ANALYSIS OF REGIONAL AQUIFERS IN THE CENTRAL MIDWEST OF THE UNITED STATES IN KANSAS, NEBRASKA, AND PARTS OF ARKANSAS, COLORADO MISSOURI, NEW MEXICO, OKLAHOMA, SOUTH DAKOTA, TEXAS, AND WYOMING—SUMMARY

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1414–A

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Analysis of Regional Aquifers in the Central Midwest of the United States in Kansas, Nebraska, and Parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming—Summary

By DONALD G. JORGENSEN, JOHN O. HELGESEN, DONALD C. SIGNOR, ROBERT B. LEONARD, JEFFREY L. IMES, and SCOTT C. CHRISTENSON

REGIONAL AQUIFER-SYSTEM ANALYSIS—CENTRAL MIDWEST

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1414—A

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Gordon P. Eaton
Director

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CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
square foot (ft^2)	0.09290	square meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre-foot (acre-ft)	1,233	cubic meter
gallon (gal)	3.785	liter
million gallons (Mgal)	3,785	cubic meter
foot per second (ft/s)	0.3048	meter per second
square foot per second (ft^2/s)	0.09290	square meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
gallon per day (gal/d)	0.06309	liter per day

Temperature in degree Fahrenheit (°F) can be converted to degree Celsius (°C) as follows:

$$°C = (°F-32)/1.8.$$

SEA LEVEL

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

ANALYSIS OF REGIONAL AQUIFERS IN THE CENTRAL MIDWEST OF THE UNITED STATES IN KANSAS, NEBRASKA, AND PARTS OF ARKANSAS, COLORADO, MISSOURI, NEW MEXICO, OKLAHOMA, SOUTH DAKOTA, TEXAS, AND WYOMING—SUMMARY

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ABSTRACT

Three regional aquifer systems were investigated in a 370,000-square-mile area extending from the foothills of the Rocky Mountains in Colorado to the Mississippi River in eastern Missouri, and from South Dakota to mountainous parts of Arkansas and Oklahoma. These aquifer systems and internal confining systems are composed of sedimentary rocks ranging in age from Cambrian through Cretaceous. The study area is informally divided into the Plains subregion and Ozark subregion.

Along the physiographic boundary between the Plains subregion and the Ozark subregion, two regional ground-water flow systems are laterally adjacent. In general, regional ground-water flow is outward from the uplands in the Ozark Plateaus and eastward from the western part of the Interior Plains. The approximate location of the boundary between these two flow systems is a broad physiographic low that roughly parallels the Central Lowland province.

The Western Interior Plains aquifer system in the Plains subregion consists of water-bearing dolostone, limestone, and shale. The lower units of this aquifer system are composed mostly of dolostone and sandstone of Cambrian and Ordovician age, and an upper unit is composed mostly of limestone of Mississippian age. The upper unit and lower units are separated at most locations by a confining unit of very slightly permeable shale. Porosity and permeability in the aquifer system, especially primary porosity, are a function of depth. Secondary porosity is a function of diagenesis, especially fracturing and dissolution. Dissolved-solids concentrations in water in the aquifer system range from less than 10,000 to more than 300,000 mg/L (milligrams per liter). Most water is a sodium chloride type, with chloride concentrations as large as 190,000 mg/L. A numerical-model analysis of flow in the aquifer system indicates that fluid velocities are extremely slow, and little flow moves out of a geopressured zone in the Anadarko Basin.

The Western Interior Plains confining system restricts flow between the Western Interior Plains aquifer system and overlying geohydrologic units, principally the Great Plains aquifer system and the High Plains aquifer. The confining system is composed of rocks ranging in age from Pennsylvanian through Jurassic. The confining system consists mostly of very slightly permeable shale beds, which are confining units, and sandstones and limestones, which are aquifers in some areas. In part of the Anadarko Basin, the lower sandstone beds in the confining system are geopressured. The geopressure is transmitted but attenuated to the subjacent Western Interior Plains aquifer system. Formations of Permian age include halite and gypsum as well as shale, limestone, and sandstone. These evaporite deposits are only slightly permeable and, where present, virtually eliminate vertical flow through the system.

The Great Plains aquifer system consists of two regional aquifers separated in much of the area by a confining unit. The lower aquifer, the Apishapa, is not as areally extensive as the upper aquifer, the Maha (which consists mostly of the Dakota Sandstone). Concentrations of dissolved solids in the water in this aquifer system exceed 5,000 mg/L in most of the interior part of the system; concentrations of less than 1,000 mg/L exist in recharge areas. A regional flow model indicates that the predevelopment, steady-state flow rate was about 342 ft^3/s (cubic feet per second), most of which represented leakage to or from vertically adjacent units near the edges of the aquifer system rather than lateral flow from or to outcrop areas. The aquifer system is recharged mainly at outcrops in southeastern Colorado and northeastern New Mexico. Transient simulations show that oil and gas development in the Denver Basin and development of freshwater in other areas have resulted in declines in the potentiometric surface. Withdrawals of about 800 ft^3/s during 1970–79 were derived mostly from induced recharge or intercepted discharge to overlying units or to a lesser extent from storage depletion.

The Ozark subregion is an area of highly dissected karstic terrain characterized by numerous streams and springs. Nearly all well water or spring water in the subregion is from the Ozark Plateaus aquifer system. The Ozark Plateaus aquifer system consists of five units, which from bottom to top are the St. Francois aquifer, St. Francois confining unit, Ozark aquifer, Ozark confining unit, and the Springfield Plateau aquifer. Recharge to all the aquifer units is from precipitation. Discharge is mostly to the streams of the Ozarks and the Missouri, Mississippi, and other rivers along the perimeter of the subregion. Water in the aquifer system is a calcium bicarbonate type and generally has dissolved-solids concentrations less than 500 mg/L. Regional predevelopment flow of 7,091 ft^3/s through the

aquifer system was simulated. Pumping rates are small compared to the large natural rates of recharge and discharge.

INTRODUCTION

The study area of the Central Midwest Regional Aquifer-System Analysis (CMRASA) includes about 370,000 mi^2 (fig. 1). It extends from the foothills of the Rocky Mountains in Colorado to the Missouri and Mississippi Rivers in eastern Nebraska and Missouri and from South Dakota to the Ouachita, Arbuckle, and Wichita Mountains in Arkansas and Oklahoma.

Several important regional-aquifer systems containing both fresh and saline water were studied. Prior to this study, little was known about the regional flow and hydrochemistry of aquifer systems in much of the area.

Within the central United States, four other regional aquifer-system analyses (RASA) (fig. 2) share geographic or hydrologic boundaries with this study. These other RASA studies are the High Plains (Weeks and others, 1988), the Northern Great Plains (Downey and Dinwiddie, 1988), the Northern Midwest (Young, 1992), and the Gulf Coast (Grubb, in press).

PURPOSE AND SCOPE

The investigation summarized in this report is one of several studies of the U.S. Geological Survey's Regional Aquifer-System Analysis (RASA) program, which is described in the "Foreword." The background, purpose, scope, objectives, and planned approach of this study are described in the project-planning report (Jorgensen and Signor, 1981). The major purpose of the CMRASA study is to describe the water resources in the regional aquifers that occur in rocks of Cambrian through Cretaceous age. In most of the study area, except for the Ozarks of southern Missouri, northwestern Arkansas, southeastern Kansas, and northeastern Oklahoma, little is known about these water resources. Other purposes of the study are to evaluate potential uses of the water considering quantity, current use, water quality, and contamination. The scope of the study does not specifically include the High Plains aquifer, although, at a few locations, the High Plains aquifer is in direct hydraulic connection with aquifer units of the CMRASA. The High Plains aquifer is a separate regional aquifer that overlies some of the units described herein.

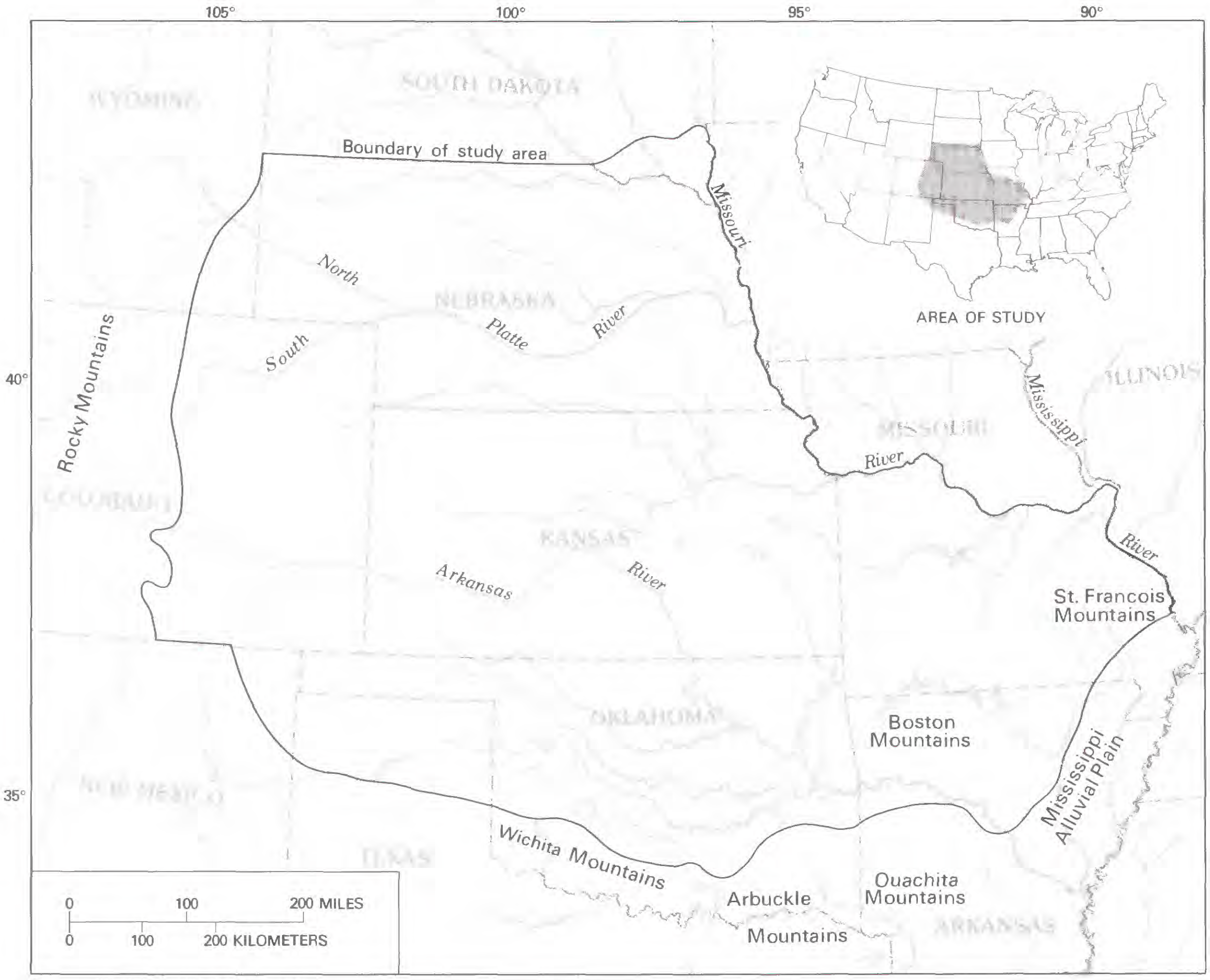
The findings of the CMRASA are reported in five chapters of U.S. Geological Survey Professional Paper 1414: Chapter A (this report) is the summary chapter, which collates the important findings reported in other chapters; chapter B describes the geohydrologic framework; chapter C describes the modeling analysis of the regional aquifer systems; chapter D describes the geohydrologic and model analyses of the Ozark Plateaus aquifer system; and chapter E describes the geohydrologic and model analyses of the Great Plains aquifer system.

PHYSICAL SETTING

Much of the study area is bounded laterally by major geologic structural features (Rocky Mountain Uplift on the west, the Sioux Uplift on the northeast, and a series of uplifts on the south), or by major rivers (Mississippi, Missouri, and Arkansas Rivers) and includes parts of two major physiographic divisions (Interior Plains and Interior Highlands). The Interior Plains includes the Great Plains and the Central Lowland, and the Interior Highlands includes the Ozark Plateaus and the Ouachita Province (fig. 3). The Ouachita Province includes the Arkansas Valley, which is between the Boston Mountains of the Ozark Plateaus, and the Ouachita Mountains south of the study area.

Land-surface altitude ranges from less than 500 ft along the Fall Line on the Mississippi Alluvial Plain and the Arkansas Valley to about 6,000 ft in the extreme western part of the area adjacent to the Rocky Mountains. Topography of the Ozark Plateaus is hilly to rugged and is mostly covered with hardwood forest, whereas most of the Interior Plains area is characterized by a relatively flat land surface and vegetation cover is mostly grass and rowcrops.

