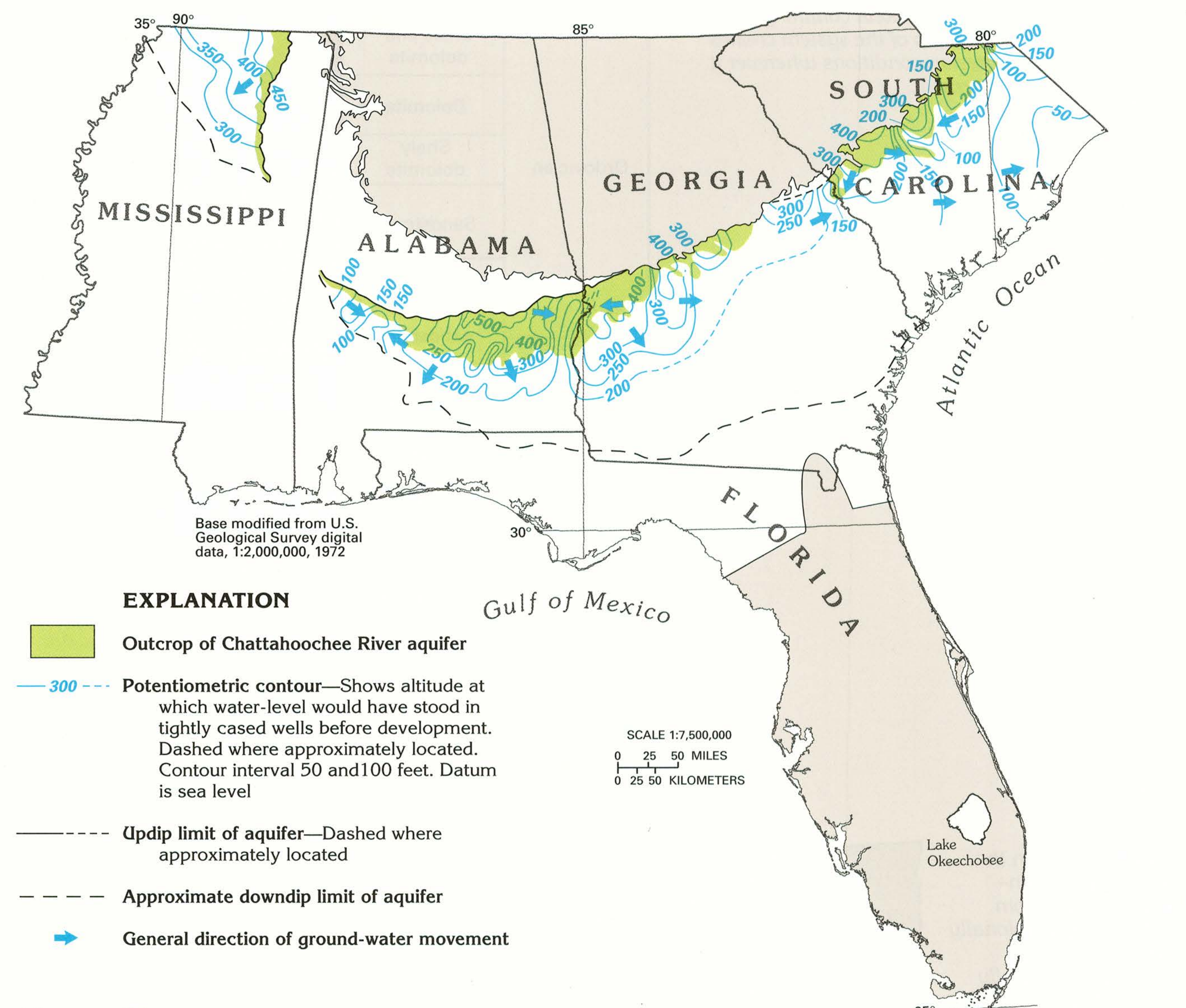


Figure 17. Movement of water in the Chattahoochee River aquifer is similar to that in the overlying Pearl River aquifer. The downdip limit of the Chattahoochee River aquifer is marked by a facies change from permeable sand to almost impermeable clay in a coastward direction.

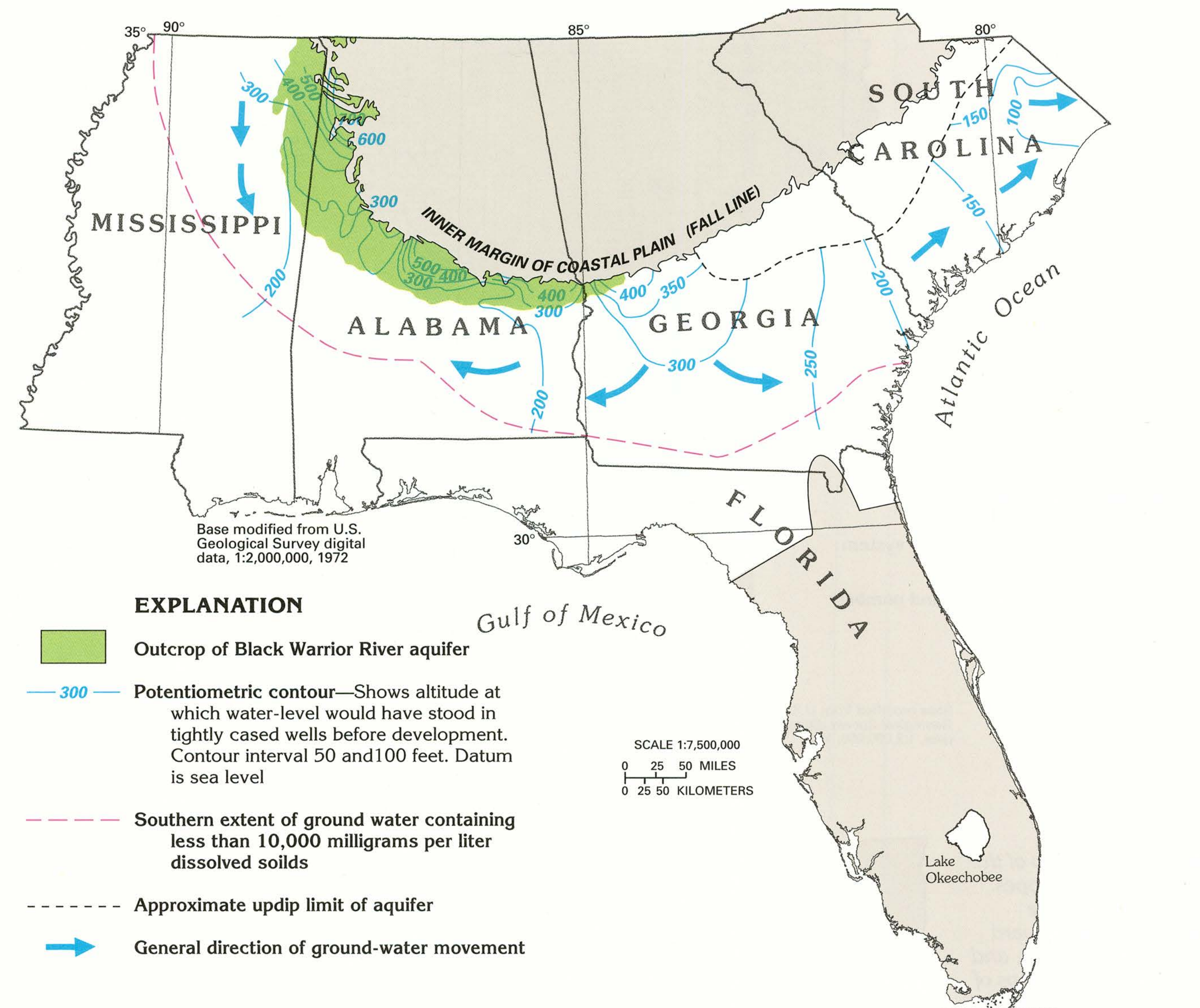


Figure 18. Water enters the Black Warrior River aquifer in outcrop areas and moves either to streams or down the dip of the aquifer. In confined areas, however, the water moves parallel to the outcrop bands or to the Atlantic coastline. Movement is along extremely long flow paths and the water eventually discharges to deeply entrenched rivers.

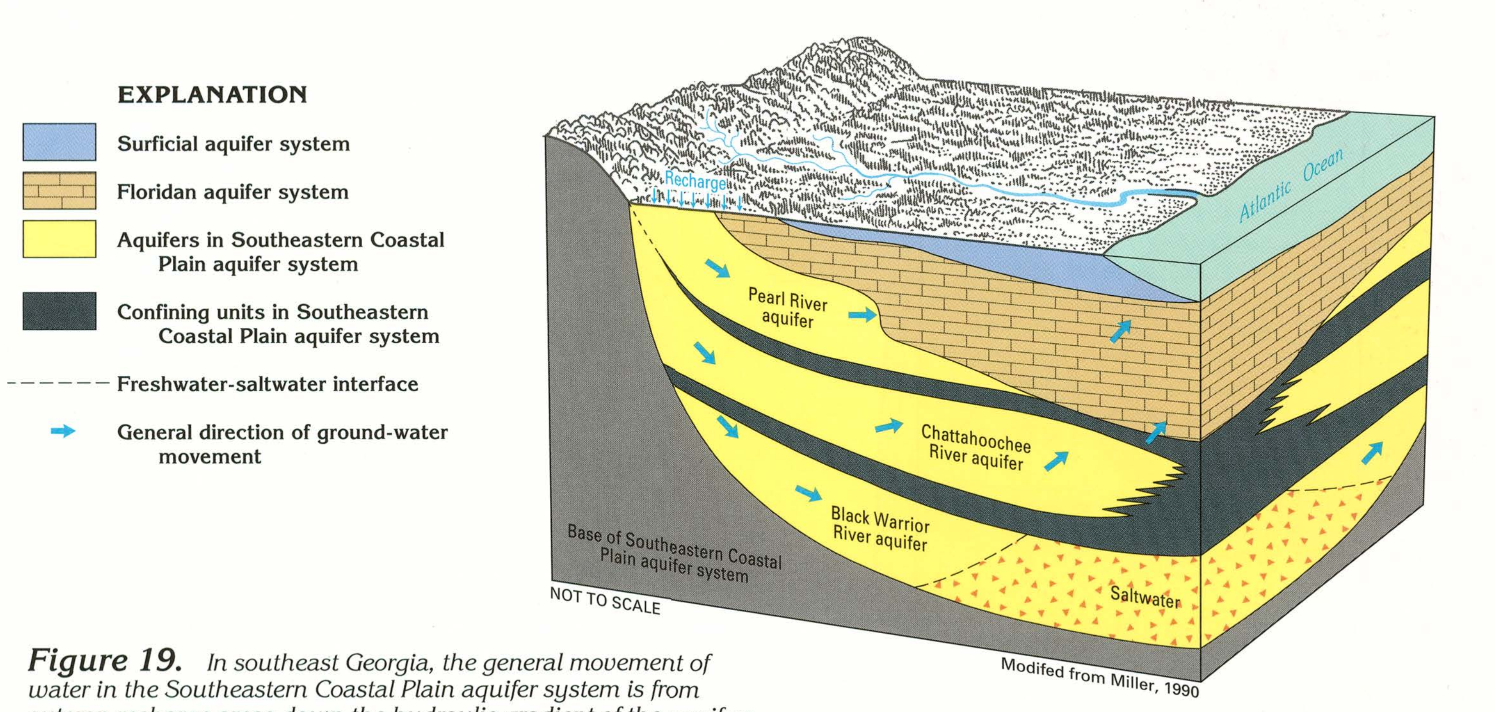


Figure 19. In southeast Georgia, the general movement of water in the Southeastern Coastal Plain aquifer system is from outcrop recharge areas down the hydraulic gradient of the aquifers until the water discharges upward to the overlying Floridan aquifer system. The downdip extent of flow is limited either by a marked decrease in permeability in the Chattahoochee River aquifer or by stagnant saline water in the Black Warrior River aquifer.

SANDSTONE AQUIFERS

Sandstone aquifers

Aquifers in sandstone are more widespread than those in all other kinds of consolidated rocks (**fig. 4**). Although the porosity of well-sorted, unconsolidated sand may be as high as 50 percent, the porosity of most sandstones is considerably less. During the process of conversion of sand into sandstone (lithification), compaction by the weight of overlying material reduces not only the volume of pore space as the sand grains become rearranged and more tightly packed, but also the interconnection between pores (permeability). The deposition of cementing materials such as calcite or silica between the sand grains further decreases porosity and permeability. Sandstones retain some primary porosity unless cementation has filled all the pores, but most of the porosity in these consolidated rocks consists of secondary openings such as joints, fractures, and bedding planes. Ground-water movement in sandstone aquifers primarily is along bedding planes, but the joints and fractures cut across bedding and provide avenues for the vertical movement of water between bedding planes.

Sandstone aquifers commonly grade laterally into fine-grained, low-permeability rocks such as shale or siltstone. Many sandstone aquifers are parts of complexly interbedded sequences of various types of sedimentary rocks. Folding and faulting of sandstones following lithification can greatly complicate the movement of water through these rocks. Despite all the above limitations, however, sandstone aquifers are highly productive in many places and provide large volumes of water for all uses.

The Cambrian–Ordovician aquifer system in the north-central United States (**fig. 20**) is composed of large-scale, predominantly sandstone aquifers that extend over parts of seven States and three segments of the Atlas. The aquifer system consists of layered rocks that are deeply buried where they dip into large structural basins. It is a classic confined, or artesian, system and contains three aquifers (**fig. 21**). In descending order, these are the St. Peter–Prairie du Chien–Jordan aquifer (sandstone with some dolomite), the Ironton–Galesville aquifer (sandstone), and the Mount Simon aquifer (sandstone). The aquifers are named from the principal geologic formations that comprise them. Confining units of poorly permeable sandstone and dolomite separate the aquifers. Low-permeability shale and dolomite compose the Maquoketa confining unit that overlies the uppermost aquifer and is considered to be part of the aquifer system. Wells that penetrate the Cambrian–Ordovician aquifer system commonly are open to all three aquifers, which are collectively called the sandstone aquifer in many reports.

The rocks of the aquifer system are exposed in large areas of northern Wisconsin and eastern Minnesota, adjacent to the Wisconsin Dome, a topographic high on crystalline Precambrian rocks. From this high area, the rocks slope southward into the Forest City Basin in southwestern Iowa and northwestern Missouri, southeastward into the Illinois Basin in southern Illinois, and eastward toward the Michigan Basin, a circular low area centered on the Lower Peninsula of Michigan. The configuration of the top of the Mount Simon sandstone (that forms the Mount Simon aquifer) is shown in **figure 22**. The map shows that this aquifer, which represents the lower part of the Cambrian–Ordovician aquifer system, is buried to depths of 2,000 to 3,500 feet below sea level in these structural basins. The configuration of the tops of the overlying Ironton–Galesville and St. Peter–Prairie du Chien–Jordan aquifers are similar to that of the Mount Simon aquifer. The deeply buried parts of the aquifer system contain saline water.

Regionally, water in the Cambrian–Ordovician aquifer system moves from topographically high recharge areas, where the aquifers crop out or are buried to shallow depths, eastward and southeastward toward the Michigan and Illinois Basins. A map of the 1980 potentiometric surface of the St. Peter–Prairie du Chien–Jordan aquifer (**fig. 23**) shows this general direction of movement. The map also shows that water moves subregionally toward major streams, such as the Mississippi and the Wisconsin Rivers, and toward major withdrawal centers, such as those at Chicago, Illinois, and Green Bay and Milwaukee, Wisconsin. In and near aquifer outcrop areas, water moves along short flow paths toward small streams. Movement of water in the underlying Ironton–Galesville and Mount Simon aquifers is similar to that in the St. Peter–Prairie du Chien–Jordan aquifer. Before development, all the water moved either toward surface streams where it discharged as base flow, or downgradient, toward the structural basins, into deeply buried parts of the aquifer where it discharged by upward leakage into shallower aquifers.

One of the most dramatic effects of ground-water withdrawals known in the United States is shown in **figure 24**. Withdrawals from the Cambrian–Ordovician aquifer system, primarily for industrial use in Milwaukee, Wisconsin, and Chicago, Illinois, caused declines in water levels of more than 375 feet in Milwaukee and more than 800 feet in Chicago from 1864 to 1980. Many of the wells in the Chicago–Milwaukee area obtain water from all three aquifers of the aquifer system, and the water-level decline map, accordingly, is a composite map that shows the effects of withdrawals on the entire system. The declines extended outward for more than 70 miles from the pumping centers in 1980. Movement of water in the aquifers was changed from the natural flow direction (eastward toward the Michigan Basin) to radial flow toward the pumping centers. Beginning in the early 1980's, withdrawals from the Cambrian–Ordovician aquifer system decreased as some users switched to Lake Michigan as a source of supply. Water levels in the aquifer system had begun to rise by 1985 as a result of the decreased withdrawals.

Figure 20. *The Cambrian–Ordovician aquifer system, which consists of predominantly sandstone aquifers separated by poorly permeable confining units, extends over a large part of the north-central United States.*

EXPLANATION

Cambrian-Ordovician aquifer system

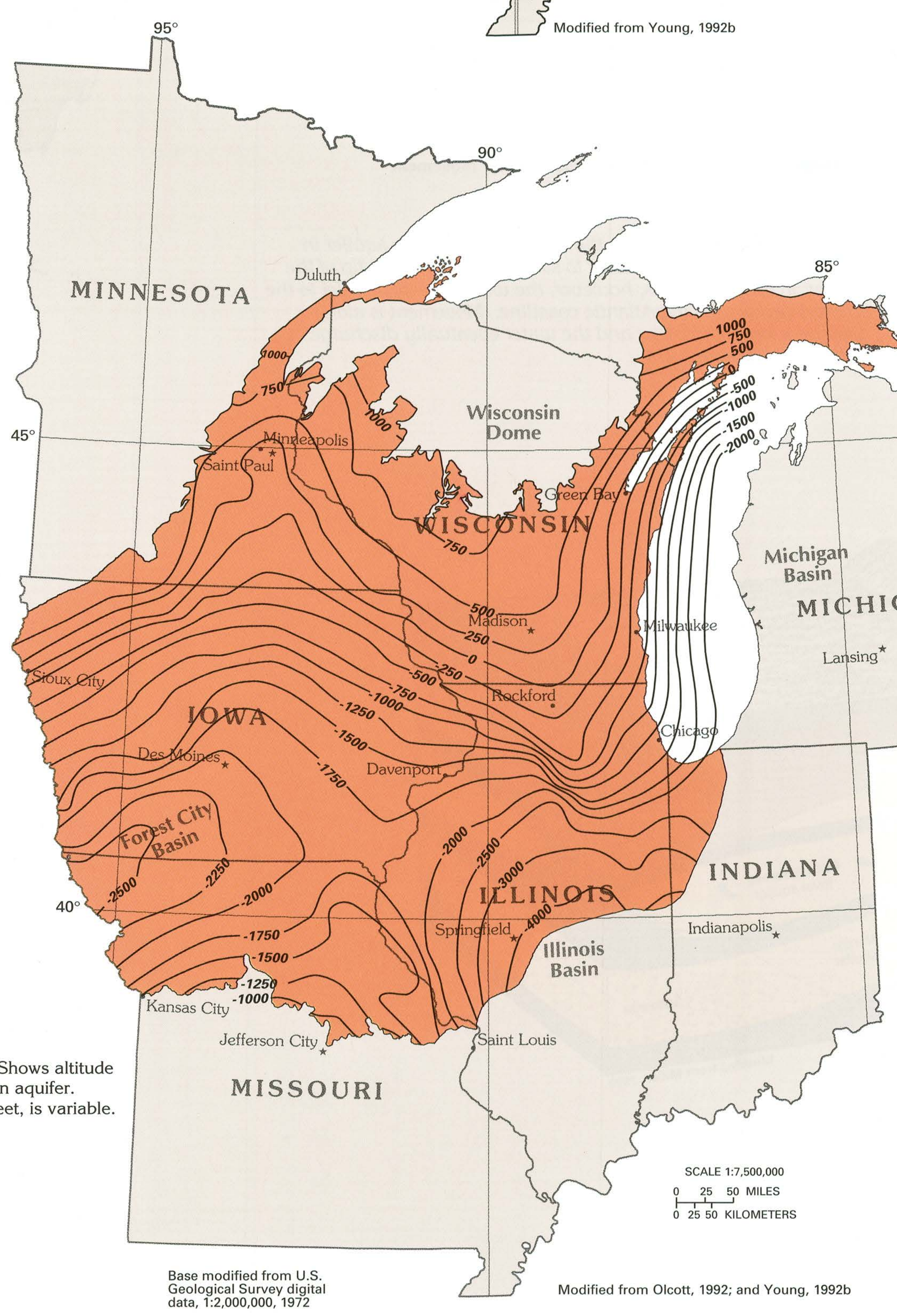
—— 9 Atlas segment boundary and number

Figure 21. *The three aquifers of the Cambrian–Ordovician aquifer system are separated by confining units. The Maquoketa confining unit at the top of the system creates artesian conditions wherever it is present.*

Geologic nomenclature	Principal lithology	Hydrogeologic nomenclature	
Ordovician	Shale and dolomite	Maquoketa confining unit	Cambrian–Ordovician aquifer system
	Dolomite		
	Shaly dolomite		
	Sandstone	St. Peter–Prairie du Chien–Jordan aquifer	
	Dolomite and sandstone		
Cambrian	Dolomite and fine-grained sandstone	St. Lawrence-Franconia confining unit	
	Sandstone	Ironton–Galesville aquifer	
	Shaly sandstone	Eau Claire confining unit	
Precambrian	Sandstone	Mount Simon aquifer	

Modified from Olcott, 1992

Figure 22. *The top of the Mount Simon aquifer slopes from high areas near the Wisconsin Dome downward into the Michigan, Illinois, and Forest City Basins. The tops of the overlying Ironton–Galesville and St. Peter–Prairie du Chien–Jordan aquifers have the same general shape.*

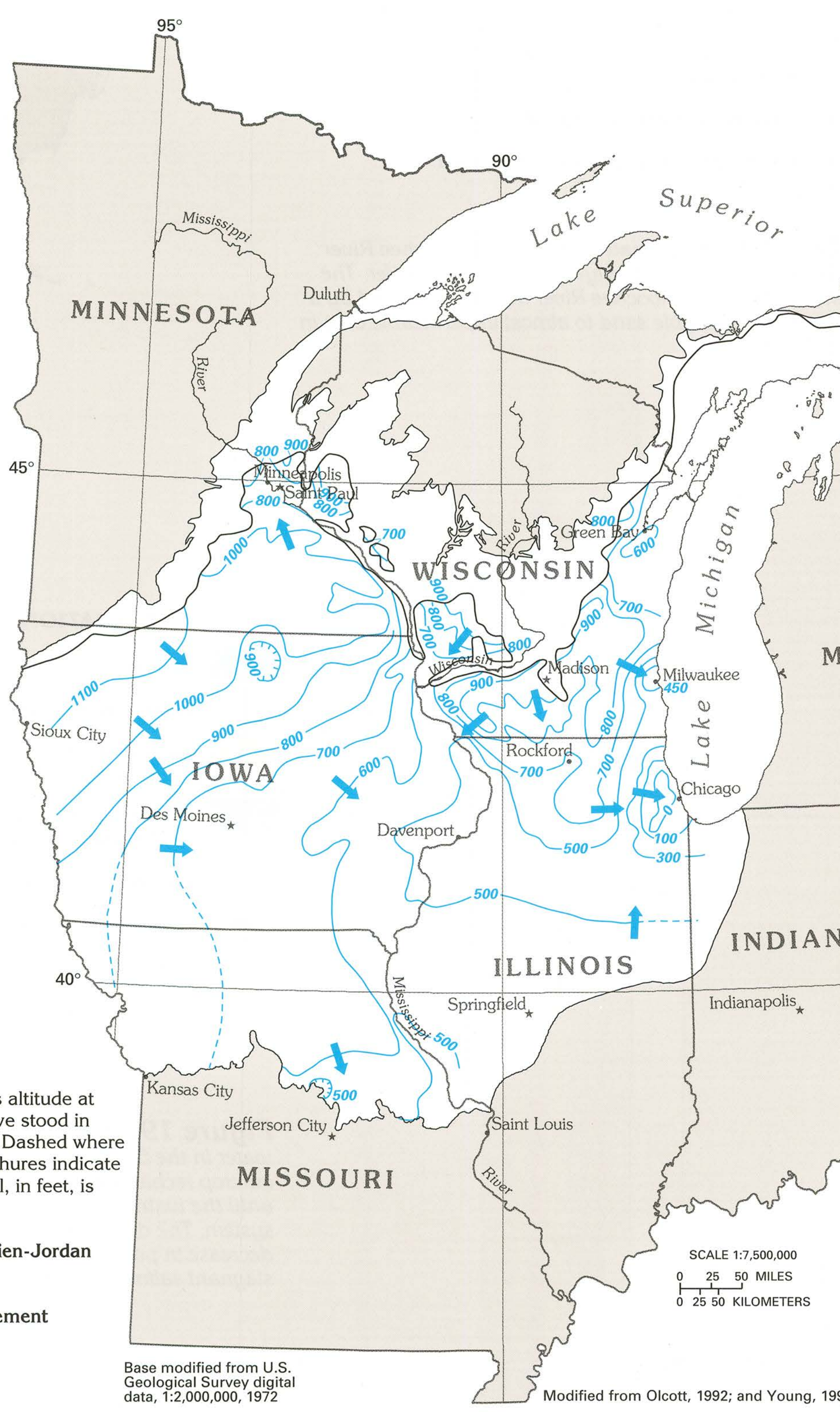


EXPLANATION

Mount Simon aquifer

—-250— Top-of aquifer contour—Shows altitude of top of Mount Simon aquifer. Contour interval, in feet, is variable. Datum is sea level

Figure 23. *Water in the St. Peter–Prairie du Chien–Jordan aquifer moves from aquifer outcrop areas regionally toward the Michigan and Illinois Basins, subregionally toward large rivers and major pumping centers, and locally toward smaller streams.*



EXPLANATION

— 800 - - - Potentiometric contour—Shows altitude at which water-level would have stood in tightly cased wells in 1980. Dashed where approximately located. Hachures indicate depression. Contour interval, in feet, is variable. Datum is sea level

—— Limit of St. Peter-Prairie du Chien-Jordan aquifer

➡ Direction of ground-water movement

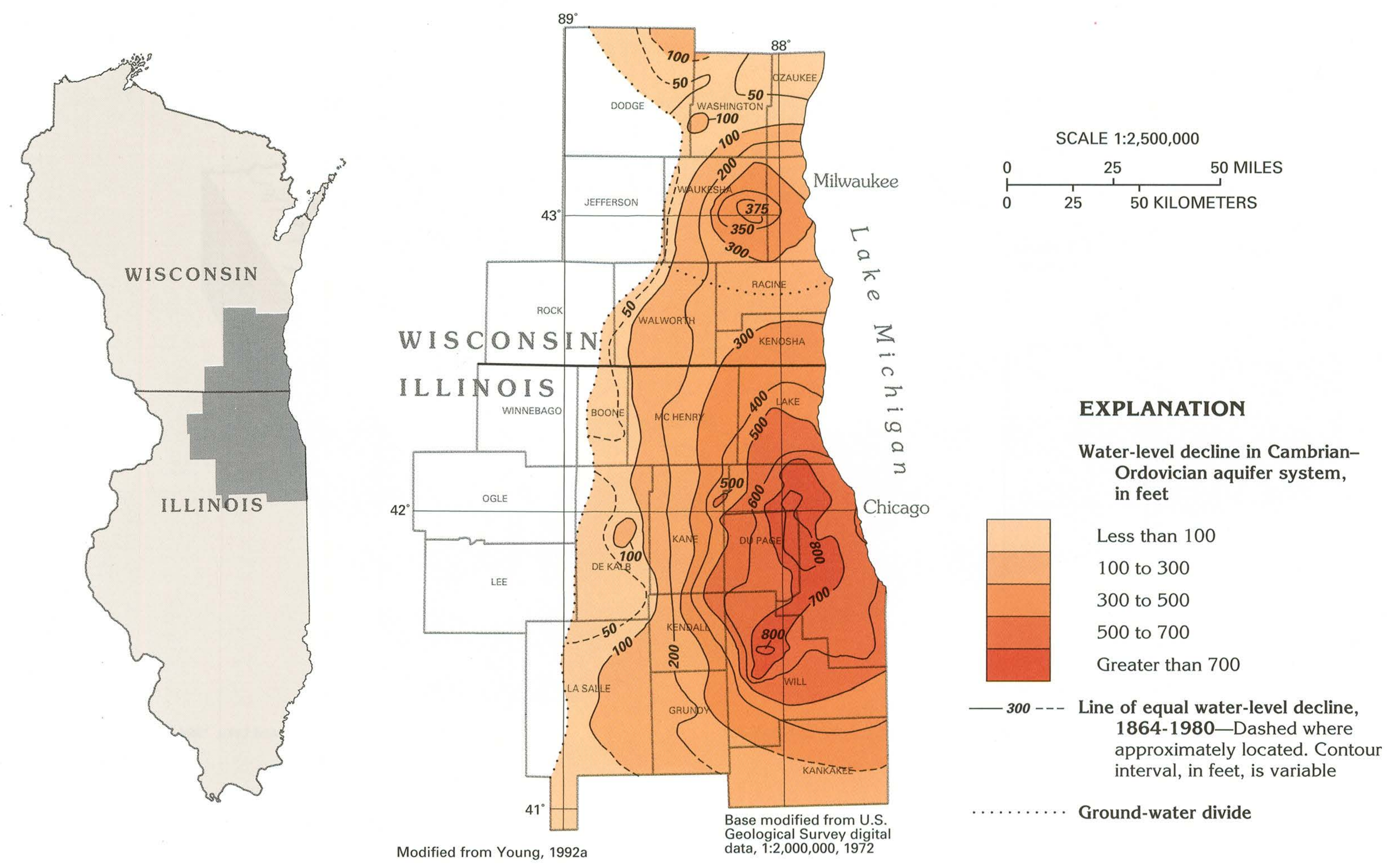


Figure 24. *Water levels in the Cambrian–Ordovician aquifer system declined more than 800 feet at Chicago as a result of large withdrawals from 1864 to 1980.*

SANDSTONE AQUIFERS— Continued

The ground-water flow system of the Cambrian–Ordovician aquifer system is summarized in **figure 25**. Water from precipitation moves downward through surficial deposits of glacial drift, shallower aquifers, and the Maquoketa confining unit into the St. Peter–Prairie du Chien–Jordan aquifer. Some of the water moves horizontally along short flow paths to local streams, such as the Little Cannon River, where it moves upward to discharge to the streams as base flow. Some water moves in a similar fashion along flow paths of intermediate length and discharges to larger streams, such as the Cannon River. Some of the water continues to percolate downward through successively deeper confining units into successively deeper aquifers. Water in these deeper aquifers moves laterally over long distances and eventually discharges to major rivers, such as the Mississippi River. A small part of the water moves down the regional hydraulic gradient, perpendicular to the plane of the section shown in **figure 25** and toward deeply buried parts of the aquifer system. This deep, regional flow discharges by upward leakage to shallower aquifers or is captured by pumping wells.