Characteristics related to climate, including runoff and potential evapotranspiration, are shown in figure 4. Precipitation for 1931–60, which included two major droughts (1933–37 and 1952–57), ranged from more than 40 in. in the Ozark Plateaus to 12 in. in eastern Colorado (Eagleman, 1976, fig. 3). Potential evapotranspiration greatly exceeds precipitation (fig. 4). Another regional study (Dugan and Peckenpaugh, 1985) determined that the amount of water passing the root zone and recharging the water table during 1951–80 ranged from more than 15 in. annually in part of the Ozarks to less than 1 in. annually in Colorado (fig. 5). The southeastern part of the study area has abundant water resources, especially surface water. Annual surface-water runoff ranged from more than 25 in. in the Ozark Plateaus to 1 in. or less in western Kansas and eastern Colorado during 1931–60. Annual runoff exceeded 27 in. during 1951–80 in the Ozarks (Hedman and others, 1987). Most of the



Base modified from U.S. Geological Survey 1:7,500,000, National Atlas, 1970

FIGURE 1.—Location and extent of study area.

western part of the study area is deficient in surface water but has substantial ground-water resources, mainly the High Plains aquifer, which overlies some of the aquifers described in this report.

STUDY APPROACH

Large quantities of hydrologic, geologic, and water-quality data were collected, evaluated for accuracy and adequacy, and collated into data files (Helgesen and Hansen, 1989). In general, these data are available in the District offices of the U.S. Geological Survey in each state. Much of the data are available in publications, including data reports, and as computer-stored data. On the basis of data and other general information, a conceptual model of the hydrologic system was developed. Computer models of the aquifer were constructed to test the conceptualization of hydrologic-system operation. The computer models required extensive information on numerous aquifer properties and hydrologic relations. Data for various models were not always available; in these cases, special studies were conducted to obtain the additional data or information. Also, special techniques to estimate the information needed for the models were developed to supplement available information. The computer models also were used to improve estimates of hydrologic data.

Water-chemistry data were evaluated for accuracy and plotted or otherwise displayed. The resulting maps and displays were interpreted in reference to geochemical processes that could produce observed geochemical conditions. The geochemical processes were, in turn, evaluated to determine whether they

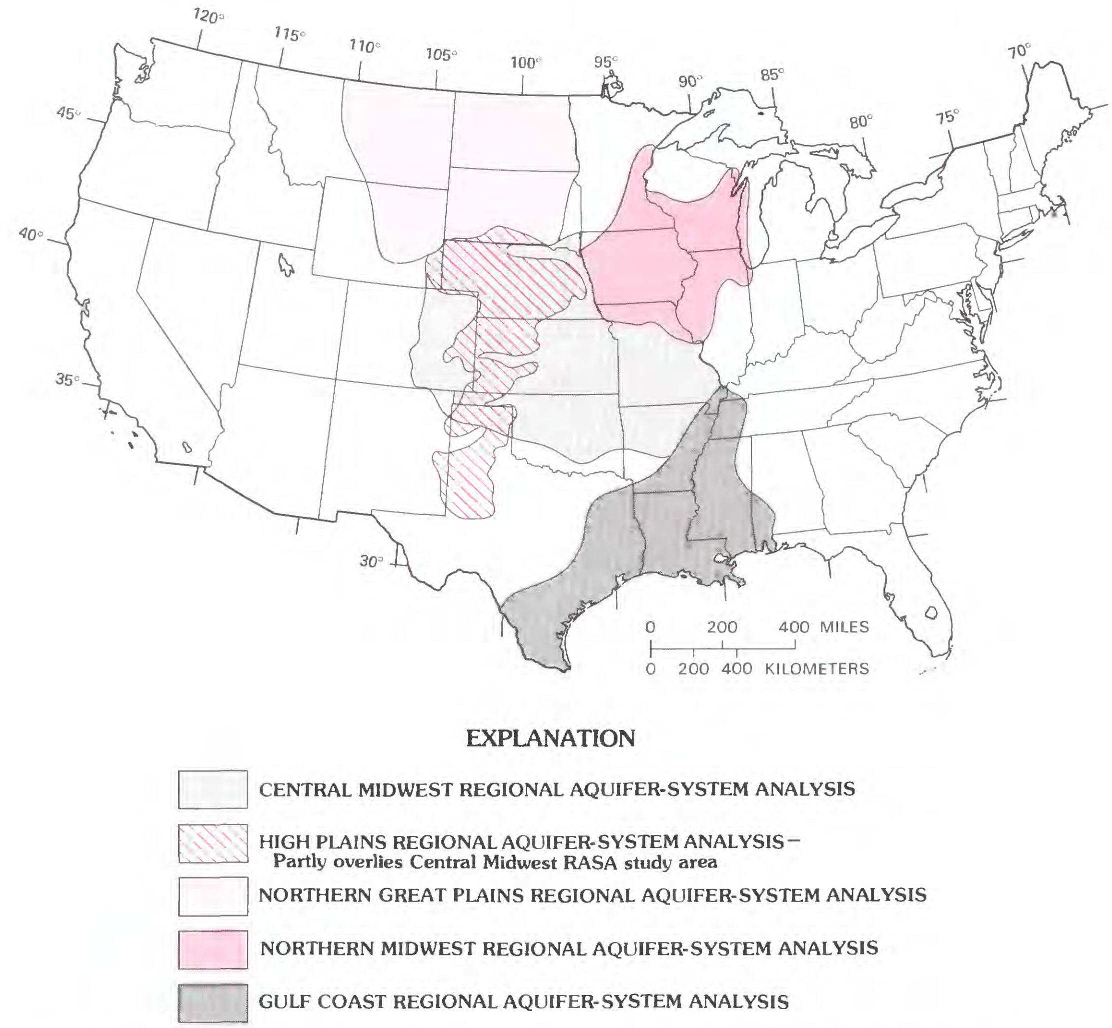


FIGURE 2.—Regional aquifer-system analyses contiguous to the Central Midwest regional aquifer-system analysis (RASA).

were consistent with flow processes simulated by the computer models.

Finally, the information and results of the modeling and geochemical analyses were interpreted in reference to potential use of the water resources. The study was diverse and wide in scope and required a multidiscipline team approach.

Many supplementary studies were conducted as part of the larger study. An extensive study to determine the quantity of flow to the water table was conducted by Dugan and Peckenpaugh (1985) and by Dugan (1986). Several detailed surface-water analyses were made to investigate ground-water and surface-water interchange: Hedman and others (1987) investigated the low-flow characteristics of streams in the Ozark subregion; Hedman and Engel (1989) investigated the low-flow characteristics of the Plains subregion; and Hedman and Jorgensen (1990) investigated hydrologic relations between the Missouri River, the Missouri River alluvial valley, and the regional aquifers in a reach of the Missouri River between Yankton, South Dakota, and St. Louis, Missouri. Special techniques were developed for the study including (1) log analyses to estimate permeability (Jorgensen, 1989), (2) ground-water and surface-water interaction (Jorgensen and others, 1989a and b), (3) simulation of oil and gas withdrawals in a ground-water model, and (4) a method for determining direction of flow in an aquifer containing water of variable density (Jorgensen and others, 1982).

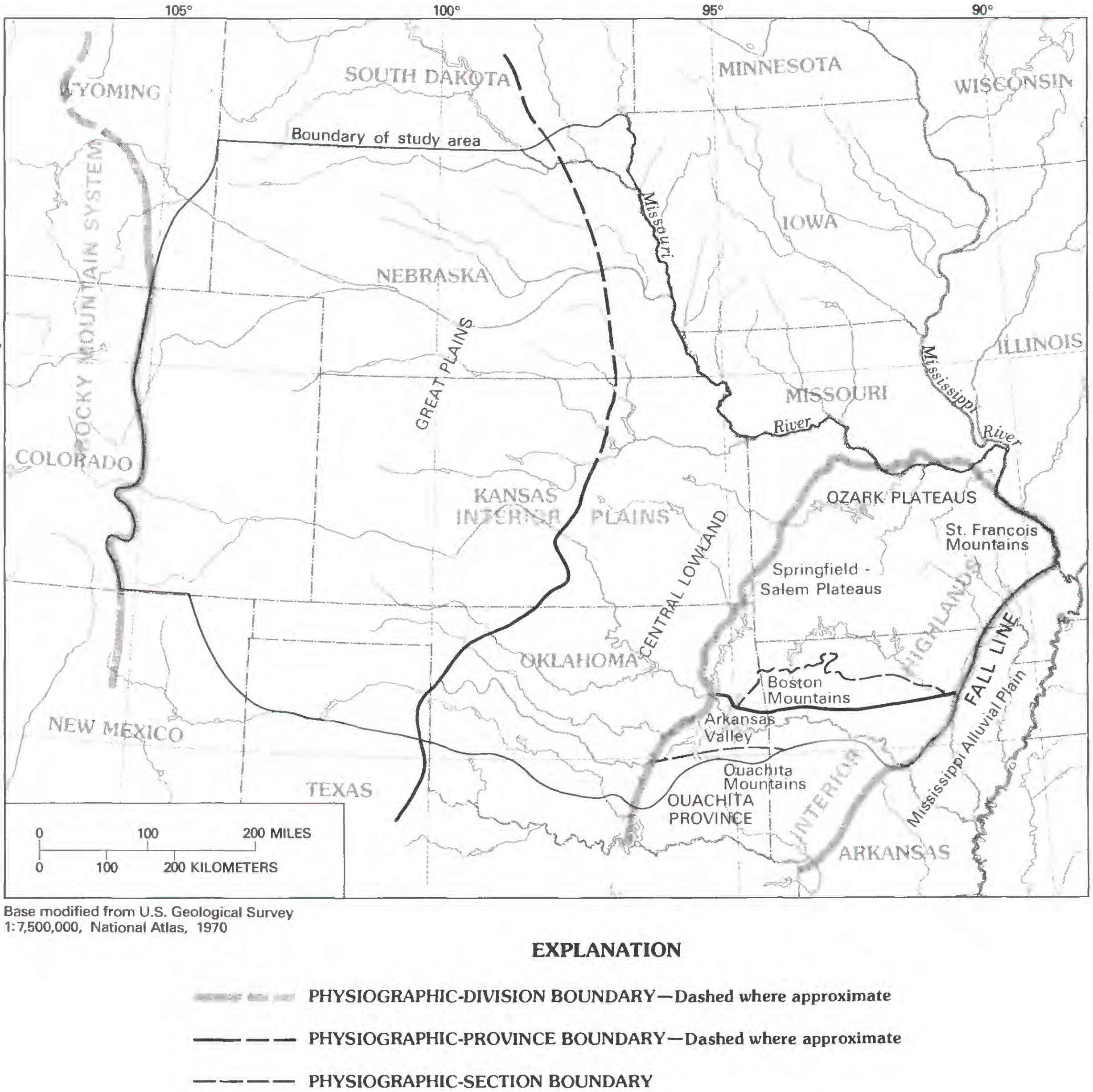


FIGURE 3.—Physiographic subdivisions (modified from Fenneman, 1946).

ACKNOWLEDGMENTS

The plan for this investigation was developed with the assistance of the Arkansas Geological Commission, the Colorado Geological Survey, the Kansas Geological Survey, the Missouri Division of Geology and Land Survey, the Nebraska Conservation and Survey Division, the South Dakota Geological Survey, and the Oklahoma Geological Survey.

The study was greatly aided by a Liaison Committee between State agencies and the U.S. Geological Survey. The Liaison Committee not only disseminated information concerning the study to State agencies but also helped identify sources of data, defined areas of concern, and made valuable suggestions that aided the study. Committee members included: Orville Wise, Arkansas Geological Survey Commission; Robert Longenbaugh, Office of Colorado State Engineer; William Hambleton, Kansas Geological Survey; Donald Miller, Missouri Division of Geology and Land Survey; Verlon Vrana, Nebraska Natural Resources Commission; and Robert Arndt, Oklahoma Geological Survey.