The chemical quality of the water in large parts of the aquifer system is suitable for most uses. The water is not highly mineralized in areas where the aquifers crop out or are buried to shallow depths, but mineralization generally increases as the water moves downgradient toward the structural basins. The distribution of dissolved-solids concentrations in the St. Peter–Prairie du Chien–Jordan aquifer (**fig. 26**) shows this increase. Where the aquifer is at or near the land surface in southeastern Minnesota, northeastern Iowa, southern Wisconsin, the Upper Peninsula of Michigan, and central Missouri, it contains water with dissolved-solids concentrations of less than 500 milligrams per liter (the limit recommended for drinking water by the U.S. Environmental Protection Agency) or less. Concentrations increase to more than 1,000 milligrams per liter in western and southern Iowa, north-central Illinois, and along the northwestern shore of Lake Michigan. Where the aquifer is deeply buried and ground-water movement is almost stagnant in parts of Missouri, concentrations are greater than 10,000 milligrams per liter. The lobe of water with low dissolved-solids concentrations that extends southward in central Iowa is thought to represent unflushed subglacial meltwater that moved into the aquifer during the Pleistocene Epoch from an area of extremely high hydraulic head created by the weight of the glacial ice. Dissolved solids in water from the Mount Simon aquifer show the same trends as those in water from the St. Peter–Prairie du Chien–Jordan aquifer.

Other layered sandstone aquifers that are exposed adjacent to domes and uplifts or that extend into large structural basins or both are the Colorado Plateaus aquifers, the Denver Basin aquifer system, the lower Tertiary aquifers, the Upper Cretaceous aquifers, the Lower Cretaceous aquifers, the Wyoming Tertiary aquifers, the Mississippian aquifer of Michigan, and the New York sandstone aquifers (**fig. 4**). The Rush Springs, Central Oklahoma, and Ada–Vamoosa aquifers of Oklahoma are small aquifers that contain water largely under unconfined conditions and generally yield small amounts of water. The Jacobsville aquifer on the Upper Peninsula of Michigan is also small, mostly unconfined, and yields little water; however, the glacial deposits that cover this aquifer store precipitation and release it slowly into the underlying sandstone. The Pennsylvanian aquifers that cover large parts of the east-central United States cap hills and plateaus, are poorly permeable, and yield water mostly from shallow fracture systems and interbedded, cleated coals. The early Mesozoic basin aquifers of the eastern part of the Nation occupy titled grabens or half-grabens, are commonly interbedded with fine-grained sediments and intruded by traprock, and generally yield only small amounts of water.

Figure 25. *Water in the stacked sandstone aquifers moves vertically downward, then horizontally toward major rivers, where it moves upward to discharge as base flow. Regional flow, not shown here, is perpendicular to the section and into deep, confined parts of the aquifers.*

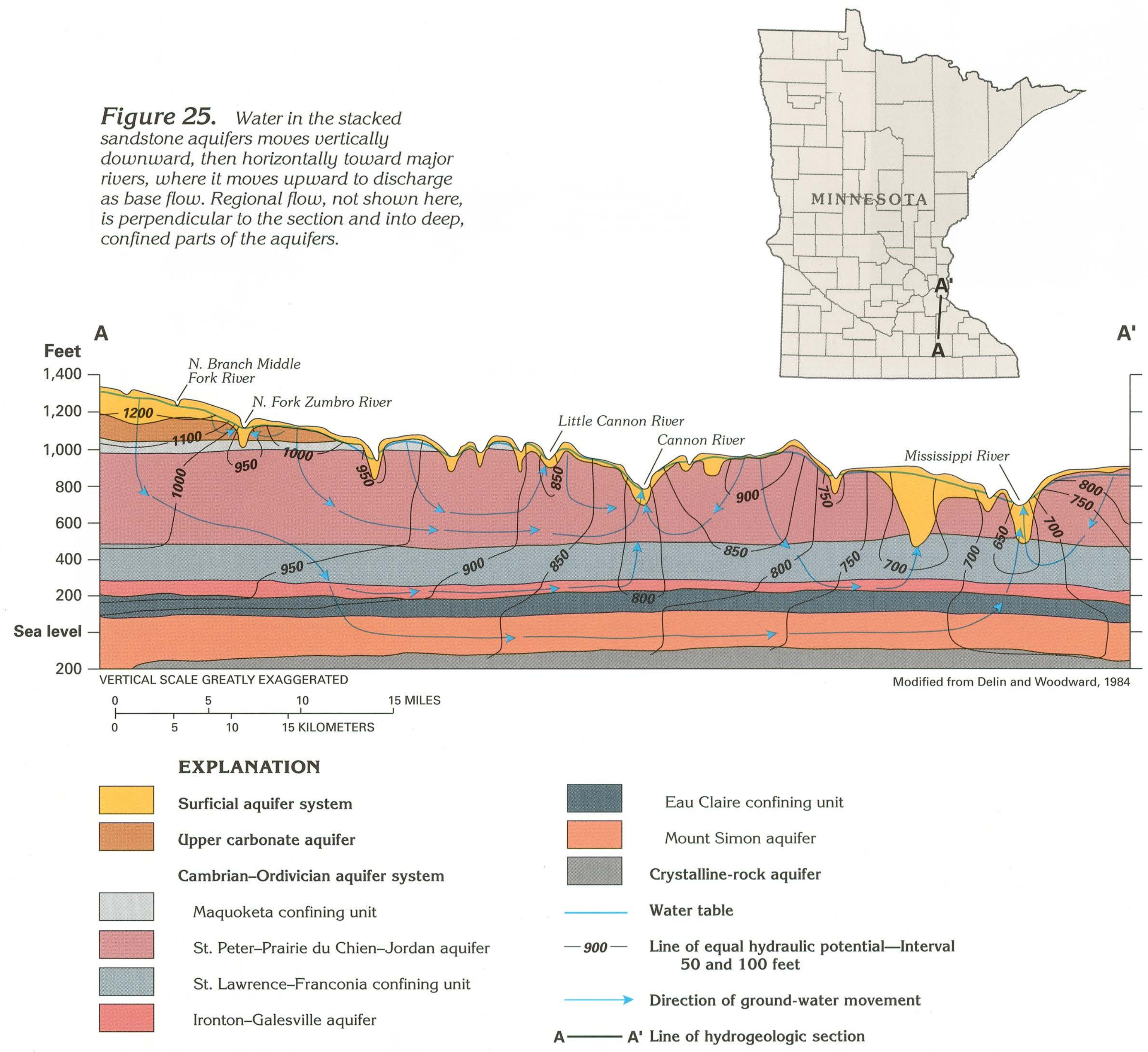
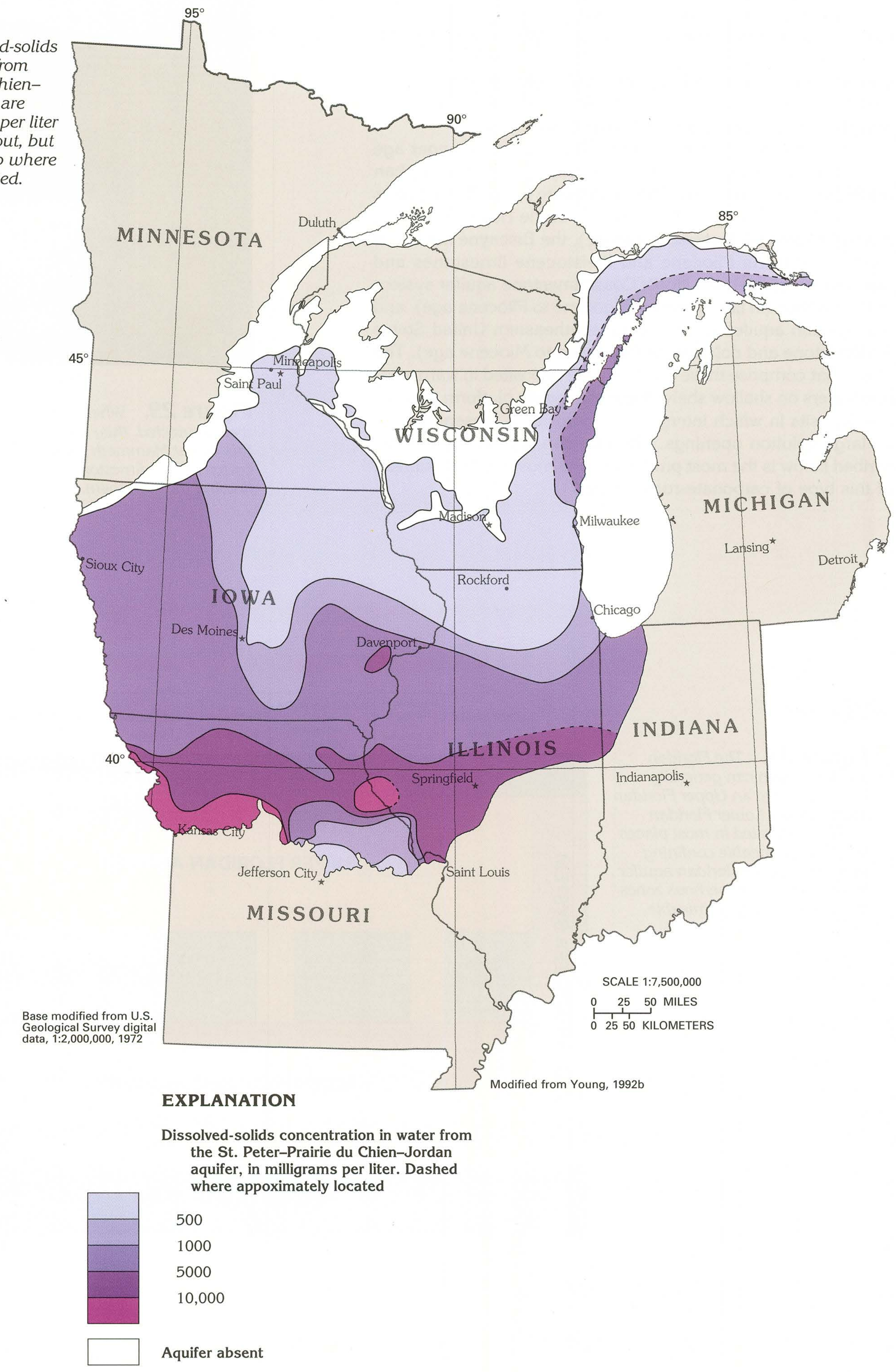


Figure 26. *Dissolved-solids concentrations in water from the St. Peter–Prairie du Chien–Jordan aquifer generally are less than 500 milligrams per liter where the aquifer crops out, but increase greatly downdip where the aquifer is deeply buried.*



CARBONATE-ROCK AQUIFERS

Aquifers in carbonate rocks are most prominent in the central and southeastern parts of the Nation, but also occur in small areas as far west as southeastern California and as far east as northeastern Maine and in Puerto Rico (**fig. 4**). The rocks that comprise these aquifers range in age from Precambrian to Miocene. Most of the carbonate-rock aquifers consist of limestone, but dolomite and marble locally are sources of water. The water-yielding properties of carbonate rocks are highly variable; some yield almost no water and are considered to be confining units, whereas others are among the most productive aquifers known.

Most carbonate rocks form from calcareous deposits that accumulate in marine environments ranging from tidal flats to reefs to deep ocean basins. The deposits are derived from calcareous algae or the skeletal remains of marine organisms that range from foraminifera to molluscs. Minor amounts of carbonate rocks are deposited in fresh to saline lakes, as spring deposits, geothermal deposits, or dripstone in caves. The original texture and porosity of carbonate deposits are highly variable because of the wide range of environments in which the deposits form. The primary porosity of the deposits can range from 1 to more than 50 percent. Compaction, cementation, and dolomitization are diagenetic processes which act on the carbonate deposits to change their porosity and permeability.

The principal post-depositional process that acts on carbonate rocks is dissolution. Carbonate rocks are readily dissolved to depths of about 300 feet below land surface where they crop out or are covered by a thin layer of material. Precipitation absorbs some carbon dioxide as it falls through the atmosphere, and even more from organic matter in the soil through which it percolates, thus forming weak carbonic acid. This acidic water partially dissolves carbonate rocks, initially by enlarging pre-existing openings such as pores between grains of limestone or joints and fractures in the rocks. These small solution openings become larger especially where a vigorous ground-water flow system moves the acidic water through the aquifer. Eventually, the openings join as networks of solution openings, some of which may be tens of feet in diameter and hundreds to thousands of feet in length. The end result of carbonate-rock dissolution is expressed at the land surface as karst topography, characterized by caves, sinkholes, and other types of solution openings, and by few surface streams. Where saturated, carbonate-rock aquifers with well-connected networks of solution openings yield large volumes of water to wells that penetrate the solution cavities, even though the undissolved rock between the large openings may be almost impermeable (**fig. 27**). Because water enters the carbonate-rock aquifers rapidly through large openings, any contaminants in the water can rapidly enter and spread through the aquifers.

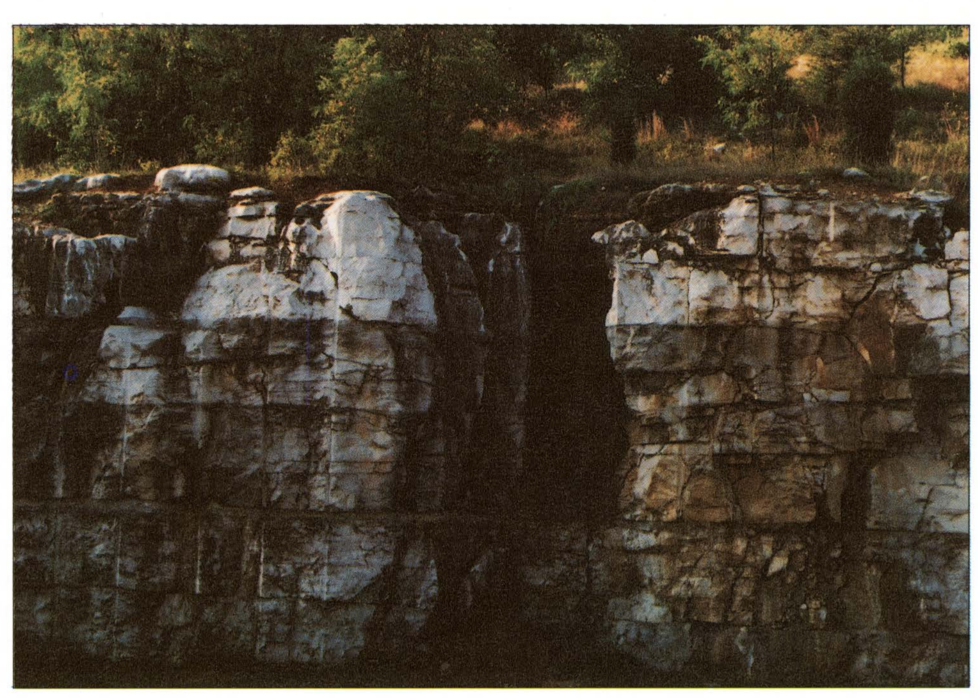


Figure 27. *Dissolution along joints and bedding planes in carbonate rocks forms extremely permeable conduits that conduct large volumes of water through the almost impermeable undissolved rock.*

Carbonate-rock aquifers

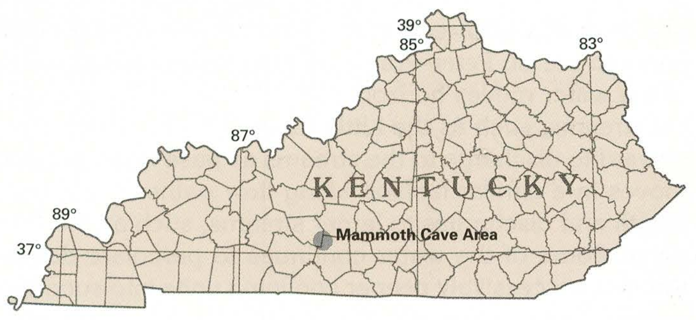
CARBONATE-ROCK AQUIFERS—
Continued

Some of the common types of karst features that develop on the land surface where limestone is exposed in the Mammoth Cave area of central Kentucky are shown in **figure 28**. Recharge water enters the aquifer through sinkholes, swallow holes, and sinking streams, some of which terminate at large depressions called blind valleys. These depressions, along with karst valleys and sinkholes, form when all or part of a cavern roof collapses. Uncollapsed remnants of the cavern roof form natural bridges. Surface streams are scarce because most of the water is quickly routed underground through solution openings. In the subsurface, most of the water moves through caverns and other types of large solution openings.

Solution cavities riddle the Mississippian limestones that underlie the Mammoth Cave Plateau and the Pennyroyal Plain that borders the plateau to the south and southwest. Some of these cavities form the large, extensive passages of Mammoth Cave (**fig. 29**), one of the Nation's largest and best studied cave systems. As the cave's network developed, surface streams were diverted into the passages through sinkholes and flowed as underground streams through openings along bedding planes. Sand and other sediment carried by the underground streams abraded the limestone, thus further enlarging the solution openings through which the stream flowed. Vertical passages, usually developed at the intersections of joints, connect the horizontal bedding plane openings. Dissolution and erosional processes are still active at Mammoth Cave.

Aquifers in carbonate rocks of Cretaceous to Precambrian age yield water primarily from solution openings. Except for a basal sandstone aquifer, the Ozark Plateaus aquifer system consists of carbonate-rock aquifers whose hydrologic characteristics are like those of the limestones at Mammoth Cave. The Silurian–Devonian aquifers, the Ordovician aquifers, the Upper Carbonate aquifer of southern Minnesota, the Arbuckle–Simpson aquifer of Oklahoma, and the New York carbonate-rock aquifers are all in layered limestones and dolomites of Paleozoic age, in which solution openings are locally well developed. The Blaine aquifer in Texas and Oklahoma likewise yields water from solution openings, some of which are in carbonate rocks and some of which are in beds of gypsum and anhydrite interlayered with the carbonate rocks.

Aquifers in carbonate rocks of Tertiary and younger age have different permeability and porosity characteristics than aquifers in Cretaceous and older carbonate rocks. The aquifers in Tertiary and younger rocks are the Castle Hayne aquifer of North Carolina (in Eocene limestone), the Biscayne aquifer of South Florida (in Pliocene and Pleistocene limestones and interbedded sands), the North Coast limestone aquifer system in Puerto Rico (in limestone of Oligocene to Pliocene age), and the Floridan aquifer system of the southeastern United States (in limestone and dolomite of Paleocene to Miocene age). The strata that comprise these aquifers were deposited in warm marine waters on shallow shelves and are mostly platform carbonate deposits in which intergranular porosity is present as well as large solution openings. The Floridan aquifer system described below is the most productive and most studied example of this type of carbonate-rock aquifer.



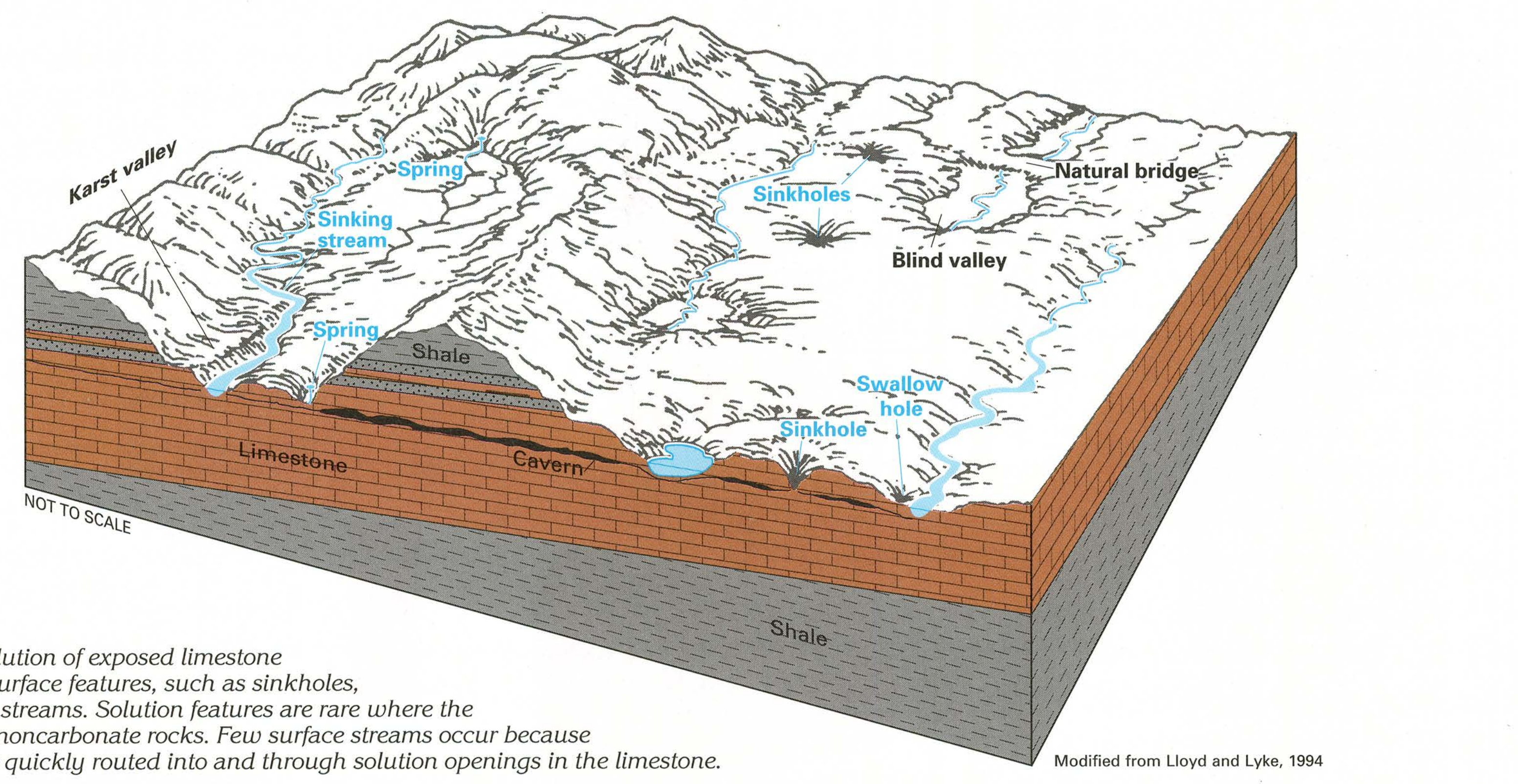


Figure 28. The dissolution of exposed limestone forms characteristic land-surface features, such as sinkholes, karst valleys, and sinking streams. Solution features are rare where the limestone is covered with noncarbonate rocks. Few surface streams occur because most of the precipitation is quickly routed into and through solution openings in the limestone.

Modified from Lloyd and Lyke, 1994

Joe Meiman, U.S. National Park Service, Mammoth Cave, Ky.

Figure 29. Where solution openings in limestone are large and well connected, they may form networks of cave passages such as this one at Mammoth Cave. The openings can be enlarged at the bottom as the limestone is eroded by sediment-laden streams flowing through them.

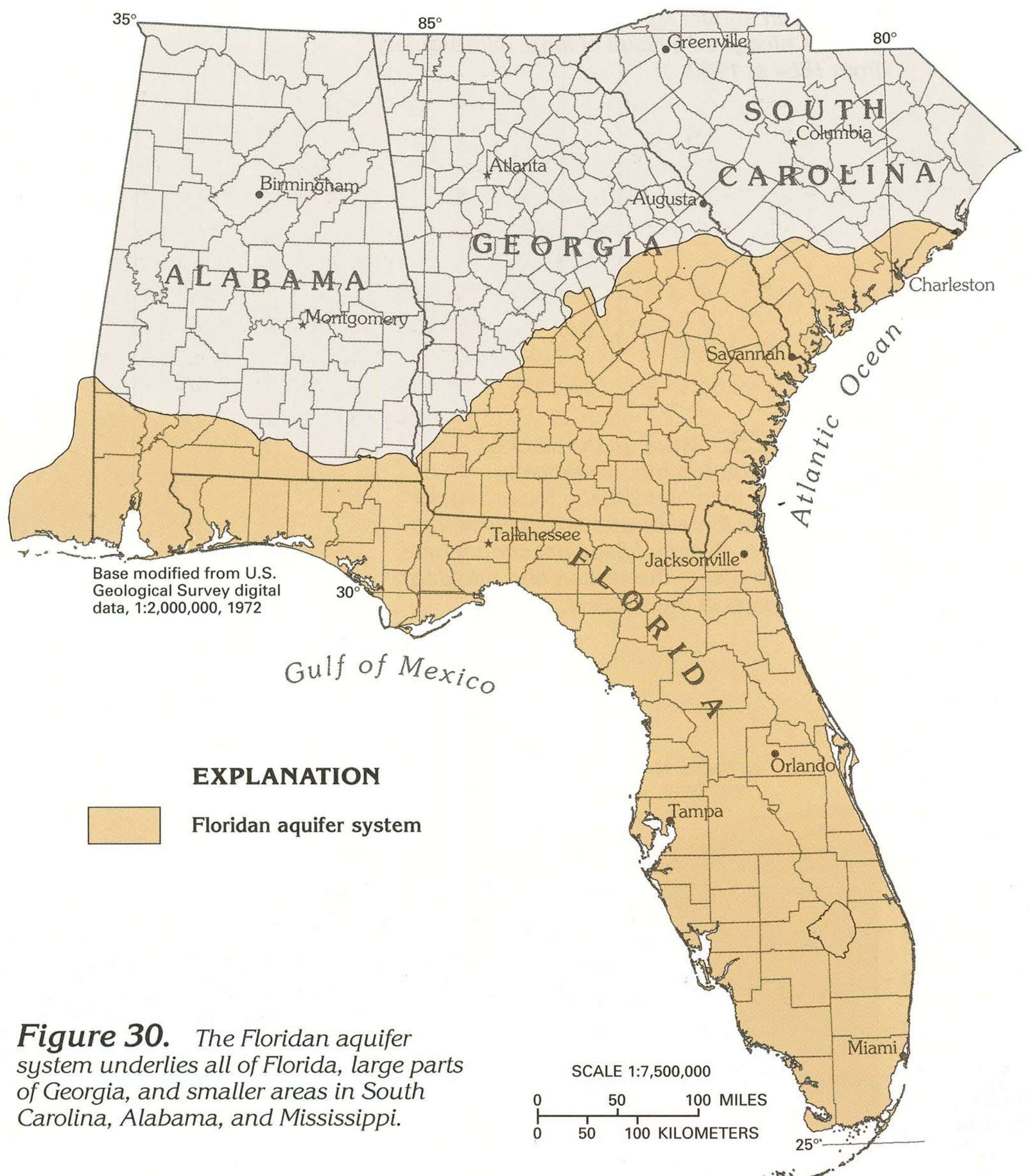
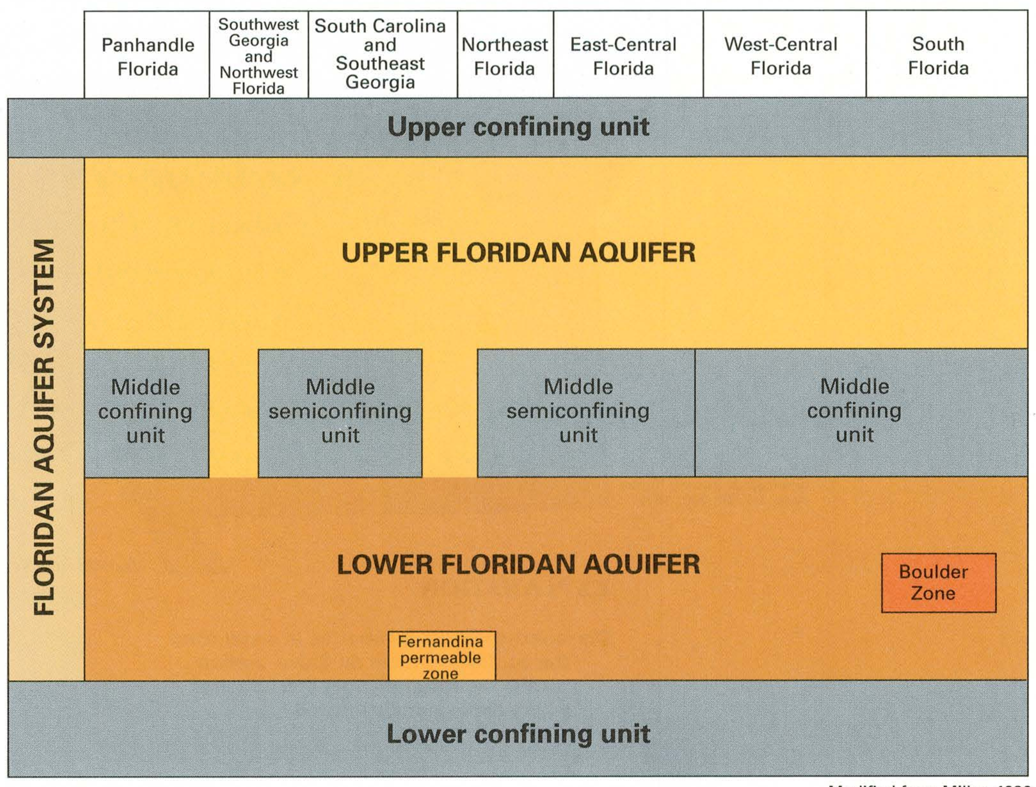


Figure 30. The Floridan aquifer system underlies all of Florida, large parts of Georgia, and smaller areas in South Carolina, Alabama, and Mississippi.

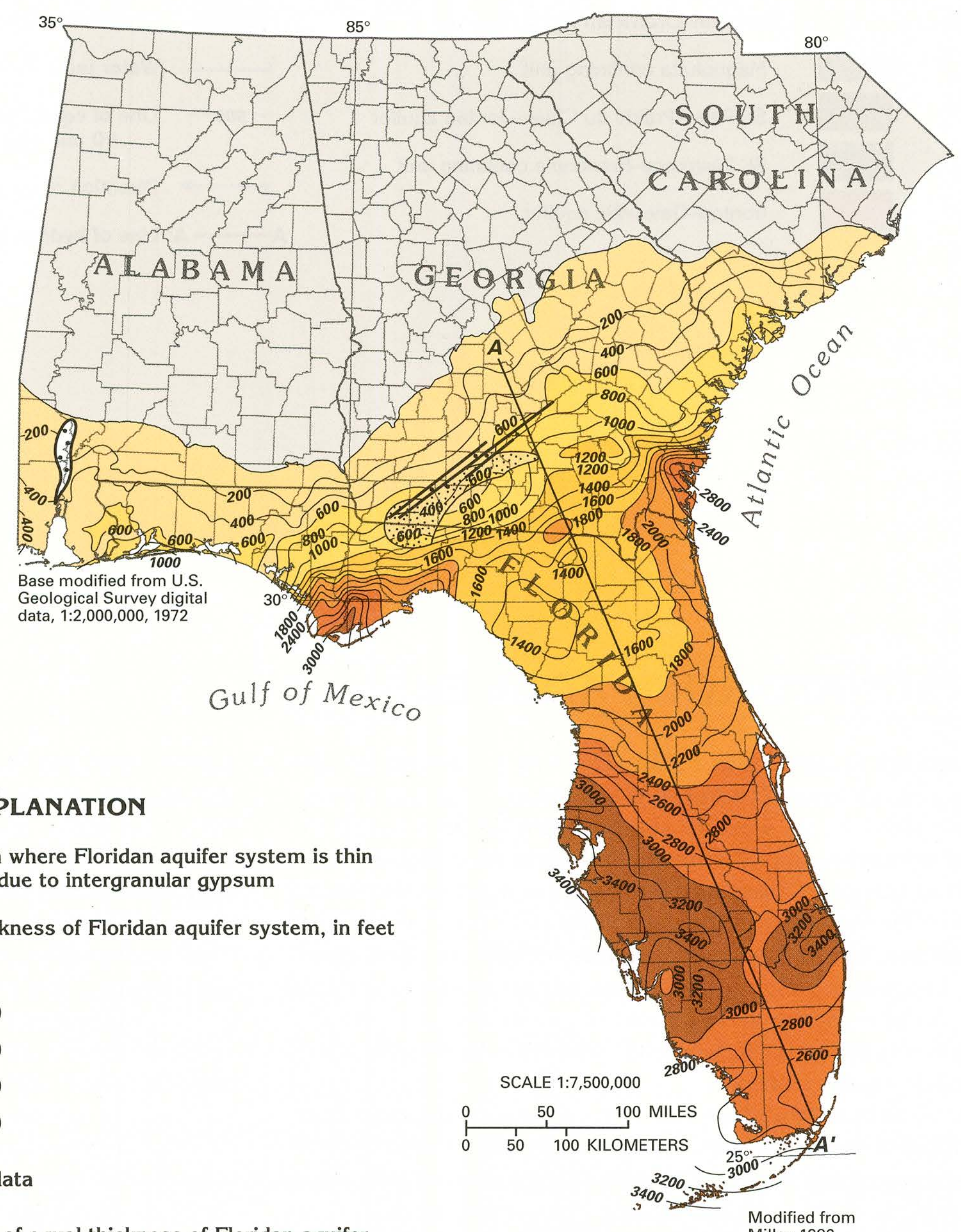
Modified from Miller, 1990

Figure 31. The Floridan aquifer system can generally be divided into an Upper Floridan aquifer and a Lower Floridan aquifer, separated in most places by a less-permeable confining unit. The Lower Floridan aquifer locally contains cavernous zones that are extremely permeable.