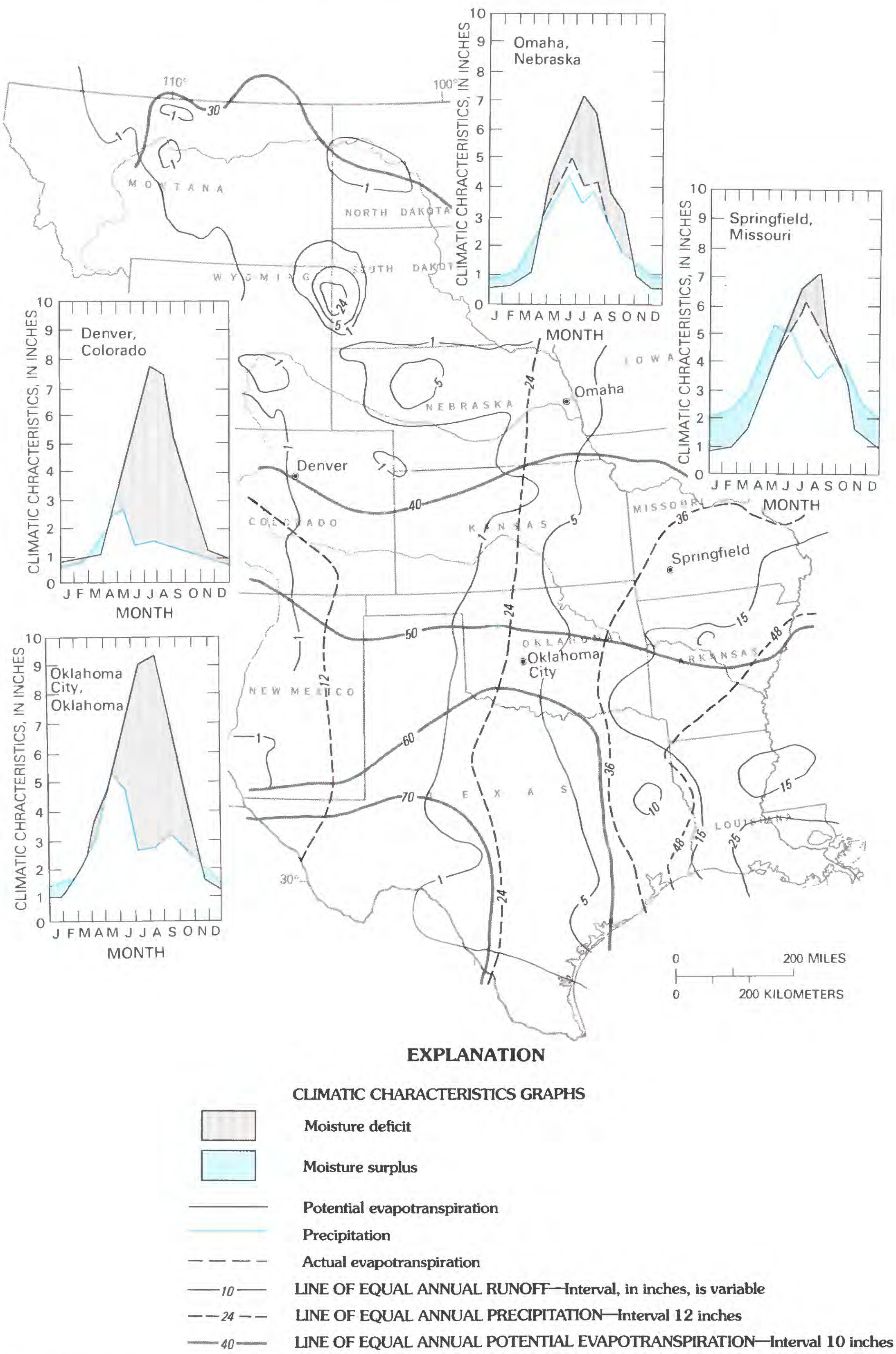


FIGURE 4.—Climatic characteristics of central United States, 1931–60 (precipitation and evapotranspiration from Eagleman, 1976; runoff from Busby, 1966).

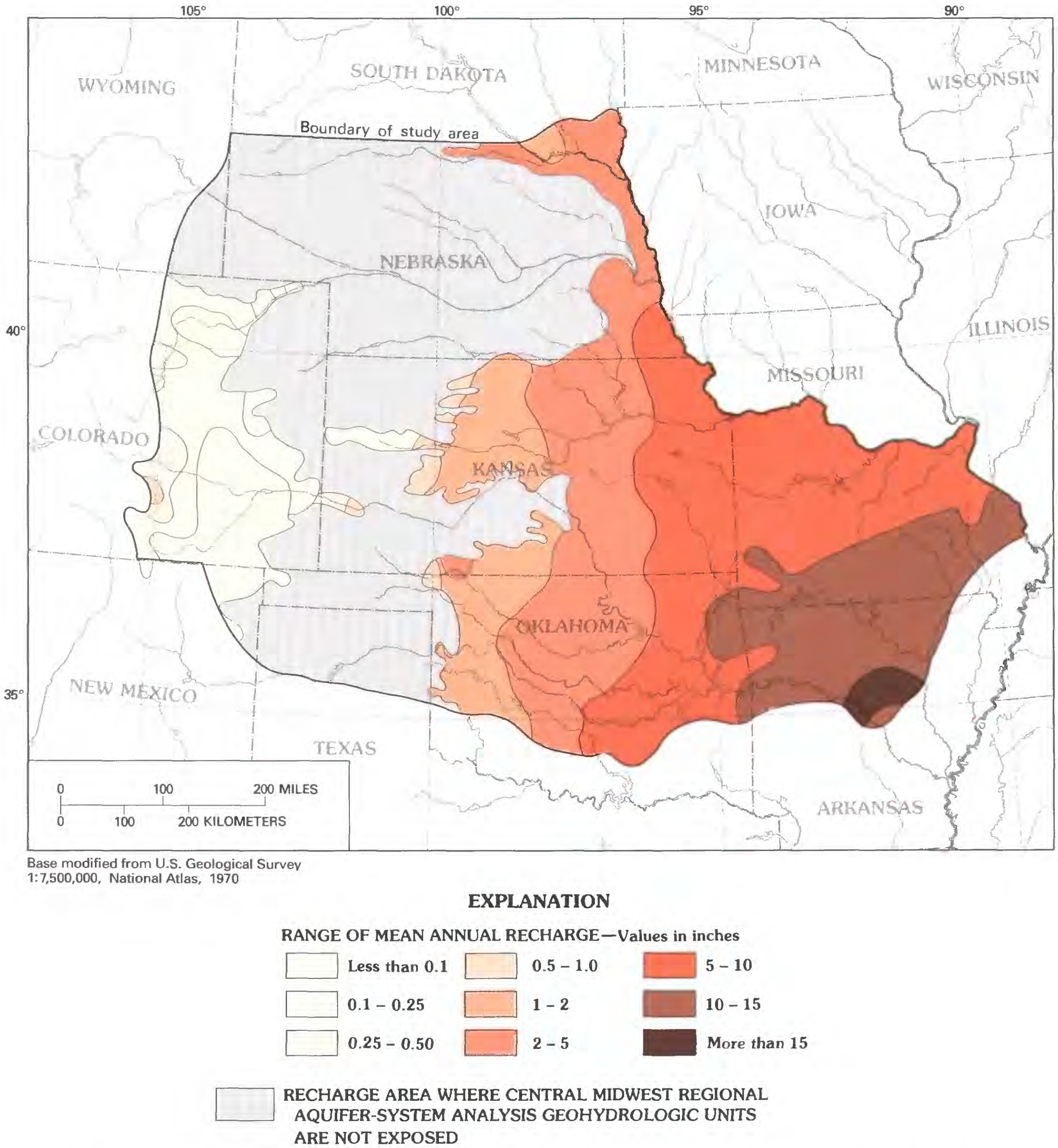


FIGURE 5.—Estimated annual recharge to exposed geohydrologic units of the Central Midwest RASA, 1951–80 (from Dugan and Peckenpaugh, 1985).

The study also was served by a stratigraphy advisory group that included: Orville Wise, Arkansas Geological Commission; Richard Pearl, Colorado Geological Survey; P. Allen Macfarlane, Kansas Geological Survey; Thomas Thompson, Missouri Division of Geology and Land Survey; Marvin Carlson, Nebraska Conservation and Survey Division; and Charles Mankin, Oklahoma Geological Survey. This group, along with Claire Davidson of the Geological Names Committee of the U.S. Geological Survey, contributed significantly to the resolution of problems related to stratigraphic correlation and nomenclature.

GEOLOGY AND PALEOHYDROLOGY

The CMRASA study area lies within the stable interior of the North American continent. The hydrologic boundaries of the area are largely controlled by structural features. Since Cambrian time, most of the study area has undergone relatively gentle deformation involving upwarp and downwarp of the Earth's crust over large areas. Structurally, the CMRASA area has been dominated by broad basins and arches. Accordingly, most folding of sedimentary rocks has been subtle, and there are few major fault zones of regional significance. However, along the south and west margins of the study area, strong crustal deformation from mountain-building forces resulted in intense folding and faulting. The lateral change from simple to complex geologic structure was the major factor in defining the southern and western boundaries of the study area. The structural change is relatively abrupt in most locations, but is transitional in others.

The present areal distribution of major time-stratigraphic units in the CMRASA study area is shown in figure 6. Geologic sections (fig. 7) illustrate the general regional continuity of the units; the severest structural deformation is along the south and west margins of the study area. Faulting (fig. 8) was substantial in these areas and caused a major offset of rock units. Most faults in the interior of the study area have much less offset than the offsets of the faults along the south and west margins.

Although structural deformation is not severe over most of the study area, stratigraphic nomenclature still differs markedly among States and structural areas (fig. 9; Jorgensen and others, 1993, plate 1). Hundreds of recognized geologic names have been assigned to rock units within the thick stratigraphic interval. The geologic units, either singly or in combination, form the geohydrologic units described in this study.

The present hydraulic characteristics and flow systems result from past geologic processes. A brief summary of geologic history is presented with special emphasis on the changes and processes that have resulted in the present hydraulic characteristics of the rocks, chemistry of the water, and distribution of the flow systems. Additional information is presented in Jorgensen (1993).

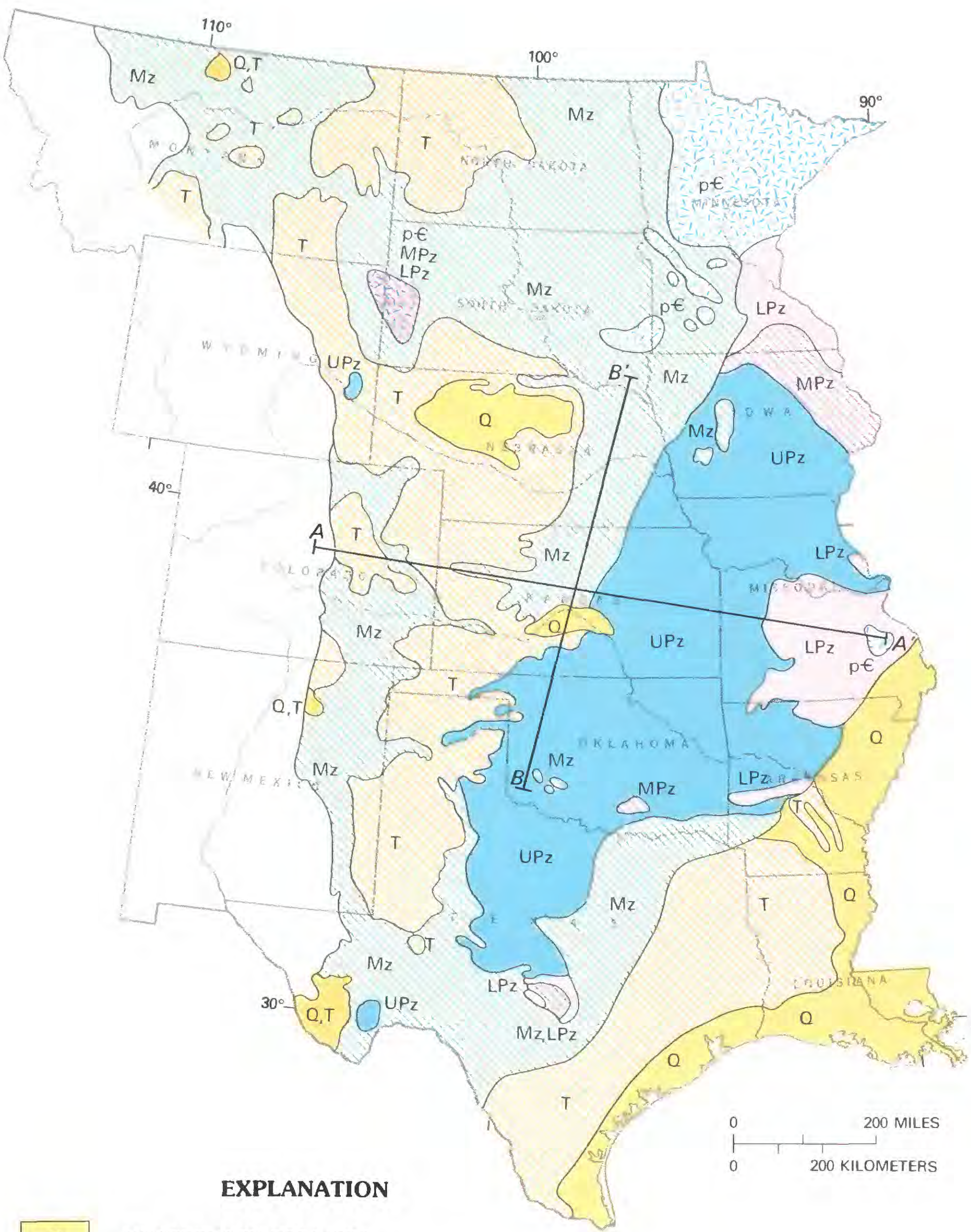
Rocks of Precambrian age underlie the stratigraphic section of interest to this study (Jorgensen and others, 1993, plate 2); they consist mainly of igneous and metamorphic rocks of various types that together form the so-called "basement complex." Deep burial of these rocks at most locations has precluded detailed knowledge of their nature. The geologic configuration of the rocks of Precambrian age over most of the study area has been mapped by Sims (1985).

Information concerning faults and fractures in the rocks of Precambrian age is of special importance because these features mark zones of weakness in the rocks that were reactivated at various intervals during geologic time. The orientation of fractures, faults, and anticlines also indicates something about the tectonic stresses on the rocks.

Large faults oriented to the present northwest-southeast existed in Precambrian time. This alignment is the same as the boundary between metamorphic and igneous rocks of Precambrian age in the region (Warner, 1980, p. 14). Warner concludes that the central United States was moderately mobile during Precambrian time. Precambrian tectonic activity may have started the Transcontinental Arch (fig. 10). Lineaments within rocks of Precambrian age mapped by Hayes (1962) are aligned North 50° West and North 65° East.

The top of the basement surface represents a major unconformity (resulting from a long period of erosion or nondeposition). Permeable broken or weathered rock on the basement surface, sometimes termed "granite wash," is included in the rocks studied because of its sediment-like character. Faulting and fracturing of competent rocks in the basement complex established permeable paths for ground-water flow and created anisotropic permeability. The alignment of faults and fractures and other lineaments changed somewhat during the Paleozoic Era but kept the general trends of approximately North 35° West and North 55° East.

At the beginning of the Cambrian Period, the study area was above sea level, and rocks of Precambrian age were being eroded. Erosion continued through Middle Cambrian. However, during Late Cambrian, the area was inundated, except for the Transcontinental Arch and small islands, by a marine sea (fig. 10). The first deposits were nearshore sand, parent material of the Lamotte, Sawatch, and Reagan Sandstones. Calcareous mud was deposited in some areas along with the sand. The thickest sediment was deposited in a subsiding basin that extended from central Oklahoma through central Arkansas. The advances of the sea were interrupted by periods of sea recession. During the recessions, sand and calcareous mud was lithified to sandstone and limestone. The entire study area, except for the center of the present Anadarko and Arkoma Basins, was above water at some time. The saline water deposited with the sediment probably was flushed from the Cambrian mantle and subjacent rocks. Erosion removed overburden load



EXPLANATION

Q	QUATERNARY DEPOSITS
T	TERTIARY DEPOSITS
Mz	MESOZOIC ROCKS—Cretaceous, Jurassic, and Triassic age
UPz	UPPER PALEOZOIC ROCKS—Permian, Pennsylvanian, and Mississippian age
MPz	MIDDLE PALEOZOIC ROCKS—Devonian and Silurian age
LPz	LOWER PALEOZOIC ROCKS—Ordovician and Cambrian age
pЄ	PRECAMBRIAN ROCKS
A —— A'	TRACE OF SECTION—Shown in figure 7
——	CONTACT

FIGURE 6.—Regional geology of central United States (modified from Kinney, 1966).

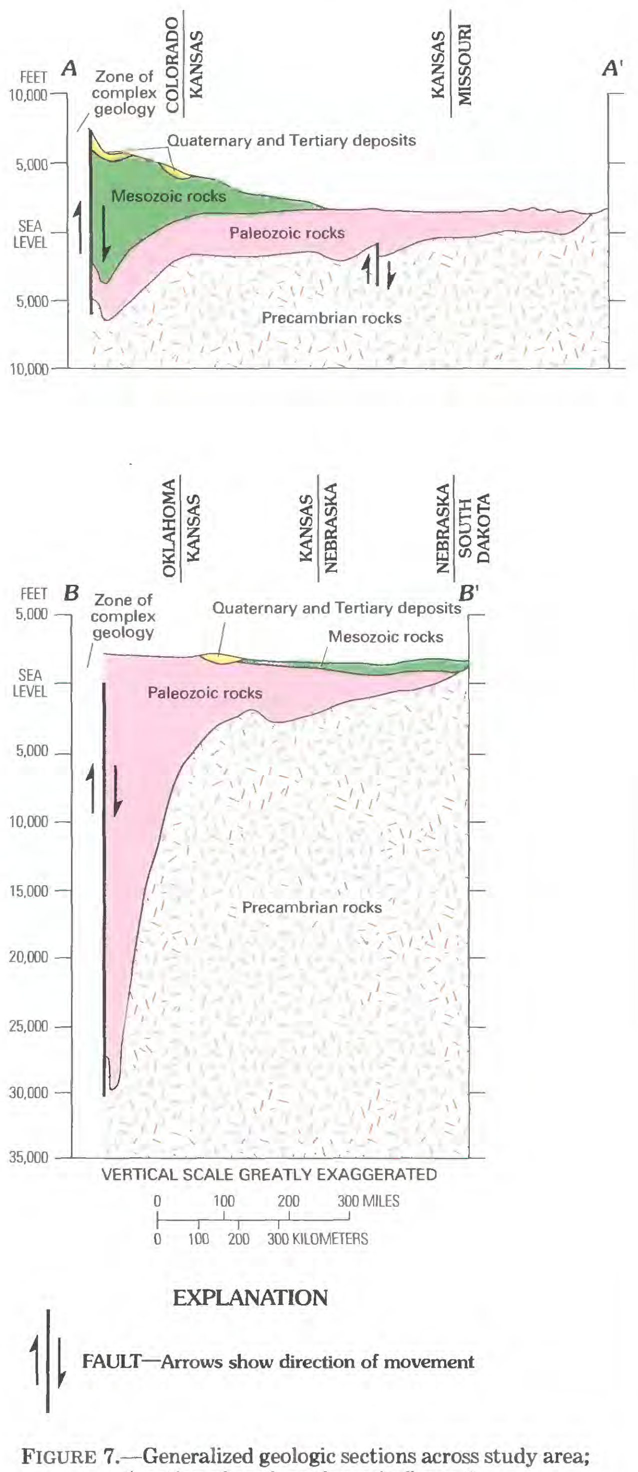


FIGURE 7.—Generalized geologic sections across study area; location of sections shown in figure 6.

and resulted in extensional fracturing. The fracturing created secondary permeability but, more importantly, created paths along which dissolution, especially of calcareous material, occurred. At some locations, especially near coastlines, rocks containing saline water were in contact with fresh ground water from the land masses. At these locations, dissolution and dolomitization occurred.

During the Ordovician Period, the Oklahoma-Arkansas Basin continued to subside and the Ozark Uplift began. Sediment thickness in excess of 6,000 ft accumulated. Compaction of the sediment squeezed water from the rock as primary porosity was reduced. At temperatures normally found at depths of 5,000 ft or greater, thermal diagenesis of organic material and clay minerals could be expected. Thermal diagenesis of organic material results in the production of CO_2 (carbon dioxide), water, and hydrocarbons. Thermal diagenesis of clay results in liberation of water and the changing of smectite to illite. These processes generate pressure and generally create fluids rich in CO_2 that, in turn, result in the dissolution of selected carbonate and silicious material and selectively increase secondary porosity and permeability. Most sediment of Ordovician age was nearshore calcareous mud, largely algal lime. As during Late Cambrian time, the sea was cyclic but generally advancing. During periods of sea recession, the calcareous mud was lithified to limestone, and dolomitization occurred near coastlines. Erosion removed sediment and resulted in extensional fracturing, which, in turn, created paths for dissolution of carbonate and other rock material by near-surface ground water of meteoric origin. All processes, in general, increased porosity and permeability.

Nearly the entire study area, except for southern Oklahoma, Arkansas, and the present Salina Basin, was uplifted during the Silurian and Devonian Periods (fig. 11). The exposed rocks were severely eroded; large quantities of pre-Silurian rock were removed, resulting in unloading and extensional fracturing. Regional flow systems of ground water of meteoric origin developed and flushed the formational waters from the rocks of Cambrian and Ordovician age. Near-surface dissolution of carbonate material greatly increased the permeability of the exposed rocks. At the end of the Devonian, or possibly during very early Mississippian time, the transgressing sea is believed to have completely submerged the area exclusive of the Transcontinental Arch. Sand was deposited nearshore, and extensive clay was deposited offshore. The extensive clay of very slight permeability restricted fluid flow from the underlying carbonate rocks to the overlying sediment. The dominant positive element during Early Mississippian time was the Colorado-Wyoming Uplift, and the dominant negative element was the subsiding Anadarko Basin (fig. 12). The most important characteristic of the Mississippian Period was the active tectonism that initiated large structural

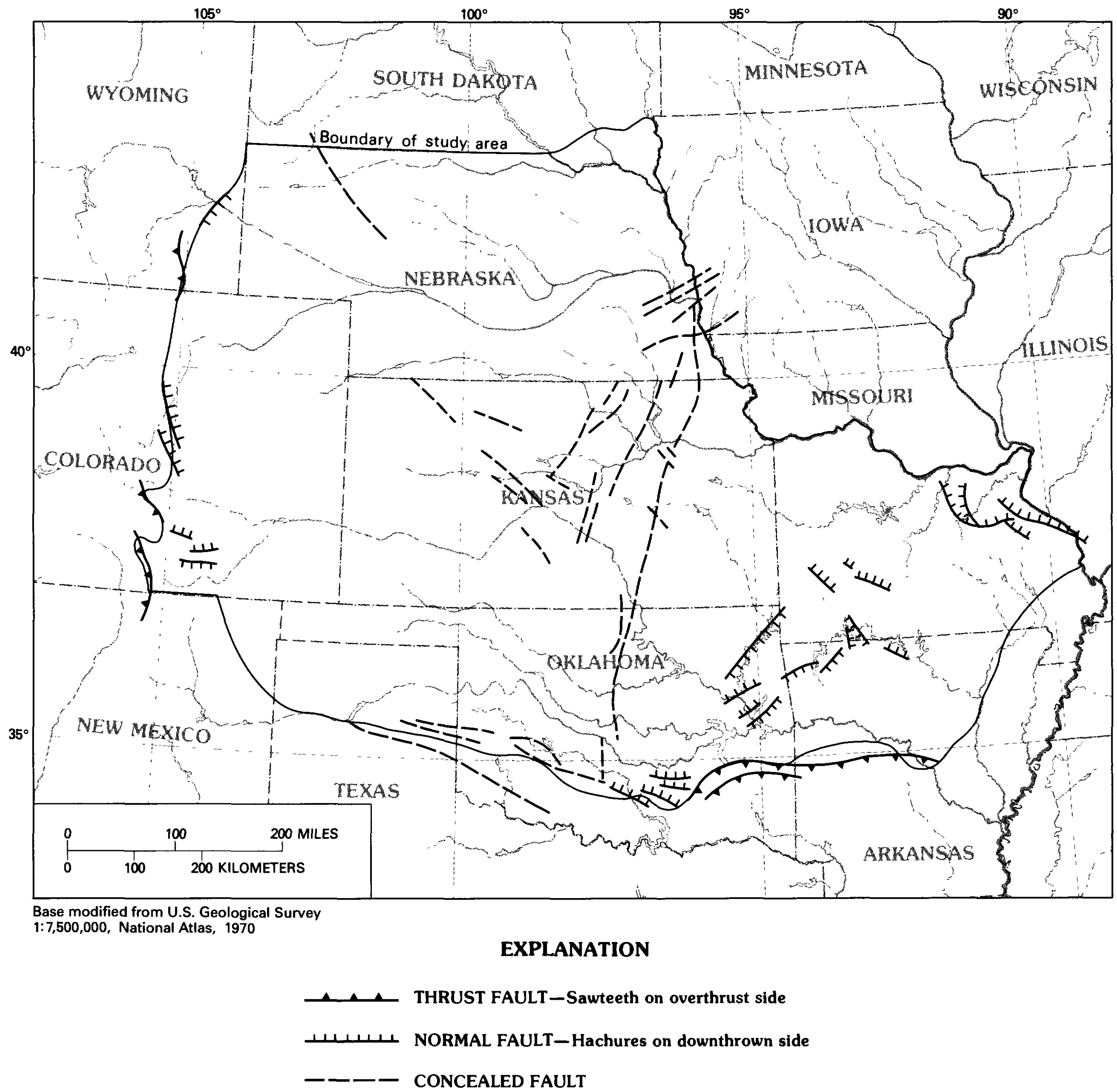


FIGURE 8.—Major faults (modified from King, 1968; Sims, 1985; Krueger and Keller, 1986).

features, which henceforth were to affect geology and hydrology. In addition to the Colorado-Wyoming Uplift and the Anadarko Basin, the Nemaha Uplift (Ridge) and the Arkoma Basin (Ouachita Trough) also were forming. Calcareous sediment was deposited in the shallow equatorial seas over the clay.

Late Mississippian time was characterized by a cyclic but generally receding sea and, by the end of the Mississippian, only the deeper parts of the Anadarko and Arkoma Basins were submerged. Thermal diagenesis of organic material continued in these basins. Elsewhere lithification, erosion, fracturing, and dissolution occurred.