Modified from Miller, 1986

Figure 32. The thickness of the Floridan aquifer system varies considerably. Some of the variations reflect major warping of the Earth's crust during deposition of the carbonate rocks that compose the system and some reflect faulting after the rocks were deposited.



Modified from Miller, 1986

EXPLANATION

Area where Floridan aquifer system is thin due to intergranular gypsum

Thickness of Floridan aquifer system, in feet

600
1200
1800
2400
3000
No data

—2000— Line of equal thickness of Floridan aquifer system—Interval 200 feet

Fault—Vertical or nearly so. Bar and ball on downthrown side

A——A' Line of hydrogeologic section—Section shown in figure 33

The Floridan aquifer system underlies an area of about 100,000 square miles in southeastern Mississippi, southern Alabama, southern Georgia, southern South Carolina, and all of Florida (**fig. 30**). The Floridan is one of the most productive aquifer systems in the world; an average of about 3.4 billion gallons per day of freshwater was withdrawn from it during 1990. Despite the huge withdrawals, water levels in the Floridan have not declined regionally; however, large declines have occurred locally at a few pumping centers.

The Floridan aquifer system is extremely complex because the rocks that compose the system were deposited in highly variable environments, and their texture accordingly varies from coarse coquina that is extremely permeable to micrite that is almost impermeable. Diagenesis has changed the original texture and mineralogy of the carbonate rocks in many places. The principal diagenetic processes that influence the porosity and permeability of the aquifer system are dolomitization (which increases the volume of connected pore space in fine-grained limestones) and calcite or dolomite overgrowths (which fill part or all of the connected pore space in pelletal limestone or coquina). Dissolution of the limestone has produced small to large conduits at different levels in the aquifer system. These factors produce much local variability in the lithology and the permeability of the aquifer system, but regionally the system consists of an upper and a lower aquifer, which are separated by a less-permeable confining unit (**fig. 31**). In parts of northeastern and northwestern Florida and southwestern Georgia, no confining unit exists and the Upper and Lower Floridan aquifers are directly connected. Two cavernous zones, the Fernandina permeable zone and the Boulder Zone, are present in the Lower Floridan aquifer. Low-permeability confining units bound the aquifer system above and below.

The thickness of the Floridan aquifer system ranges from a thin edge at its northern limit to more than 3,400 feet in parts of southern Florida (**fig. 32**). The map shows the combined thicknesses of the Upper and Lower Floridan aquifers and the middle confining unit where it is present. Some of the large-scale features on the thickness map are related to geologic structures. For example, the thick areas in southeastern Georgia and in the eastern panhandle of Florida coincide with downwarped areas which are called the Southeast and Southwest Georgia Embayments, respectively. In north-central peninsular Florida, the aquifer system thins over an upwarp which is called the Peninsular Arch. Faults in southern Georgia and southwestern Alabama form the boundaries of trough-like grabens. Clayey sediments within these downdropped structural blocks have been juxtaposed opposite permeable limestone of the Floridan aquifer system, and the low-permeability clay creates a damming effect that restricts the lateral movement of ground water across the grabens.

CARBONATE-ROCK AQUIFERS—
Continued

Some of the variations within the Floridan aquifer system and the complexity of the system are shown by a geohydrologic section that extends from south-central Georgia to southern Florida (**fig. 33**). The aquifer system thickens southeastward; it is only about 250 feet thick in south-central Georgia, but is more than 3,000 feet thick in southern Florida. A graben called the Gulf Thrugh, shown near the left side of the section, is between two faults that completely cut the aquifer system; thick clay of the upper confining unit of the Floridan accumulated in the graben. In Georgia, the aquifer system contains only scattered, local confining units or none at all. By contrast, in most of Florida, the system contains one to several thick confining units of regional extent. These confining units consist of carbonate rocks that are much less permeable than the water-yielding strata of the aquifer system, and retard the vertical movement of water within it. The Boulder Zone in southern Florida is a deeply-buried, cavernous zone that is filled with saline water and used as a receiving zone for injected wastes. In Georgia, the Floridan aquifer system directly overlies the Southeastern Coastal Plain aquifer system, which consists of interbedded sand aquifers and clayey confining units, all of which are much less permeable than the carbonate rocks of the Floridan.

The major features of the regional ground-water flow system of the Floridan aquifer system are shown by a map of the potentiometric surface of the Upper Floridan aquifer (**fig. 34**). The water moves regionally southeastward and southward from recharge areas in central Georgia and southern Alabama where the aquifer is exposed at the land surface or is covered by a thin layer of younger sediments. Water also moves outward in all directions from local potentiometric highs in south-central Georgia and in the northern and central parts of the Florida peninsula. Depressions on the potentiometric surface mark major withdrawal centers at Savannah, Georgia, and at Fernandina Beach, Fort Walton Beach, and the Hillsborough–Pinellas County area, Florida. The band of closely spaced contours that extends northeastward from Grady County to Jeff Davis County, Georgia, is located just up the hydraulic gradient from the Gulf Trough graben that is filled with a thick sequence of clay. This clay, which is part of the upper confining unit of the Floridan aquifer system, has been downdropped opposite the permeable limestone of the Floridan, thus impeding the coastward flow of water in the aquifer. This impedance is represented by the closely spaced contours.

Florida has 27 first-magnitude springs (**fig. 35**), or springs which discharge 100 cubic feet per second or more, out of 78 in the Nation. All these springs issue from the Upper Floridan aquifer, and practically all of them are located in places where the aquifer is exposed at the land surface or is covered by less than 100 feet of clayey upper confining unit. Dissolution of the carbonate rocks of the aquifer in these places has resulted in the development of large caverns, many of which channel the ground water to major spring orifices. Some of the springs are large enough to form the headwaters of surface streams.

Large withdrawals from the Upper Floridan aquifer at several major pumping centers lowered hydraulic heads in the aquifer more than 80 feet from predevelopment levels in several places by 1980 (**fig. 36**). Regional declines of 10 to 30 feet have developed in three multicounty areas, one of which extends over almost half the Georgia Coastal Plain. The withdrawals have locally reversed predevelopment hydraulic gradients in some coastal areas, creating the potential for the encroachment of saline water from the Gulf of Mexico, the Atlantic Ocean, or from deep parts of the Floridan aquifer system that contain saline water. However, saline water encroachment is limited to a few localized areas at present (1998). Although withdrawals are large, they have not greatly altered the major characteristics of the predevelopment ground-water flow system. The dominant forms of discharge from the aquifer system are springflow and baseflow to streams, just as before development began. Water-budget calculations indicate that withdrawal of about 3.4 billion gallons per day of freshwater during 1990 accounts for only about 20 percent of the total discharge from the aquifer system.

The chemical quality of water in the Floridan aquifer system is suitable for most uses over an area of about two-thirds of the aquifer system. Water with dissolved-solids concentrations of 1,000 milligrams per liter or greater is not considered by the U.S. Environmental Protection Agency to be suitable for drinking. A map of dissolved-solids concentrations of water in the Upper Floridan aquifer (**fig. 37**) shows that mineralization of the water is greater near the coast than inland. The distribution of dissolved solids is related to the ground-water flow system and proximity to seawater. Where the aquifer is unconfined or overlain by a thin confining unit, ground-water flow is vigorous. Large volumes of water move quickly in and out of the aquifer, and dissolved-solids concentrations are minimal. By contrast, water that travels coastward down long, regional flow paths is in contact with aquifer materials, such as limestone or local gypsum beds, for a much longer time and dissolves more mineral material. Thus, the water has larger dissolved-solids concentrations. Near the coasts, large dissolved-solids concentrations are due to the mixing of fresh ground water with seawater that migrates into the aquifer from the ocean or the Gulf of Mexico. In southern Florida and along the St. Johns River in east-central Florida, areas of large dissolved-solids concentrations represent unflushed seawater that was either trapped in the limestone of the aquifer system as it was deposited or entered the aquifer system later, during high stands of sea level. Dissolved-solids concentrations in water from the Lower Floridan aquifer are larger than those in the Upper Floridan aquifer because the water in the Lower Floridan has followed longer flowpaths and, accordingly, has had more time to dissolve aquifer minerals.

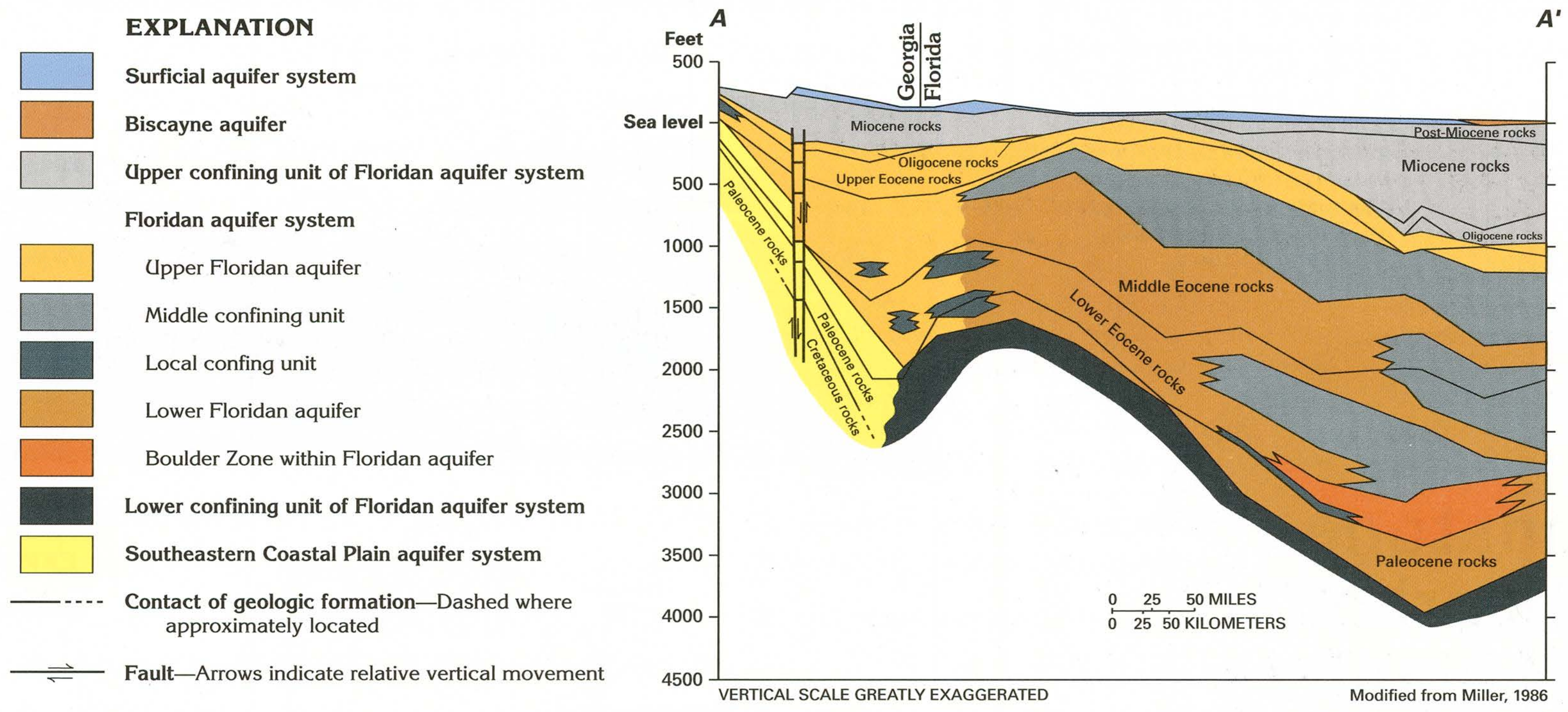


Figure 33. The Floridan aquifer system is thin in south-central Georgia, where it consists of a single aquifer that contains local confining units. The system thickens greatly in Florida, where it consists of complexly interfingering, lens-shaped bodies of permeable and less-permeable carbonate rocks. The line of the hydrogeologic section is shown in figure 32.