During Pennsylvanian time, large compressive stresses developed primarily north to south. The stresses probably were related to the collision of the African, South American, and North American plates. These stresses were relieved by downwarp and uplift. The uplift occurred in a wide arcuate belt along the west and southern boundaries of the study area, whereas the east-central part of the study area remained stable at or above sea level. The uplifts included the Front Range, Apishapa, Criner,

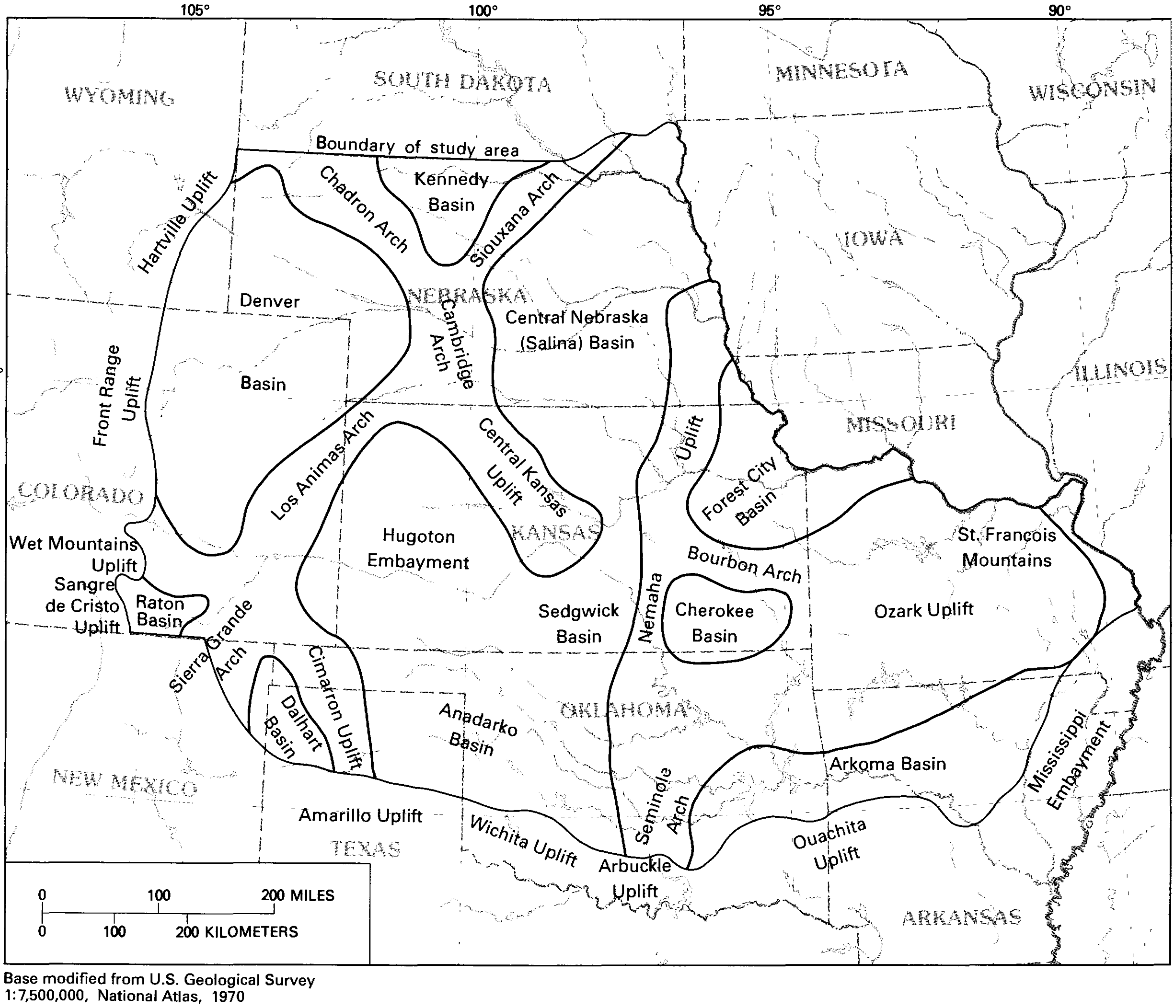


FIGURE 9.—Major structural features (modified from Carlson, 1963; Merriam, 1963; Oetking and others, 1966, 1967; Bennison and Chenoweth, 1984; Renfro, no date).

Amarillo, Wichita, Arbuckle, Ouachita, Ozark, Nemaha, and the Cambridge-Central Kansas Uplifts; subsidence was mostly in the Anadarko and Arkoma Basins.

Most sediment of Pennsylvanian age was clay, sand, calcareous mud and, in the eastern part of the area, organic material. Rapid deposition of clay and sand in the Anadarko Basin may have trapped water, creating a geopressured zone in the sediments of Morrowan age. Pre-Pennsylvanian rocks were buried to depths of nearly 20,000 ft, and thermal diagenesis of organic material was rapid and nearly complete. The deep burial reduced primary porosity, but secondary porosity and permeability were increased in selected strata. Adjacent to the Front Range and the Amarillo-Wichita Uplifts (fig. 9), permeable arkosic sediment was deposited in a band a few tens of miles in width. Fresh ground water from the adjacent uplifts moved through the arkosic deposits.

Permian time was a period of reduced tectonic activity compared to the Pennsylvanian. However, the effects of major activity during the Pennsylvanian were still being felt. The Early Permian sea, similar to the Late Pennsylvanian sea, was cyclic with alternate recessions and transgressions. During Leonardian time (Early Permian) and earlier, the seaway to the east through the Ozark area was closed as regional upward tilting occurred to the east. The closing of the seaway restricted circulation, increased salinity, and resulted in extensive evaporite deposition over nearly the entire CMRASA area (fig. 13). In addition to the regional tilting, uplift of the Ozarks continued. Major fracturing of the pre-Pennsylvanian carbonate rocks in the Ozark area occurred as a result of uplift stresses

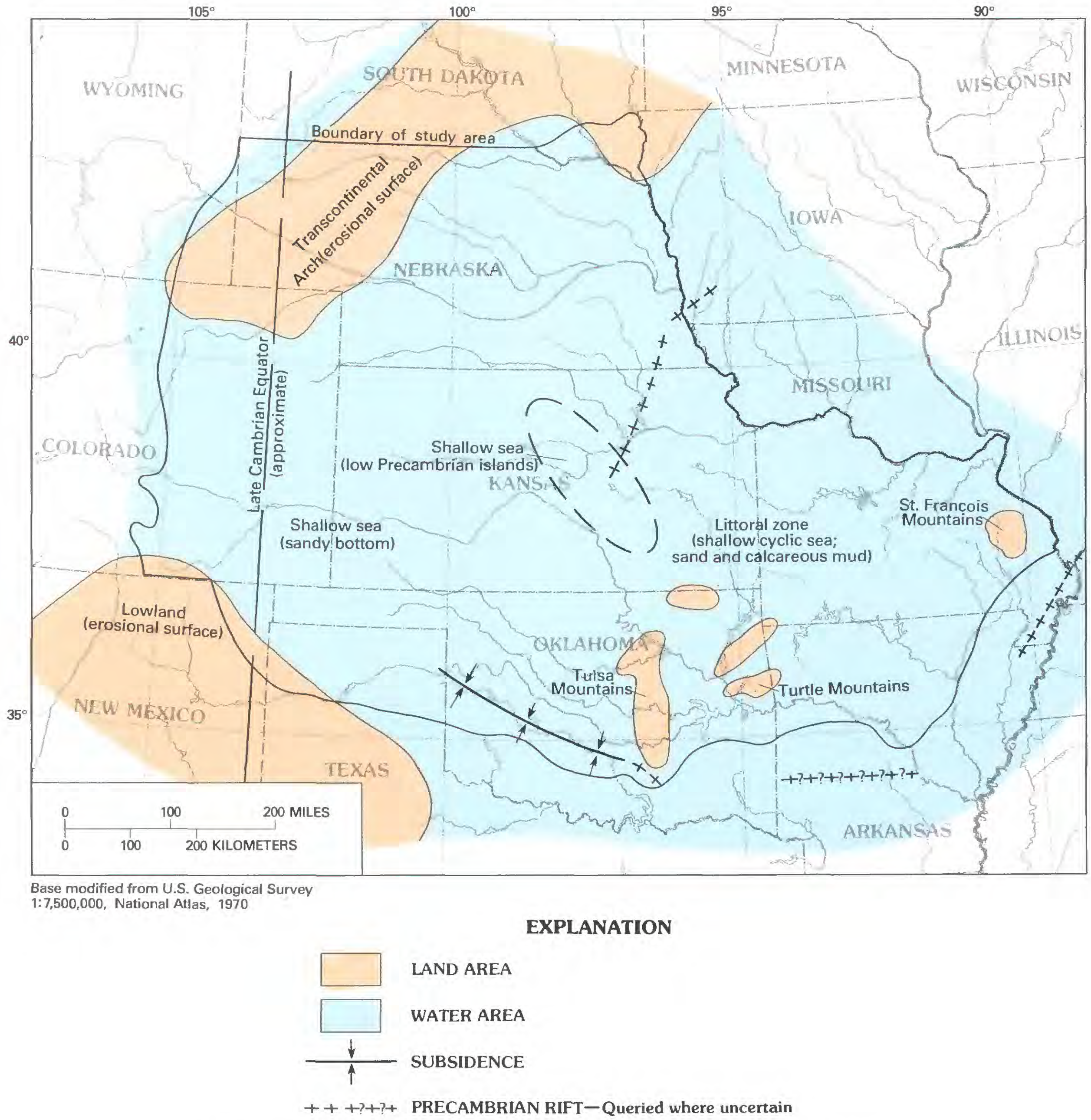


FIGURE 10.—Precambrian and Late Cambrian geographic and geologic conditions.

and, later, of the reduction in stress caused by unloading (erosion). Rocks in the Ouachita Uplift were eroding or subsiding rapidly and, by the end of the Early Permian, little relief remained.

Tectonic activity in Colorado continued from the Pennsylvanian into the Permian. Arkosic sediment continued to be deposited along the Front Range, Apishapa, and Sierra Grande Uplifts. In Oklahoma, the Anadarko Basin continued to subside, and the Wichita Uplift continued to rise. Detritus from the Wichita Uplift was a dominant source of sediment.

The sea retreated to the west during Late Permian time as the study area continued to be tilted upward to the east. At the end of the Permian, more than 20,000 ft of Pennsylvanian-Permian sediment had been deposited in the Anadarko Basin. Most rocks of Permian age are shale, sandstone, limestone, and evaporite deposits. The sandstone and limestone are relatively permeable in comparison to evaporite and

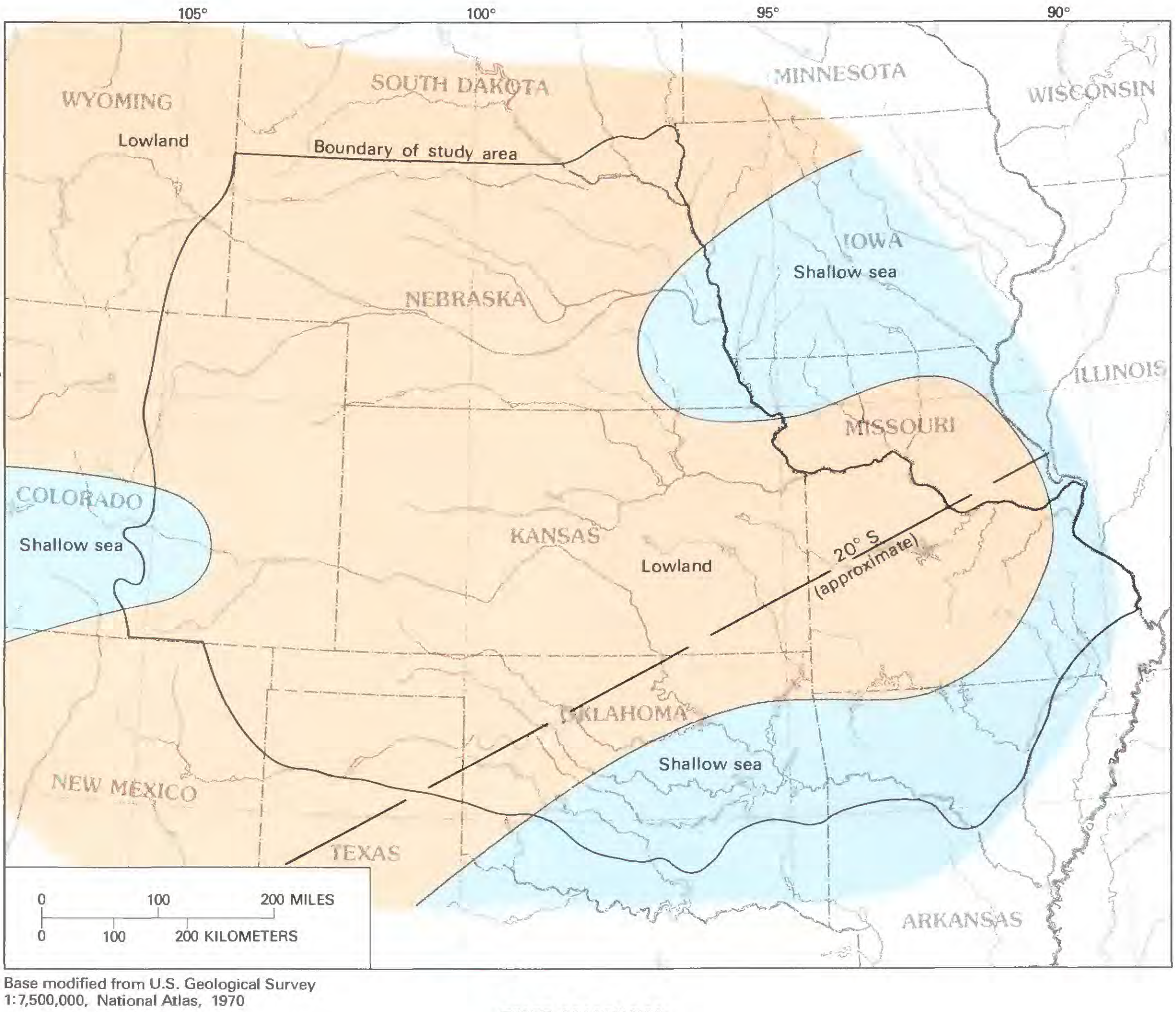


FIGURE 11.—Early Devonian geographic and geologic conditions.

shale. The extensive layers of shale and evaporite severely restricted flow to and from the subjacent rocks of pre-Pennsylvanian age.

At the end of Permian time, the rocks of Pennsylvanian age and, if present, Permian rocks around the St. Francois Mountains were being eroded. A regional flow system developed in the highly fractured, permeable rocks of Cambrian and Ordovician age. The extent of the regional flow system outward from the St. Francois Mountains (fig. 13) was controlled by topography and the extent of overlying confining shale.

Deposition during Early Triassic time occurred only in northwestern Colorado and western Nebraska. Red clay, calcareous mud, and dolomite were deposited in the sea with restricted circulation. During the Late Triassic, uplifts in central Colorado were being eroded rapidly, and the sediment was being deposited in a freshwater lake in the Dockum Basin (fig. 14).

In general during the Triassic, land masses within the CMRASA area had little relief and were not major sources of sediment. The erosion and removal of low-permeability rocks of Pennsylvanian and Permian age in the Ozark Uplift increased the extent of the

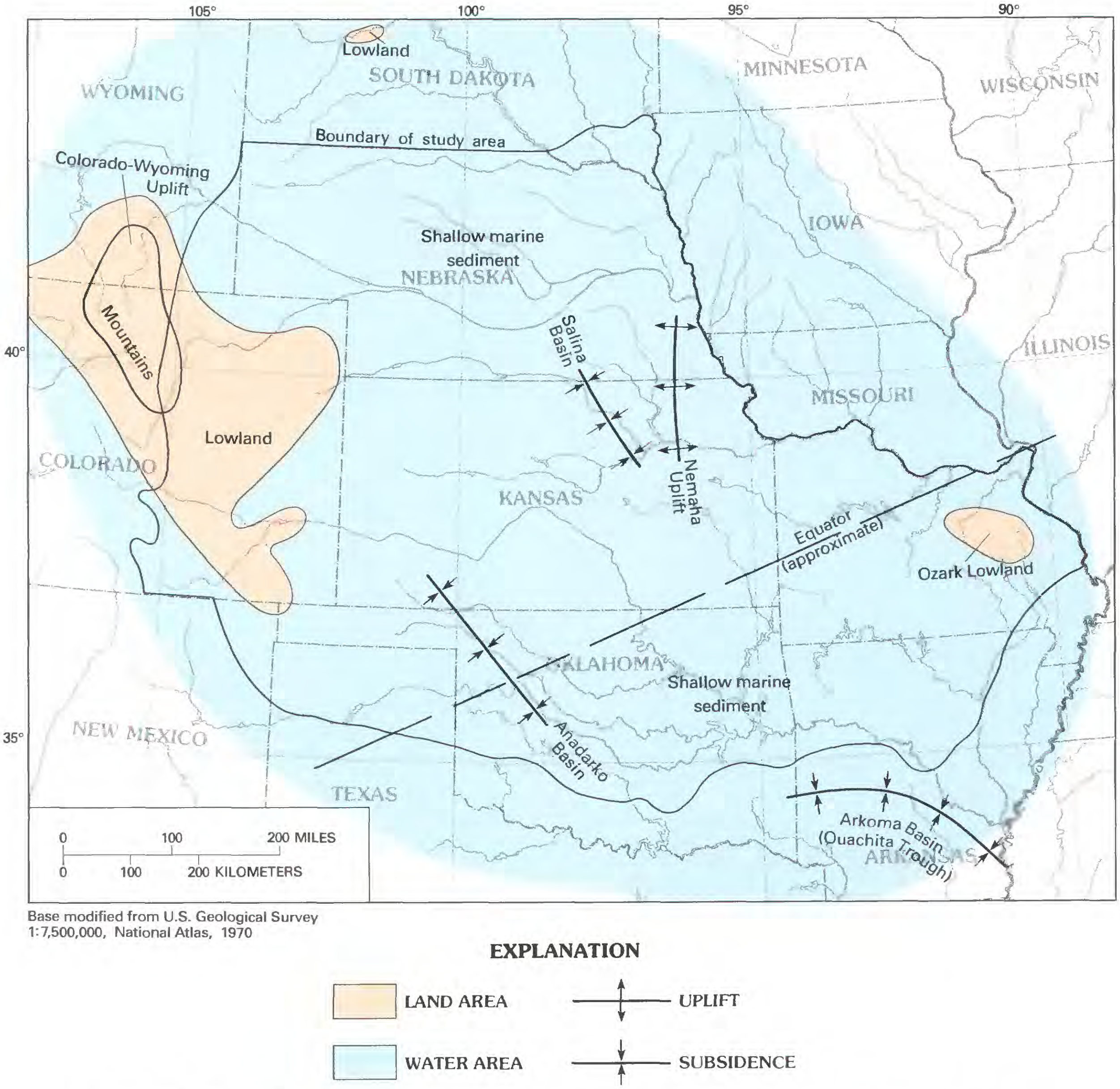


FIGURE 12.—Early Mississippian geographic and geologic conditions (modified from Craig and Varnes, 1979).

Ozark flow system. Permeability of the then-exposed carbonate rocks increased largely as a result of weathering and near-surface dissolution.

Most of the CMRASA area was above sea level during Jurassic time; however, a sea in which clay and sand were being deposited existed in the western part of the area. Subsidence along the present Mississippi Embayment was such that the Jurassic sea encroached into the new lowland. The Ozark ground-water flow system continued to expand as during the Triassic. At the end of the Jurassic, the sea receded, and the entire CMRASA area was above sea level.

At the beginning of the Early Cretaceous Epoch, nearly the entire CMRASA area was above sea level, and the rocks were being eroded. This was ended by a transgression of the Cretaceous sea from the north and south. Moderately permeable fine-grained sand and intercalated clay were deposited on alluvial plains or in nearshore estuaries by the advancing sea. As the sea advanced, offshore clay replaced nearshore sand as the dominant sediment. This very slightly permeable

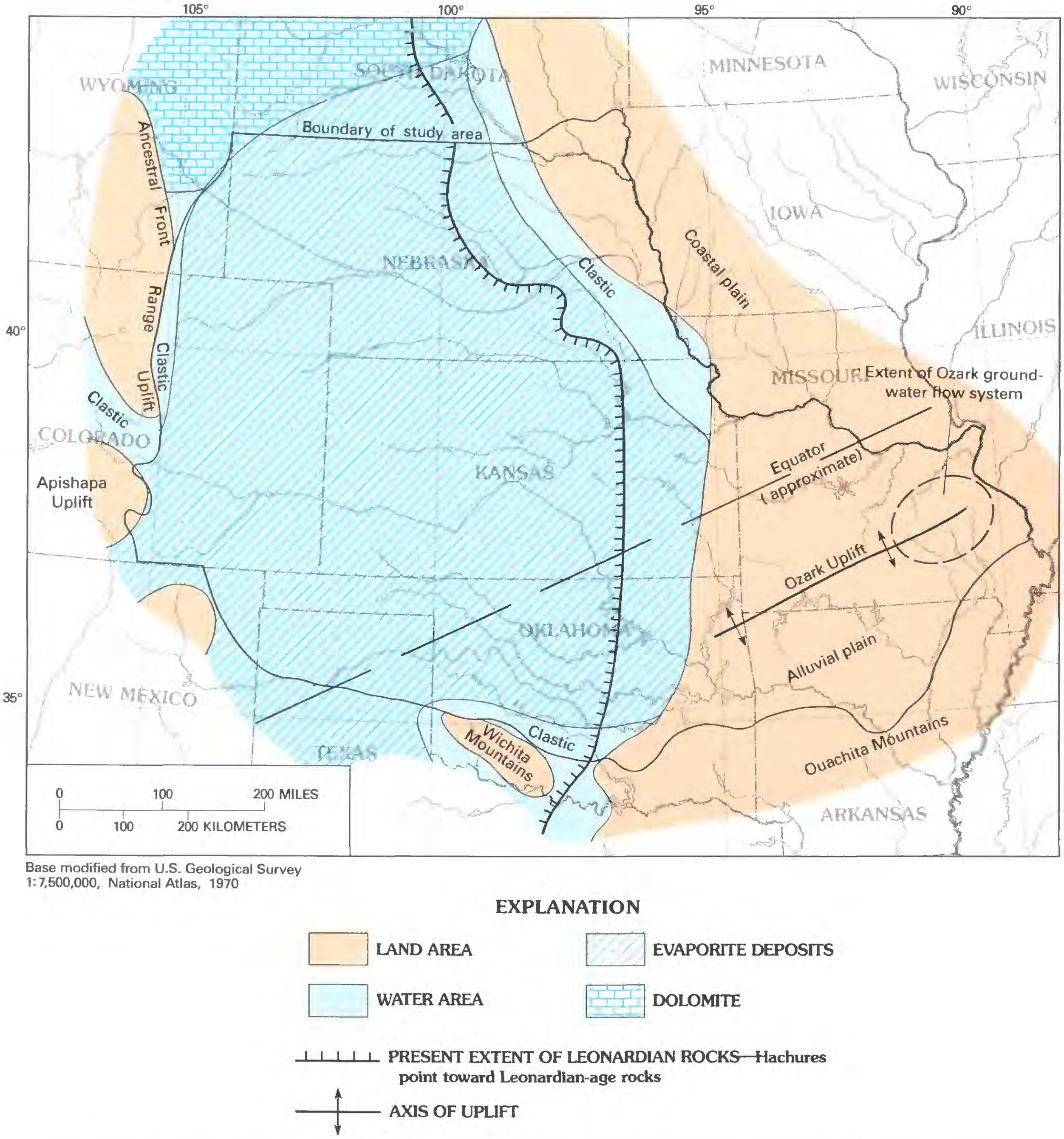


FIGURE 13.—Early Permian (Wolfcampian-Leonardian) geographic and geologic conditions (modified from McKee and others, 1967).

clay, which today forms the Kiowa Shale and equivalents, restricted vertical flow to the aquifer material below. The maximum extent of the Kiowa sea is unknown; however, it its likely that the sea covered the entire CMRASA area with the exception of part of the Siouxan Arch and the Ozark Uplift (fig. 15). Clay deposition was ended by a recession of the sea, which was partly the result of regional uplift of the eastern part of the study area. The Pascola Uplift in the bootheel area of southeastern Missouri may have been contemporaneous with this regional uplift.