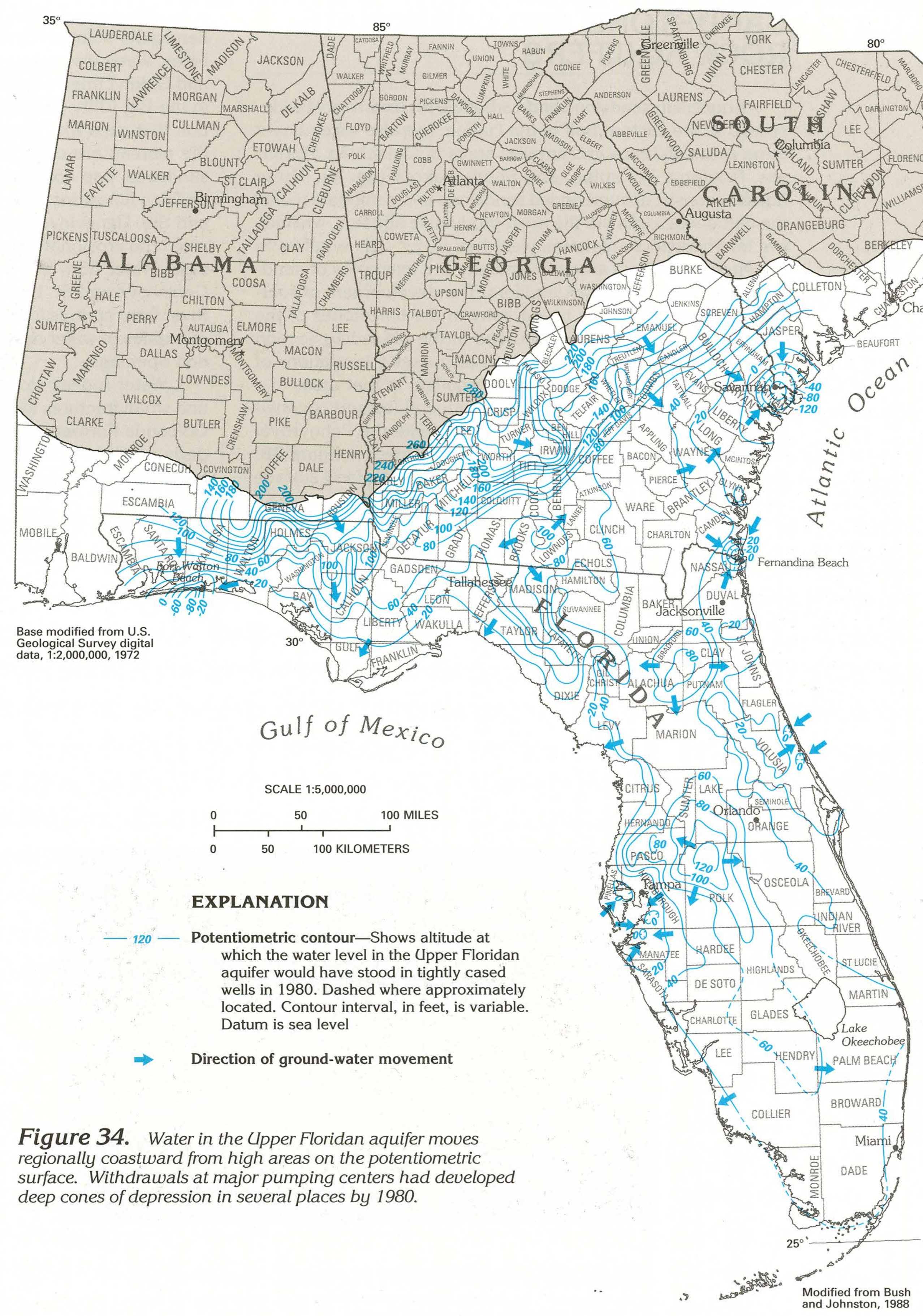


Figure 34. Water in the Upper Floridan aquifer moves regionally coastward from high areas on the potentiometric surface. Withdrawals at major pumping centers had developed deep cones of depression in several places by 1980.

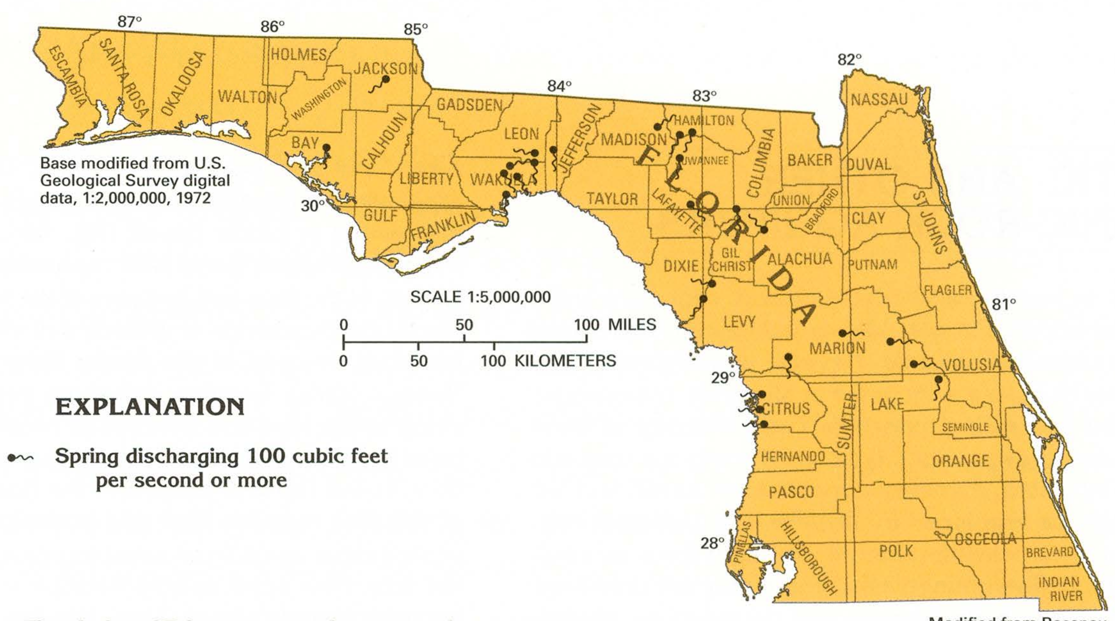


Figure 35. Florida has 27 first-magnitude springs that issue from large solution openings in the Upper Floridan aquifer. These openings are features of the karst topography that has developed on the carbonate rocks of the aquifer where its upper confining unit is thin or absent.

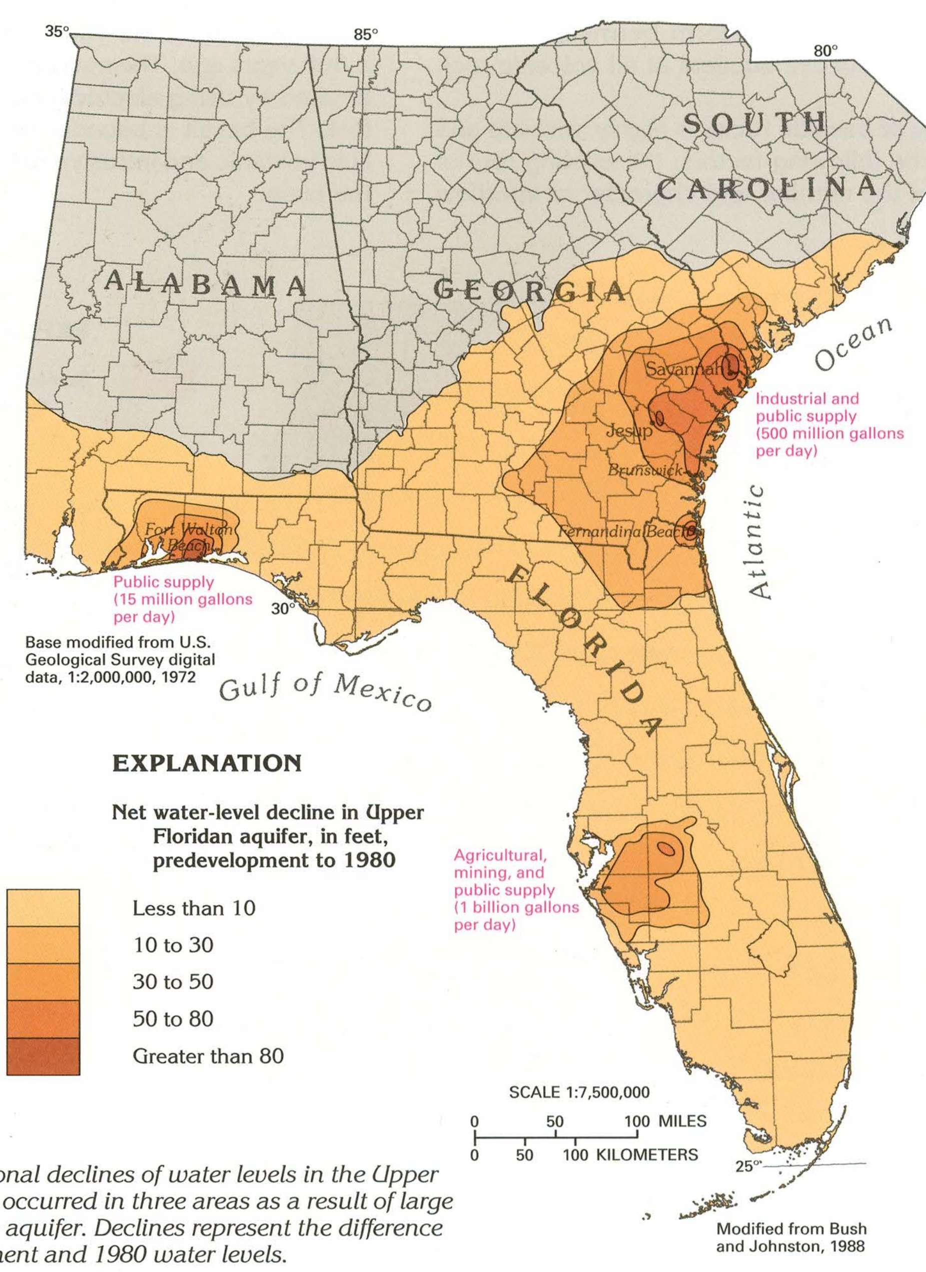


Figure 36. Regional declines of water levels in the Upper Floridan aquifer have occurred in three areas as a result of large withdrawals from the aquifer. Declines represent the difference between predevelopment and 1980 water levels.

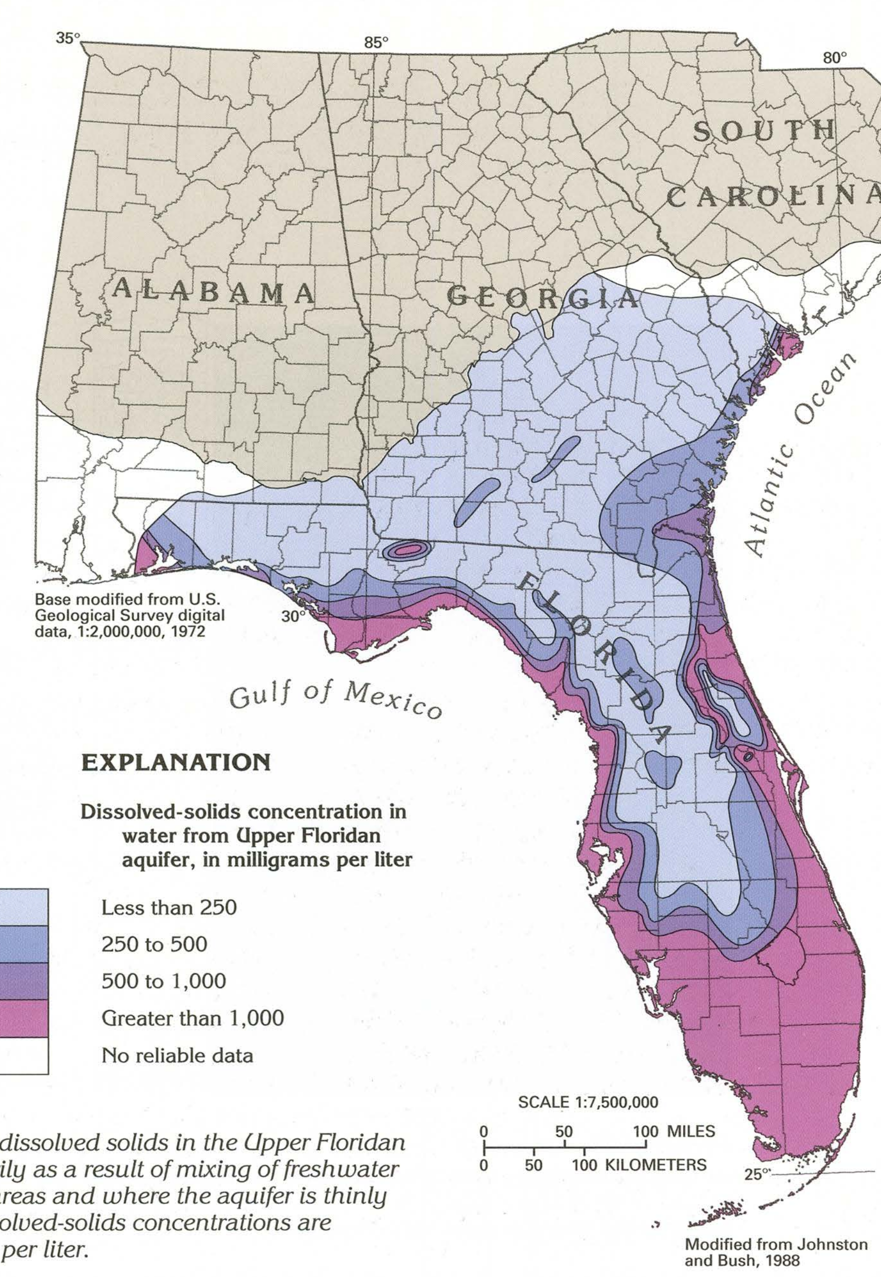


Figure 37. Concentrations of dissolved solids in the Upper Floridan aquifer increase coastward, primarily as a result of mixing of freshwater with seawater. In aquifer outcrop areas and where the aquifer is thinly confined, flow is vigorous and dissolved-solids concentrations are generally less than 250 milligrams per liter.

Sandstone and carbonate-rock aquifers

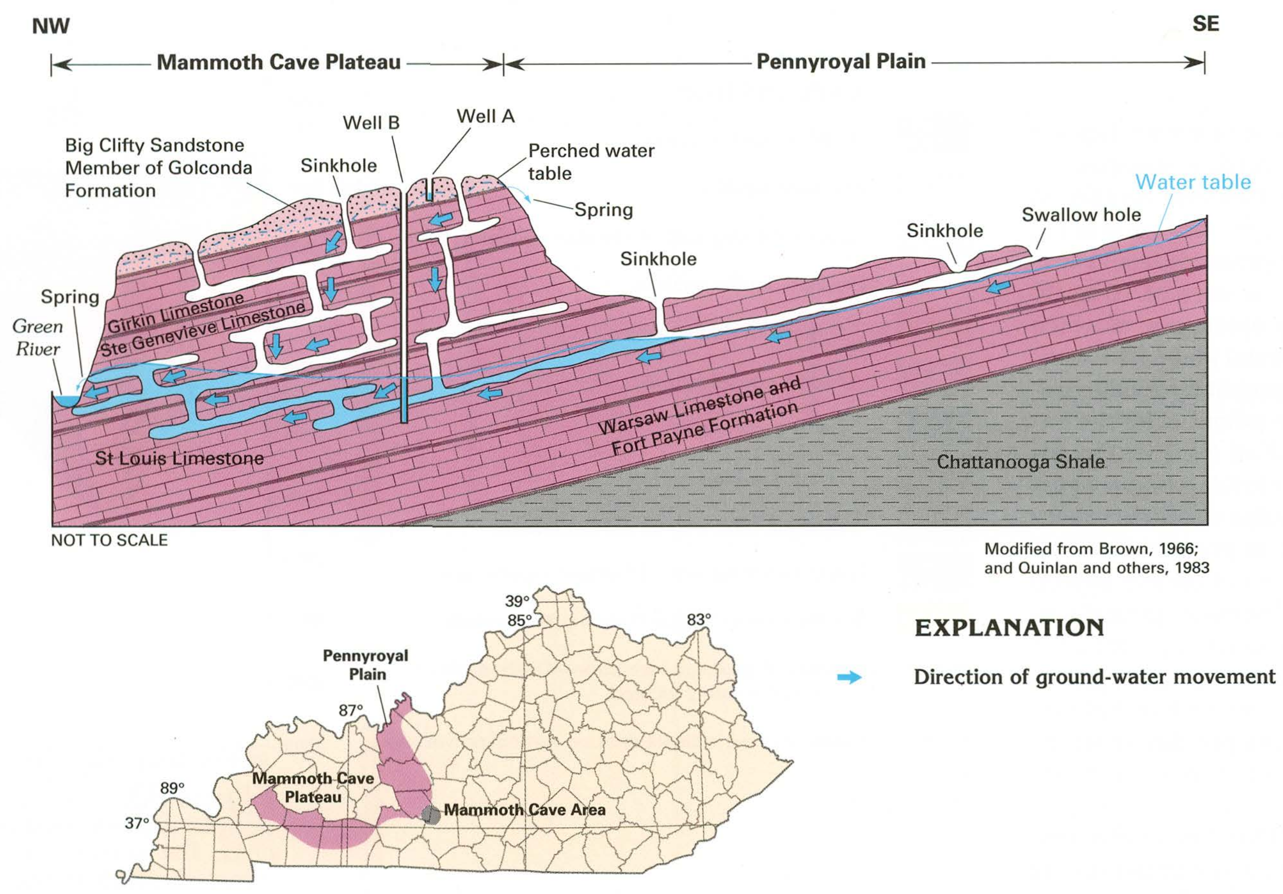


Figure 38. Large volumes of water move rapidly from sinkholes and swallow holes through a well-developed network of solution cavities in the St. Louis and Ste. Genevieve Limestones to discharge at springs or to the Green River. The openings were formed by dissolution of the limestones as water moved along bedding planes and fractures.