A period of erosion ensued until it was interrupted by a second advance of the Early Cretaceous sea. During this second advance, permeable nearshore sand (parent material of the Dakota Sandstone) was deposited initially followed by clay. The maximum extent of

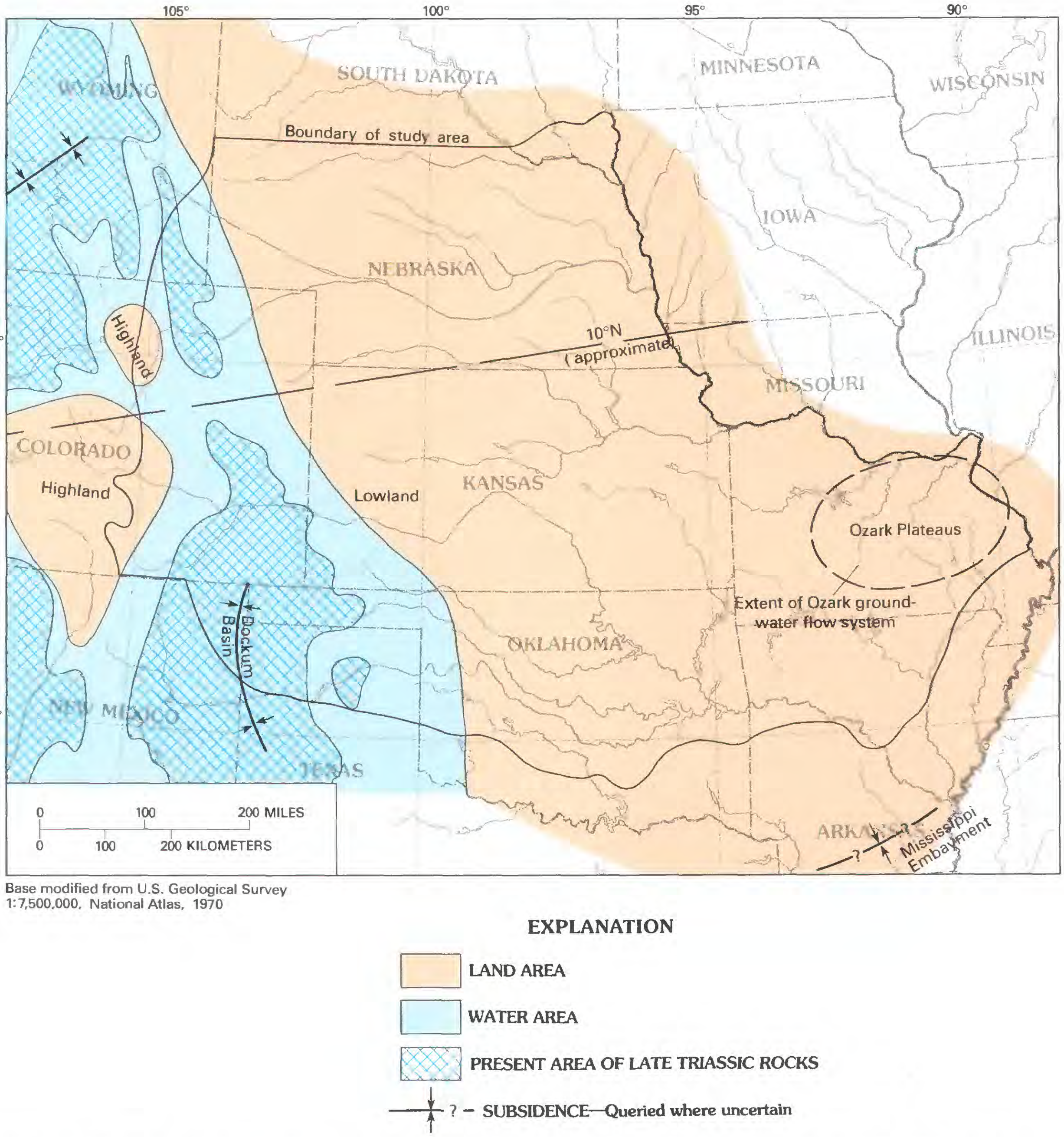


FIGURE 14.—Late Triassic (maximum sea) geographic and geologic conditions (modified from McKee and others, 1959).

the sea is not known exactly, except that it covered more than the present area of the Dakota Sandstone and may have covered most of the western part of the CMRASA area (fig. 15).

During Late Cretaceous time, clay was the dominant sediment, and maximum sedimentation was in the Denver Basin. Burial in the basin ranged from about 3,000 to 8,000 ft, and compaction reduced primary porosity and permeability. Thermal diagenesis may have increased permeability locally in the buried sandstone of Early Cretaceous age. Near the end of the Cretaceous, many areas, such as the Front Range, were uplifted rapidly during the early part of the Laramide orogeny, and the sea receded northward as the western part of the area was again tilted upward.

The Laramide orogeny continued into Tertiary time as evidenced by mountain building in central Colorado and Wyoming. Extensive erosion of the

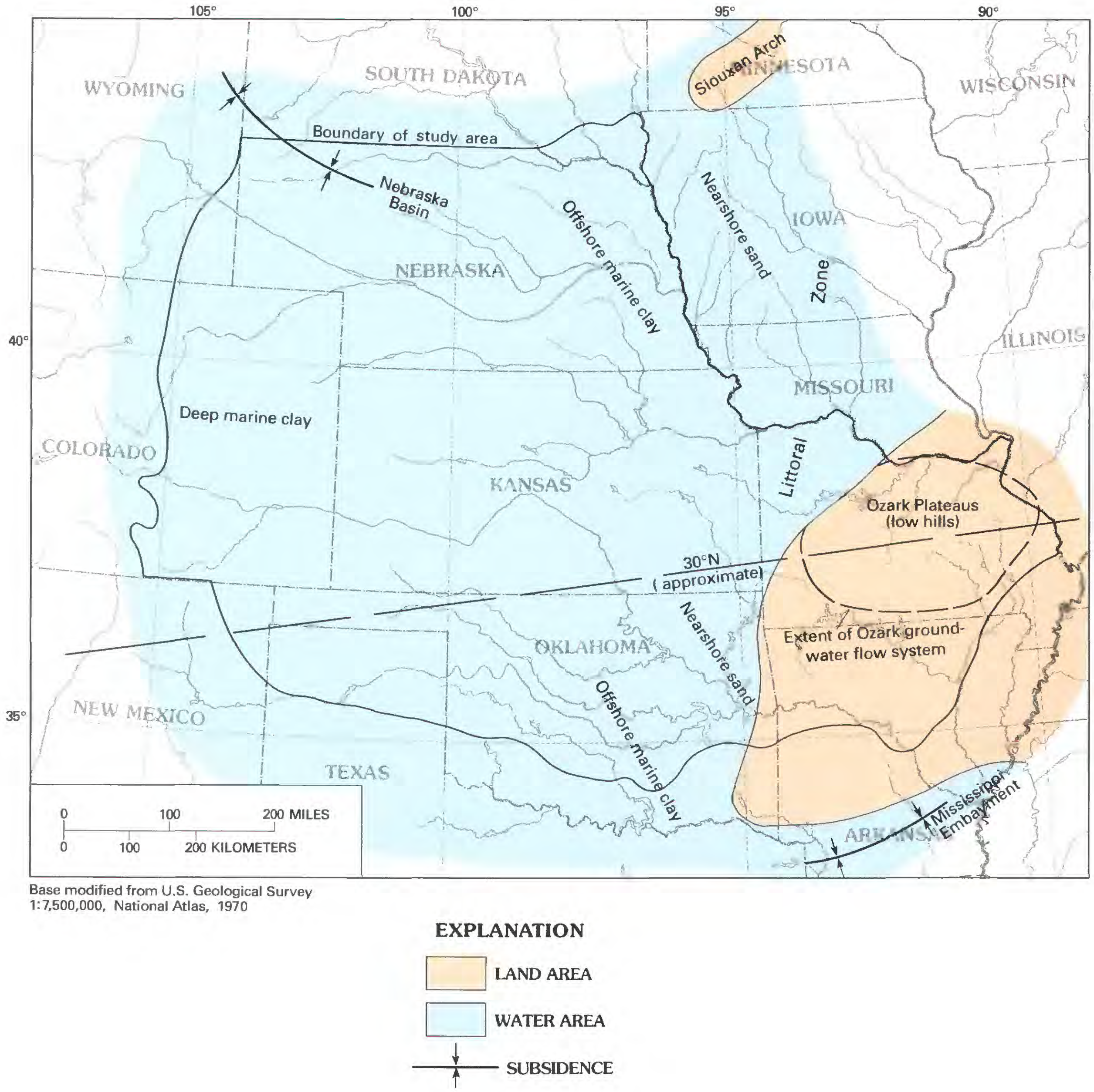


FIGURE 15.—Early Cretaceous (maximum sea) geographic and geologic conditions.

uplifted areas and widespread deposition of permeable alluvium on the plains followed. Regional ground-water flow from west to east in the Lower Cretaceous sandstone and in the underlying rocks of Cambrian to Mississippian age was established.

In the eastern part of the area, erosion continued to remove Pennsylvanian and Permian rocks from the Ozark area, and the Ozark flow system continued to develop in rocks of Cambrian to Mississippian age.

GEOHYDROLOGY

A hydraulic system delineated regionally can have more than one aquifer or confining unit and may include several formations and rock types. From a regional point of view, an aquifer also can contain a series of discontinuous confining units; however, the size of the discontinuous confining units is much smaller than the size of the delineated aquifer. On the other hand, a confining unit also can contain discontinuous zones that are permeable. Again, the size of the permeable zones is much smaller than the size of the confining unit.

In a hydrologic analysis of large regions that contain many geohydrologic units, it is useful to employ the terms aquifer system and confining system. An aquifer system consists of two or more aquifers in the same hydraulic system that are separated at most locations by one or more confining units that impede ground-water movement but do not greatly affect the regional hydraulic continuity of the system. A confining system contains two or more confining units separated by one or more aquifers that are not in the same hydraulic system. A confining system acts collectively to restrict flow to and from external aquifers that are not in the same hydraulic system.

Geohydrologic units within the study area were defined by hydrologic relations and hydraulic properties of the sedimentary rocks. The relation of the geohydrologic unit to ground-water flow is essential in conceptualization of regional-aquifer systems. The flow within most regional aquifers is controlled by the altitudes of major recharge areas, major discharge areas, and major structural features. Thus, topography is a major control on ground-water flow in regional aquifer systems.

Geohydrologic units in the CMRASA area, except adjacent to major structural uplifts, such as the Rocky Mountains, the Amarillo, Wichita, Arbuckle, and Ouachita Uplifts, and other areas of complex stratigraphic relations, coincide or correlate to a considerable degree with regional stratigraphic units. Along the physiographic boundary between the Interior Plains and the Interior Highlands (fig. 3) two regional ground-water flow systems are laterally adjacent. Regional flow westward in the Ozark Plateaus aquifer system merges with eastward flow in the Western Interior Plains along the physiographic boundary. The approximate location of the boundary between these two flow systems (figs. 16 and 17) is marked by a low in the equivalent freshwater-head surface, which is nearly coincidental with a topographic low in eastern Kansas and northeastern Oklahoma. The extent of the flow systems in most areas also is apparent from the map of dissolved-solids concentration (fig. 18). Flow systems in the Interior Highlands, except south of the Boston Mountains, contain water with less than 1,000 mg/L (milligrams per liter) dissolved solids.

The boundary between the flow systems also roughly parallels the physiographic boundary of the Central Lowland province in the western part of the Interior Plains and the Ozark Plateaus Province and Ouachita Province of the Interior Highlands north of the Arkansas River. For convenience, the CMRASA area is divided into two subregions, referred to as simply the "Plains" subregion and the "Ozark" subregion. The geohydrologic units in the two subregions are described separately. The areal extents of the regional aquifer systems studied are shown in figure 19.

The lowermost confining unit in both the Plains and Ozark subregions is the basement confining unit. The basement confining unit is composed mostly of Precambrian-age crystalline rocks. The rocks may be fractured and water yielding at many locations, such as in the Denver Basin and in southeastern South Dakota, but on a regional basis they are assumed to form the base of the regional flow system. The top of the basement unit ranges from more than 34,000 ft below sea level in central Oklahoma to more than 1,000 ft above sea level in the St. Francois Mountains of the Ozarks, and from more than 7,000 ft below sea level in the Denver Basin along the Rocky Mountains in east-central Colorado to about 500 ft above sea level in southeastern South Dakota (Jorgensen and others, 1993, plate 3).

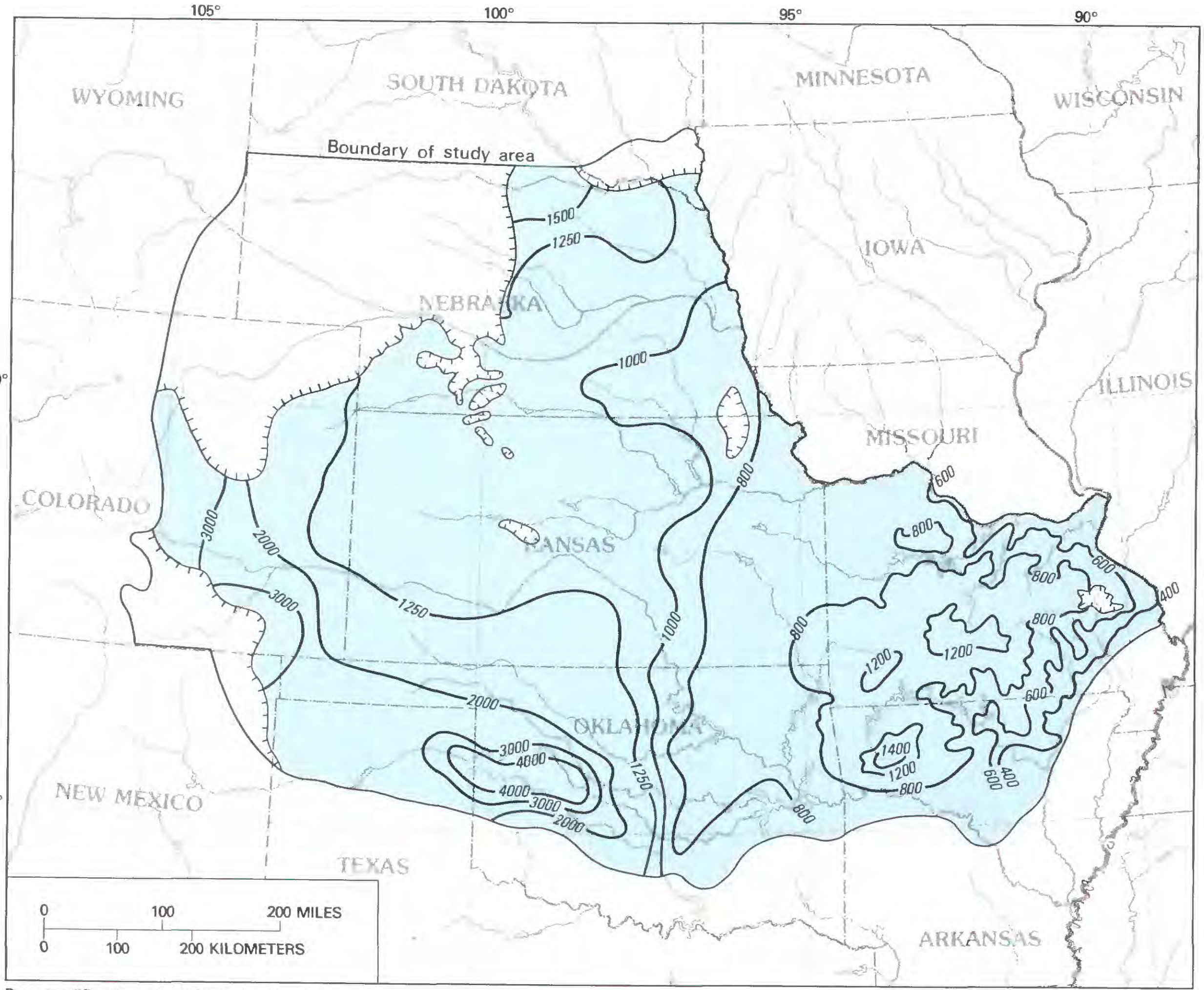
PLAINS SUBREGION

The Plains subregion is by far the larger of the two subregions in areal extent (fig. 19). As concerns the CMRASA study, the subregion is underlain by rocks that range in age from Precambrian to Late Cretaceous and comprise five geohydrologic units. From oldest to youngest, these units are the basement confining unit, the Western Interior Plains aquifer system, the Western Interior Plains confining system, the Great Plains aquifer system, and the Great Plains confining system (fig. 17).