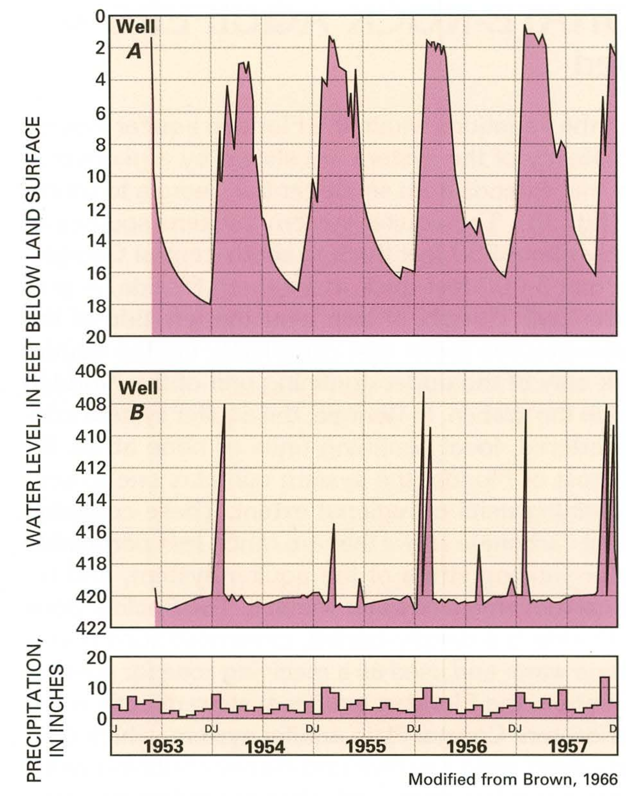


Figure 39. Water levels in wells completed in sandstone and carbonate-rock aquifers respond differently to recharge. Changes in the water level in well A, completed in sandstone, show that the sandstone is recharged quickly but drains slowly. In contrast, changes in the water level in well B, open to underlying limestone formations, show that recharge to and discharge from the carbonate-rock aquifer are rapid due to large solution openings in the limestone.

SANDSTONE AND CARBONATE-ROCK AQUIFERS

Aquifers in sandstone and carbonate rocks are most widespread in the eastern half of the Nation, but also extend over large areas of Texas and smaller areas in Oklahoma, Arkansas, Montana, Wyoming, and South Dakota (**fig. 4**). These aquifers consist of interbedded sandstone and carbonate rocks; the carbonate rocks are the most productive aquifers, whereas the interbedded sandstones yield less water. The aquifers in the Mammoth Cave area of Kentucky are examples of sandstone and carbonate-rock aquifers. The development of solution openings and karst topography in the limestones of the Mammoth Cave area are discussed in the preceding section of this report; the following section discusses the relations of the sandstone and carbonate-rock aquifers in that area.

Movement of water through the unconfined and confined parts of the limestone aquifers that underlie the Pennyroyal Plain and Mammoth Cave Plateau is summarized in **figure 38**. Where the St. Louis Limestone is exposed at the land surface in the Pennyroyal Plain, water from surface streams enters underground solution cavities through swallow holes and sinkholes. Water also enters solution cavities in the Ste. Genevieve and Girkin Limestones through sinkholes that have developed in the Big Clifty Sandstone Member of the Golconda Formation that caps the Mammoth Cave Plateau. The sinkholes on the plateau are collapse sinkholes that developed when the sandstone cap collapsed into caves which formed in the underlying limestone. Many of the solution openings in the Girkin and Ste. Genevieve Limestones are dry because they formed when the erosional base level in the area was at a higher altitude. Water from the saturated solution openings in the Ste. Genevieve and St. Louis Limestones discharges to the Green River from springs in the river channel and valley walls. Large quantities of water move rapidly to the river through the solution openings.

Water moves slowly through intergranular pore spaces and small fractures in the Big Clifty Sandstone Member of the Golconda Formation. Discontinuous layers of shale in the underlying Girkin Limestone (**fig. 38**) impede the downward movement of water and create a perched water table from which small springs discharge at the escarpments bounding the Mammoth Cave Plateau.

The presence or absence of solution openings affects aquifer recharge and discharge and is reflected by the water levels in wells completed in different rock types. The water level in well A (**fig. 39*A***), completed in the Big Clifty Sandstone Member of the Golconda Formation (**fig. 38**), rises quickly in response to seasonal increases in precipitation; after the sudden rise, the water slowly drains from the aquifer and the water level declines slowly. In contrast, the water level in well B (**fig. 39*B***), which is open to the St. Louis and Ste. Genevieve Limestones, rises sharply only in response to heavy rains. Following the abrupt rise, the water level in this well declines quickly as the solution cavities penetrated by the well are drained. The large openings allow rapid recharge and equally rapid discharge during and immediately following periods of intense precipitation. The transmissivity (rate at which water moves through an aquifer) of the part of the rock that contains solution openings is extremely high, whereas that of the undissolved rock between the solution conduits generally is very low.

Basaltic- and other volcanic-rock aquifers

R.L. Whitehead 1980

Figure 40. Pillow basalt forms when basaltic lava enters water and cools quickly. Extensive interconnected pore spaces develop in the flow as the ball-shaped pillows cool.

BASALTIC- AND OTHER VOLCANIC-ROCK AQUIFERS

Aquifers in basaltic and other volcanic rocks are widespread in Washington, Oregon, Idaho, and Hawaii, and extend over smaller areas in California, Nevada, and Wyoming (**fig. 4**). Volcanic rocks have a wide range of chemical, mineralogic, structural, and hydraulic properties. The variability of these properties is due largely to rock type and the way the rock was ejected and deposited. Pyroclastic rocks, such as tuff and ash deposits, might be emplaced by flowage of a turbulent mixture of gas and pyroclastic material, or might form as windblown deposits of fine-grained ash. Where they are unaltered, pyroclastic deposits have porosity and permeability characteristics like those of poorly sorted sediments; where the rock fragments are very hot as they settle, however, the pyroclastic material might become welded and almost impermeable. Silicic lavas, such as rhyolite or dacite, tend to be extruded as thick, dense flows and have low permeability except where they are fractured. Basaltic lavas tend to be fluid and form thin flows that have a considerable amount of primary pore space at the tops and bottoms of the flows. Numerous basalt flows commonly overlap and the flows commonly are separated by soil zones or alluvial material that form permeable zones. Basalts are the most productive aquifers of all volcanic rock types.

The permeability of basaltic rocks is highly variable and depends largely on the following factors: the cooling rate of the basaltic lava flow, the number and character of interflow zones, and the thickness of the flow. The cooling rate is most rapid when a basaltic lava flow enters water. The rapid cooling results in pillow basalt (**fig. 40**), in which ball-shaped masses of basalt form, with numerous interconnected open spaces at the tops and bottoms of the balls. Large springs that discharge thousands of gallons per minute issue from pillow basalt in the wall of the Snake River Canyon at Thousand Springs, Idaho. Interflow zones are permeable zones that develop at the tops and bottoms of basalt flows (**fig. 41**). Fractures and joints develop in the upper and lower parts of each flow, as the top and bottom of the flow cool while the center of the flow remains fluid and continues to move, and some vesicles that result from escaping gases develop at the top of the flow. Few open spaces develop in the center of the flow because it cools slowly. Thus, the flow center forms a dense, low-permeability zone between two more permeable zones. Thin flows cool more quickly than thick flows, and accordingly the centers of thin flows commonly are broken and vesicular like the tops and bottoms of the flows.

The Snake River Plain regional aquifer system in southern Idaho and southeastern Oregon (**fig. 42**) is an example of an aquifer system in basaltic rocks. The Snake River Plain is a large graben-like structure that is filled with basalt of Miocene and younger age (**fig. 43**). The basalt consists of a large number of flows, the youngest of which was extruded about 2,000 years ago. The maximum thickness of the basalt, as estimated by using electrical resistivity surveys, is about 5,500 feet. The basalt is bounded at the margins of the plain by silicic volcanic and intrusive rocks that are downwarped toward the plain.

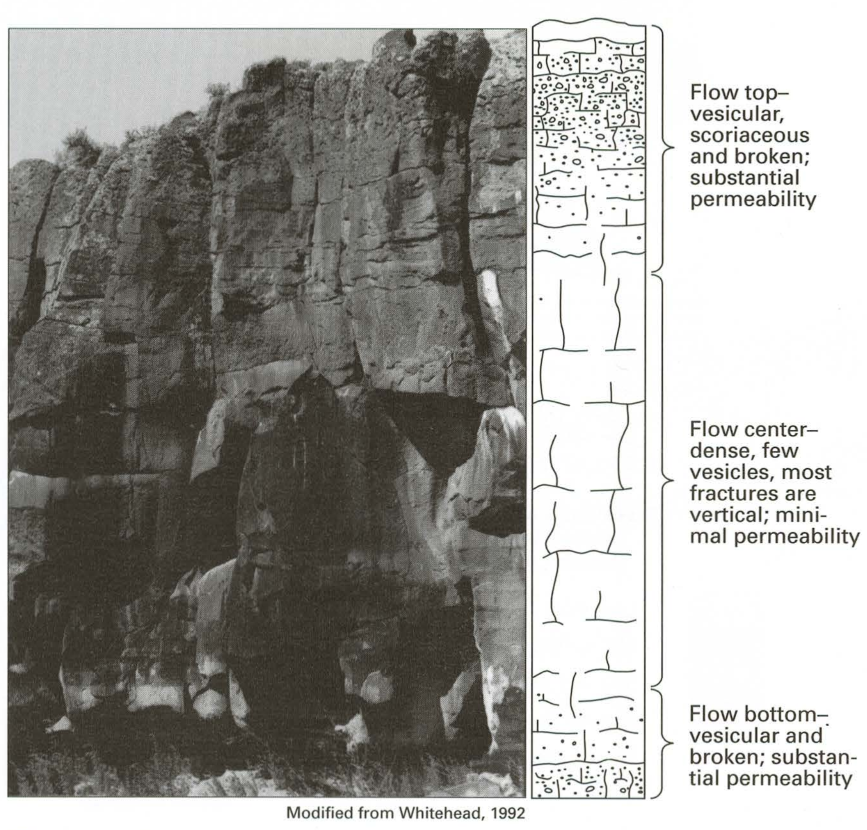


Figure 41. A typical basalt flow contains zones of varying permeability. Vesicular, broken zones at the top and bottom of the flow are highly permeable, whereas the dense center of the flow has minimal permeability.

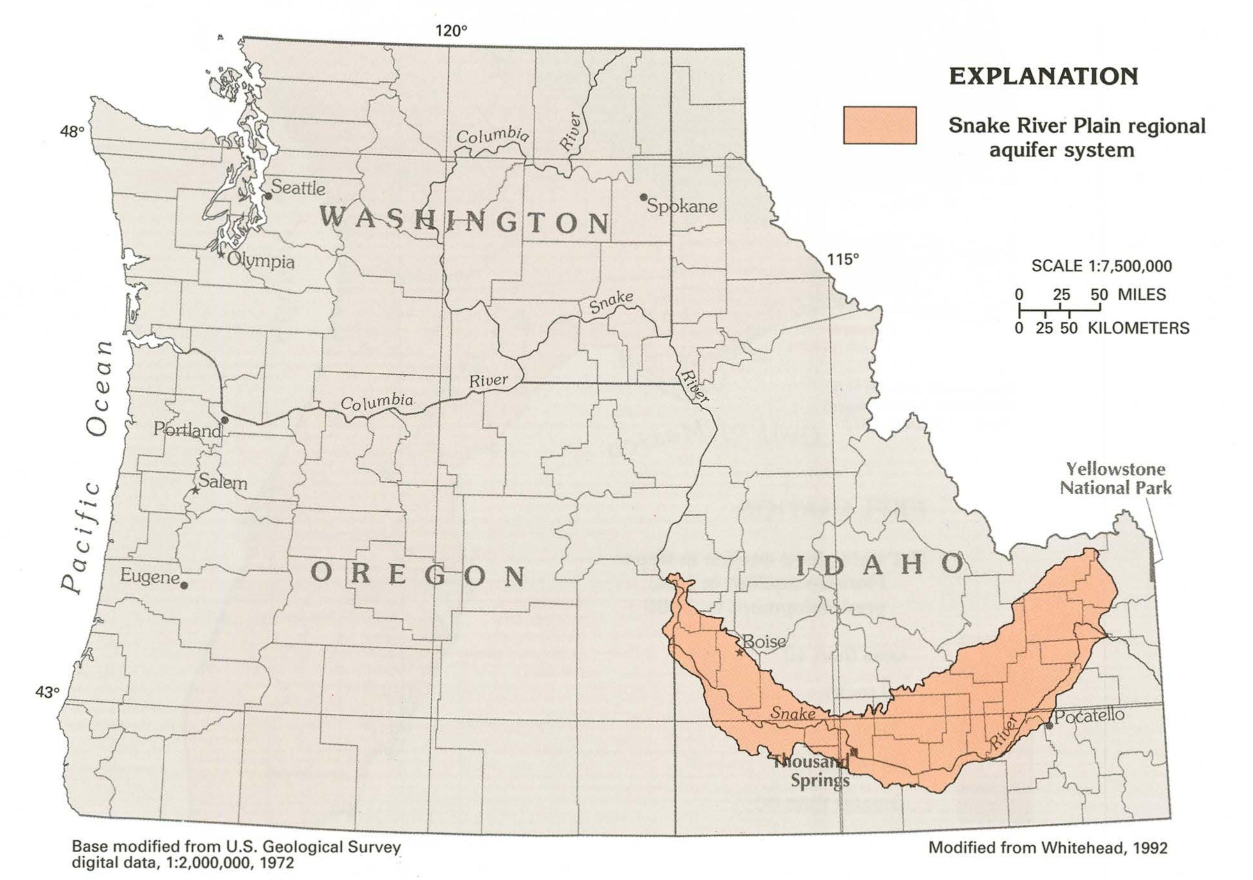


Figure 42. The Snake River Plain, which is located in southern Idaho and southeastern Oregon, is underlain by basalt aquifers.

Pliocene and younger basaltic-rock aquifers are the most productive aquifers in the Snake River Plain. The saturated thickness of the Pliocene and younger basaltic rocks is locally greater than 2,500 feet in parts of the eastern Snake River Plain but is much less in the western plain (**fig. 44**). Aquifers in Miocene basaltic rocks underlie the Pliocene and younger basaltic-rock aquifers (**fig. 43**), but the Miocene basaltic-rock aquifers are used as a source of water only near the margins of the plain. Unconsolidated-deposit aquifers are interbedded with the basaltic-rock aquifers, especially near the boundaries of the plain. The unconsolidated deposits consist of alluvial material or soil that developed on basaltic rock, or both, and were subsequently covered by another basalt flow.

The Pliocene and younger basaltic-rock aquifers consist primarily of thin basalt flows with minor beds of basaltic ash, cinders, and sand. The basalts were extruded as lava flows from numerous vents and fissures which are concentrated along faults or rift zones in the Snake River Plain. Some flows spread outward for as much as 50 miles from the vent or fissure from which the flow issued. Shield volcanoes formed around some of the larger vents and fissures (**fig. 45**). Flows that were extruded from the volcanoes formed a thick complex of interbedded basalt.

Water in the Snake River Plain aquifer system occurs mostly under unconfined (water-table) conditions. The configuration of the regional water table of the aquifer system (**fig. 46**) generally parallels the configuration of the land surface of the plain. The altitude of the water table is greatest in Fremont County, Idaho, near the eastern border of the plain and least in the Hells Canyon area along the Idaho–Oregon border. Where the water-table contours bend upstream as they cross the Snake River (for example, near Twin Falls, Idaho), the aquifer system is discharging to the river. In a general way, the spacing between the contours reflects changes in the geologic and hydrologic character of the aquifer system. Widely spaced contours in the Eastern Plain indicate more permeable or thicker parts of the aquifer system, whereas closely spaced contours in the Western Plain indicate less permeable or thinner parts. Water levels in the areas where shallow aquifers or perched water bodies overlie the regional aquifer system (**fig. 46**) are higher than those in the aquifer system. These areas are underlain by rocks that have extremely low permeability.

Other basalt aquifers are the Hawaii volcanic-rock aquifers, the Columbia Plateau aquifer system, the Pliocene and younger basaltic-rock aquifers, and the Miocene basaltic-rock aquifers. Volcanic rocks of silicic composition, volcaniclastic rocks, and indurated sedimentary rocks compose the volcanic- and sedimentary-rock aquifers of Washington, Oregon, Idaho, and Wyoming. The Northern California volcanic-rock aquifers consist of basalt, silicic volcanic rocks, and volcaniclastic rocks. The Southern Nevada volcanic-rock aquifers consist of ash-flow tuffs, welded tuffs, and minor flows of basalt and rhyolite.

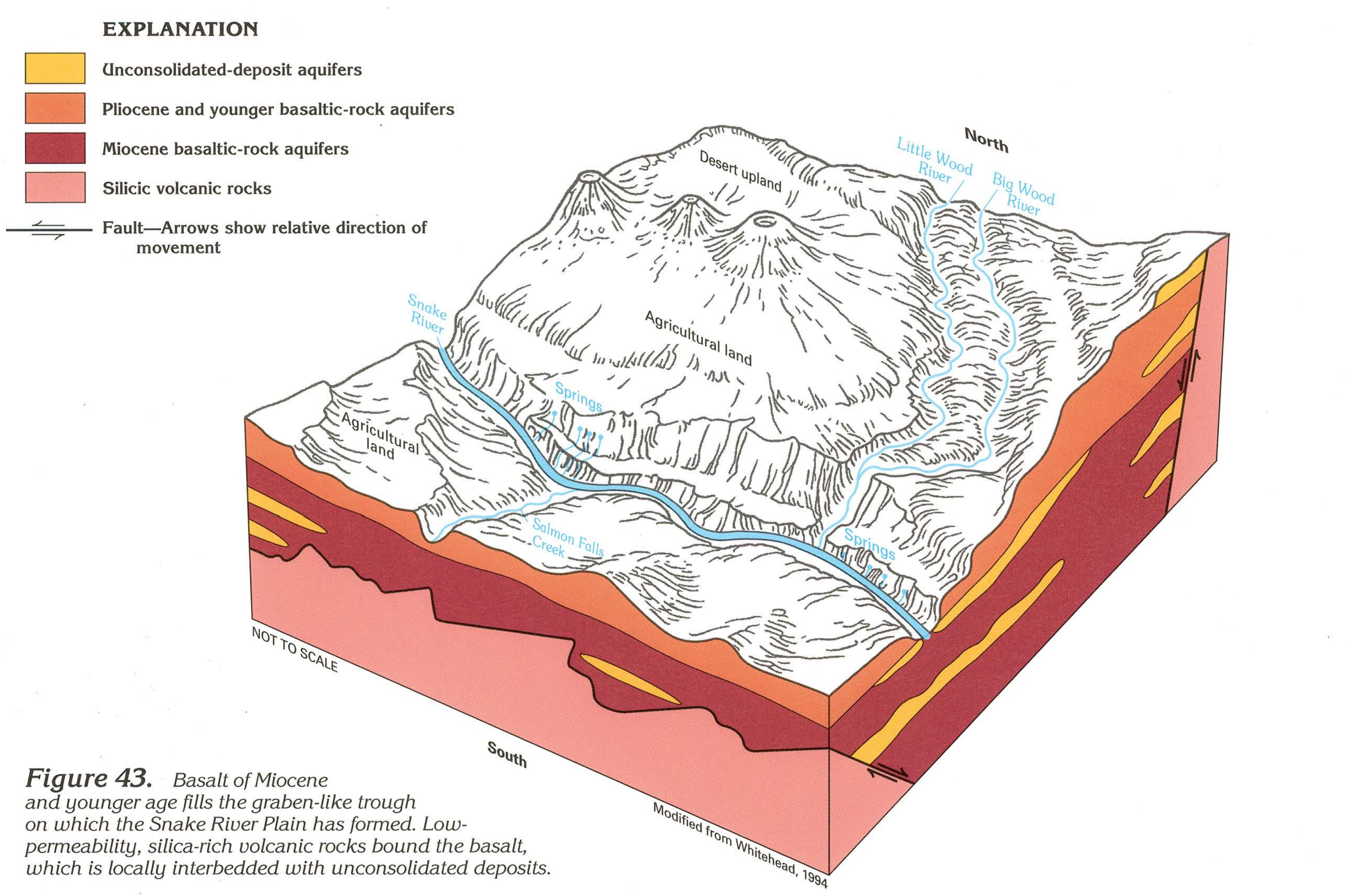


Figure 43. *Basalt of Miocene and younger age fills the graben-like trough on which the Snake River Plain has formed. Low-permeability, silica-rich volcanic rocks bound the basalt, which is locally interbedded with unconsolidated deposits.*

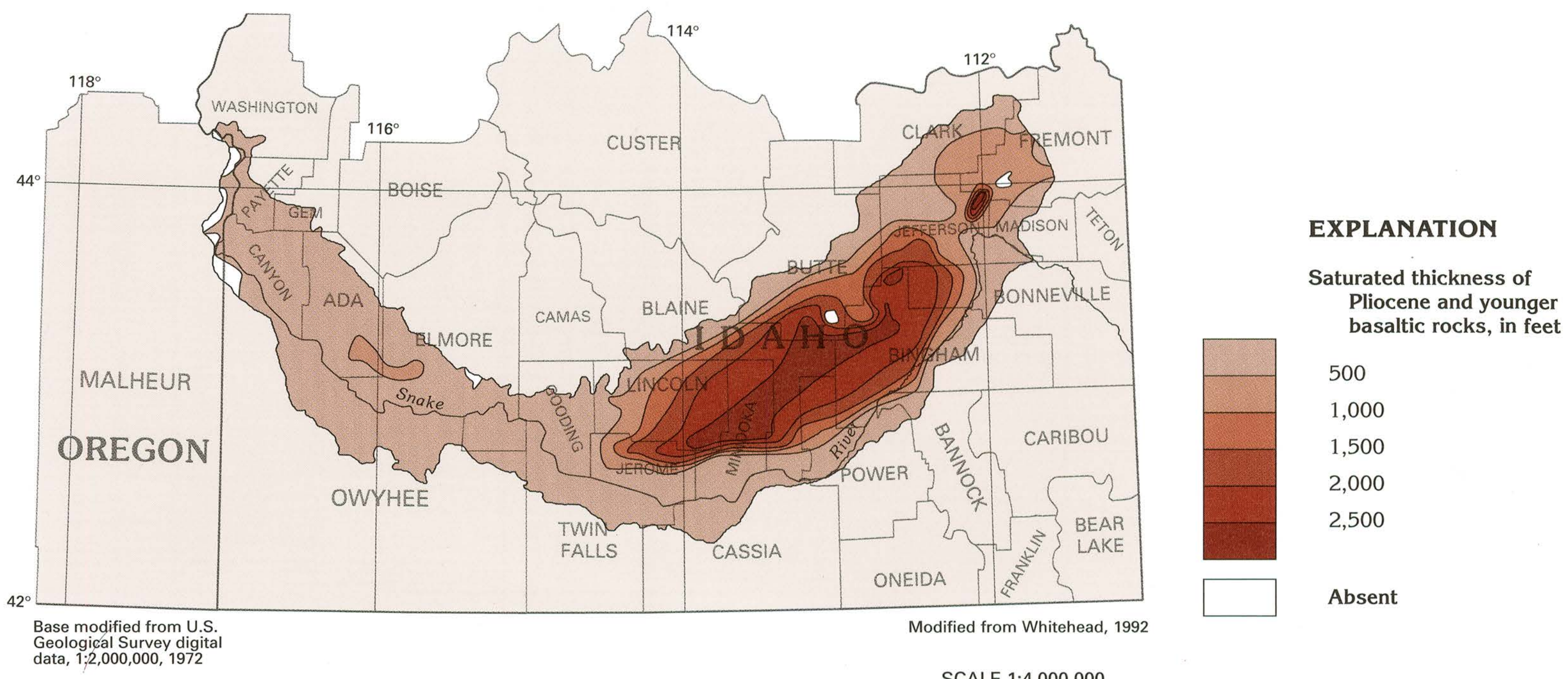


Figure 44. *The saturated thickness of Pliocene and younger basaltic rocks is locally greater than 2,500 feet in the eastern Snake River Plain but is much less in the western plain.*

SCALE 1:4,000,000
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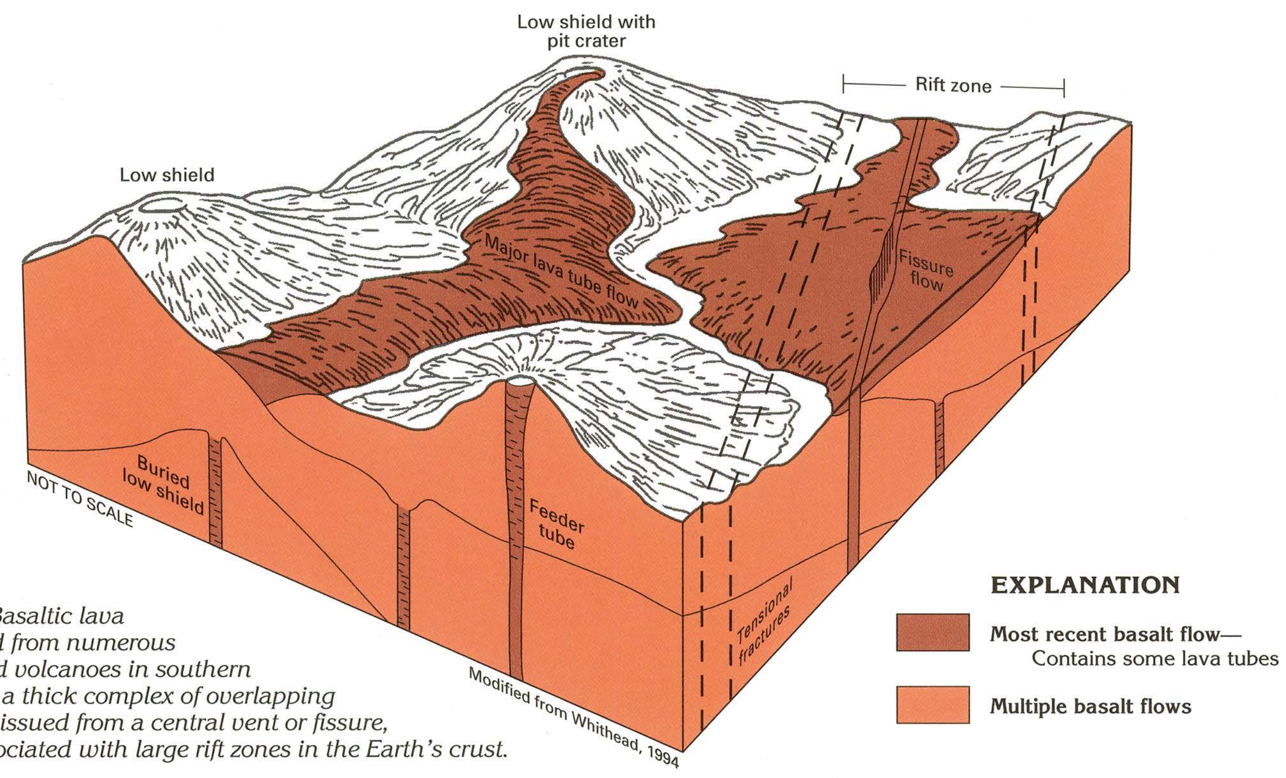

Figure 45. *Basaltic lava that was extruded from numerous overlapping shield volcanoes in southern Idaho has formed a thick complex of overlapping flows. Most flows issued from a central vent or fissure, and some are associated with large rift zones in the Earth's crust.*

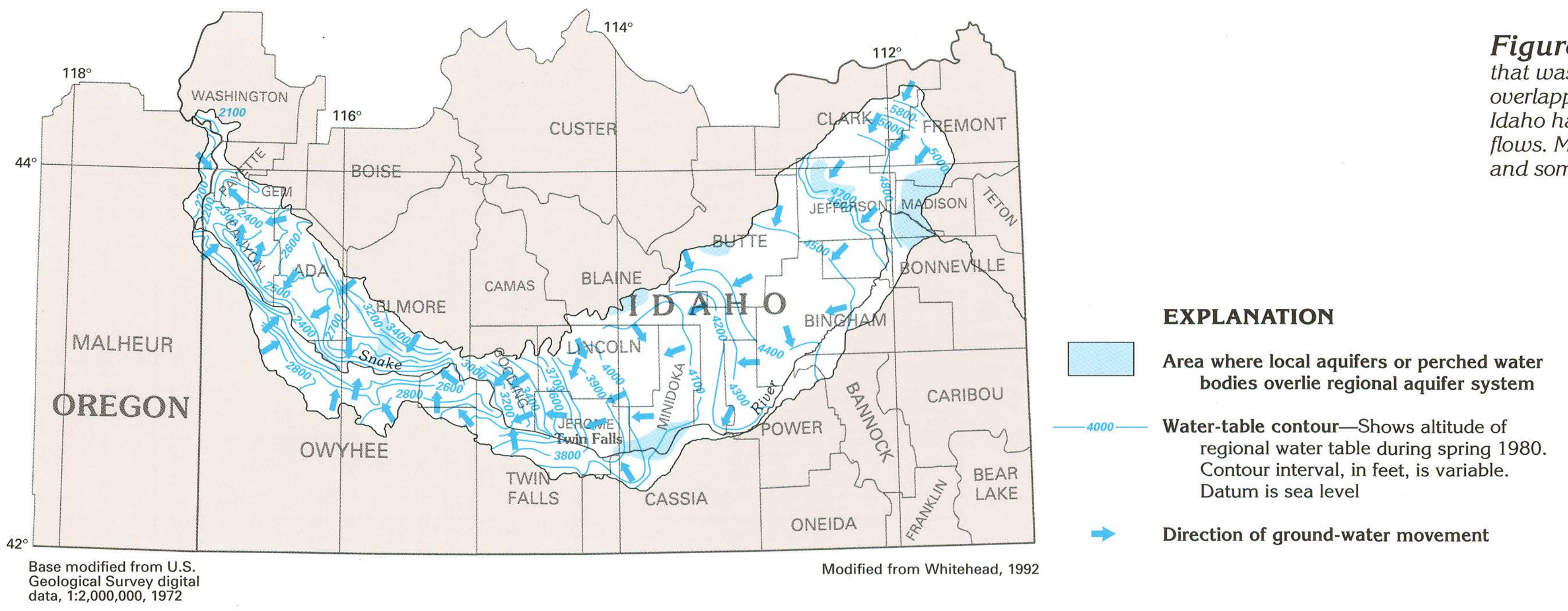

Figure 46. *The regional movement of water in the Snake River Plain aquifer system is from east to west. Much of the discharge from the aquifer system is to the Snake River. Low-permeability rocks underlie shallow local aquifers or perched water bodies.*

SCALE 1:4,000,000
0 25 50 MILES
0 25 50 KILOMETERS

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