WESTERN INTERIOR PLAINS AQUIFER SYSTEM

GEOHYDROLOGIC UNITS

The Western Interior Plains aquifer system consists of water-bearing dolostone, limestone, and shale that directly overlie the basement confining unit in the western part of the Interior Plains physiographic division. The major stratigraphic units included in the system are listed in table 1. Not all stratigraphic units listed are aquifers; some form confining units. A geologic formation may be an aquifer in one part of the area and a confining unit elsewhere. The Western Interior Plains aquifer system includes the lower units, a confining unit, and an upper unit (table 1). Equivalent freshwater-head and water-chemistry data indicate that the lower units and the upper unit,



Base modified from U.S. Geological Survey
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EXPLANATION

—600— **LINE OF EQUIVALENT-FRESHWATER HEAD—Shows approximate altitude of equivalent-freshwater head. Interval, in feet, is variable. Datum is sea level**

┴┴┴┴┴┴ **EXTENT OF CAMBRIAN AND ORDOVICIAN ROCKS**

FIGURE 16.—Predevelopment equivalent-freshwater head in Cambrian and Ordovician rocks.

which are water bearing, are within a reasonably distinctive hydraulic system.

The lower units, at most locations, consist of aquifers in dolostone, limestone, and sandstone of Cambrian and Ordovician age separated by confining units of very slightly permeable material, such as shale or limestone. The lower units of the aquifer system are separated at most locations from the overlying upper unit by a relatively thin confining unit. The confining unit is composed mostly of the slightly permeable Chattanooga and Woodford Shales. The upper unit of the aquifer system is an aquifer composed of permeable limestone that is mostly Mississippian in age.

Ground-water flow in the aquifer system is regionally (but not necessarily locally) southeastward from north-central Nebraska and otherwise from west to east toward a broad potentiometric low in eastern Kansas and Oklahoma (fig. 16). Discharge in the broad low area generally is vertically upward to streams or to the near-surface water table.

At many locations along the western and southern boundaries of the study area and near uplifts, such as

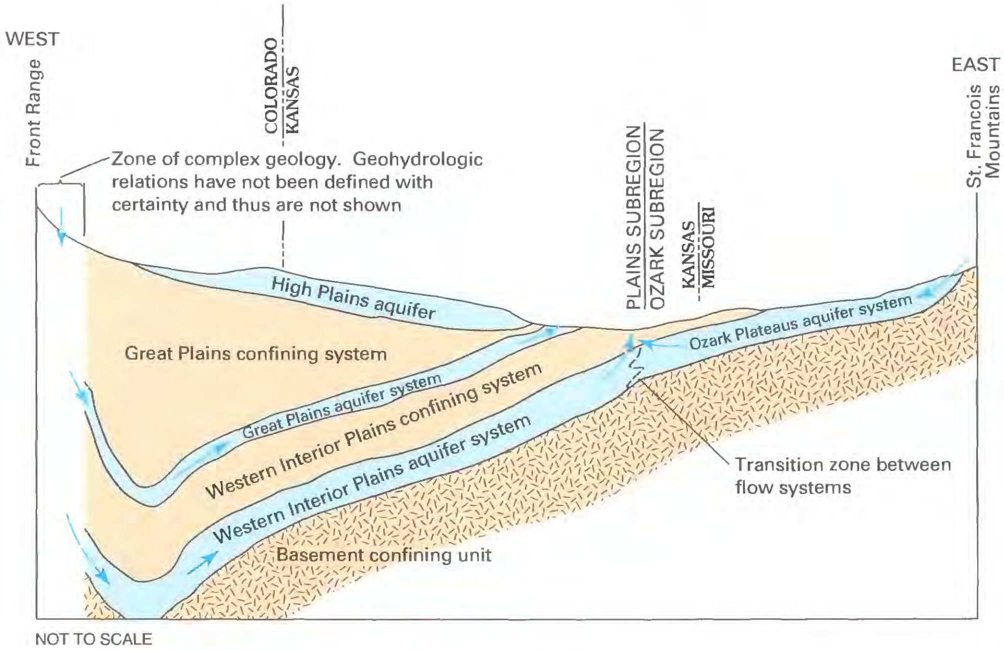


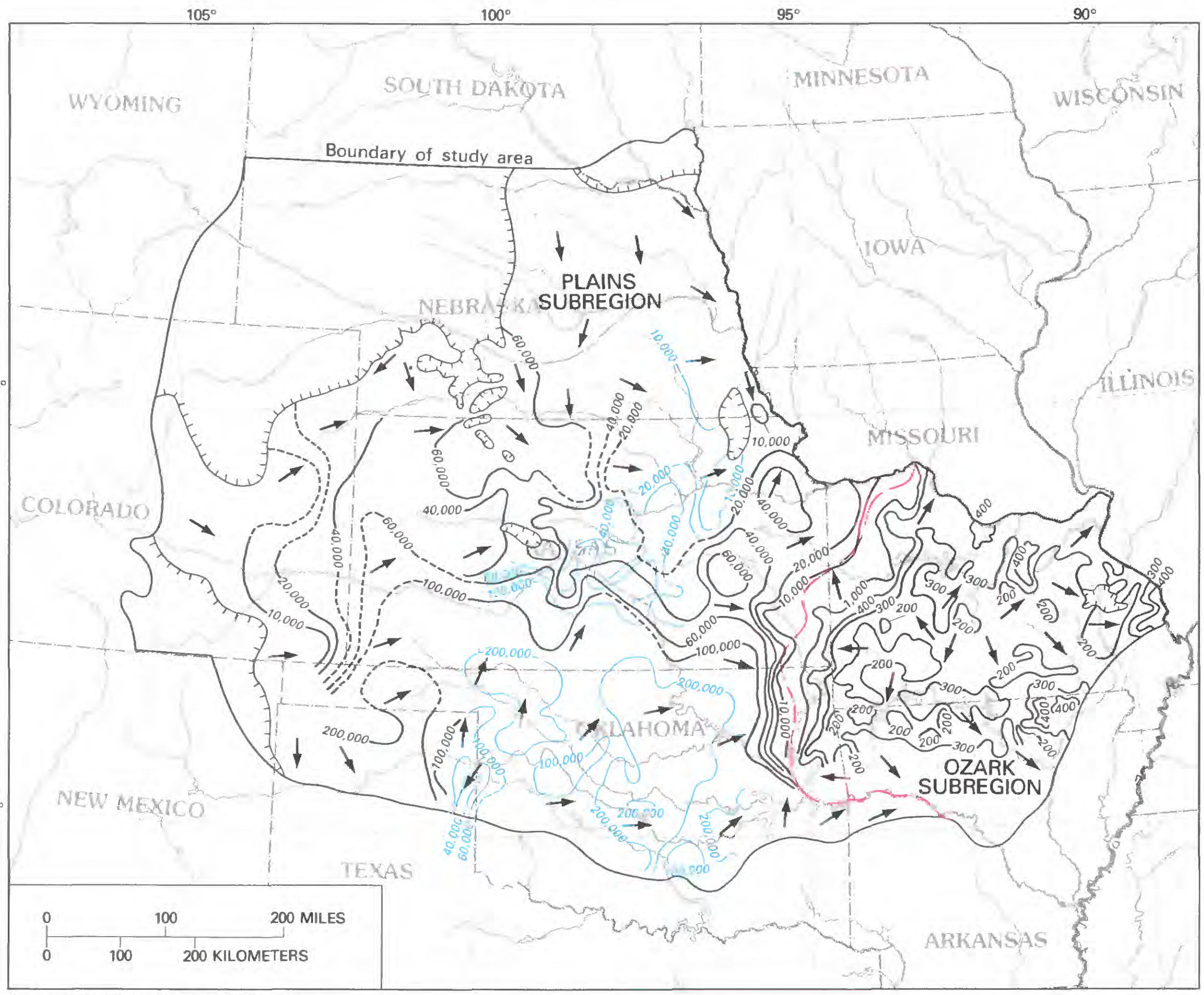
FIGURE 17.—Major regional geohydrologic units and regional flow in the Plains and Ozark subregions. Section extends from central Colorado to St. Francois Mountains in southeastern Missouri.

the Front Range, Amarillo, Wichita, and Ouachita, complex faulting has disrupted the strata. At these locations, the hydraulic relations between specific strata are complex and generally unknown, and the aquifers cannot be described in terms of a few geologic formations. However, the hydraulic continuity of the geohydrologic system is implied by the continuous distribution of equivalent freshwater head (fig. 16).

PROPERTIES

The altitudes of the tops of the lower units, the shale confining unit that separates the upper unit from the lower units, and the upper unit of the Western Interior Plains aquifer system are shown in Jorgensen and others (1993, plates 4–6). All units of the system generally slope away from the Missouri River and the Ozark Uplift toward the Denver, Anadarko, and Arkoma Basins except along the Rocky Mountains. The thickest sections of the aquifer system (exceeding 5,000 ft) are in west-central Oklahoma and west-central Arkansas in the Anadarko and Arkoma Basins (Jorgensen and others, 1993, plate 7) in which maximum deposition occurred. Additionally, these rocks have been protected, for the most part, from erosion since their deposition. Thus, diagenetic processes, which generally are associated with uplift and erosion and which result in large increases in permeability, have not acted on these rocks. Accordingly, the stratigraphic units in the deep basins that did not undergo uplift diagenesis are considerably less permeable than the same stratigraphic units elsewhere that did undergo uplift diagenesis. For example, the dolostone and limestone in and adjacent to the Ozark Uplift and the Cambridge-Central Kansas Uplift and the Nemaha Uplift in southeastern Nebraska and northeastern Kansas are fractured, solutioned, and very permeable because they have undergone uplift diagenesis and surficial weathering during several extensive periods.

Regional permeability values for the lower units and the upper unit of the Western Interior Plains aquifer system are shown in figures 20 and 21. Estimates of permeability were calculated because nearly all the measured values available are from drill-stem tests that tested sections of oil- and gas-reservoir rocks. These measured values are mostly from tests of only thin intervals of rock (a few feet) and are site specific. The estimates of permeability range from $1x10^{-11}$ ft^2 in eastern Kansas to less than $1x10^{-17}$ ft^2 in the Anadarko Basin and $1x10^{-18}$ ft^2 in the Denver and Arkoma Basins. The very slight permeability in



Base modified from U.S. Geological Survey 1:7,500,000, National Atlas, 1970

EXPLANATION

20,000 — LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION IN WATER MOSTLY FROM MIDDLE ORDOVICIAN, UPPER ORDOVICIAN, SILURIAN, AND DEVONIAN ROCKS—Dashed where approximately located. Interval, in milligrams per liter, is variable

20,000 — LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION IN WATER MOSTLY FROM UPPER CAMBRIAN AND LOWER ORDOVICIAN ROCKS—Dashed where approximately located. Interval, in milligrams per liter, is variable

LIMIT OF LOWER UNITS IN THE WESTERN INTERIOR PLAINS AND OZARK PLATEAUS AQUIFER SYSTEMS

APPROXIMATE BOUNDARY BETWEEN PLAINS AND OZARK SUBREGIONS

APPARENT DIRECTION OF LATERAL FLOW—Based on pressure and density near the center line of the geohydrologic unit

FIGURE 18.—Dissolved-solids concentrations in water from lower units in the Western Interior Plains aquifer system and the Ozark and St. Francois aquifers in the Ozark Plateaus aquifer system.

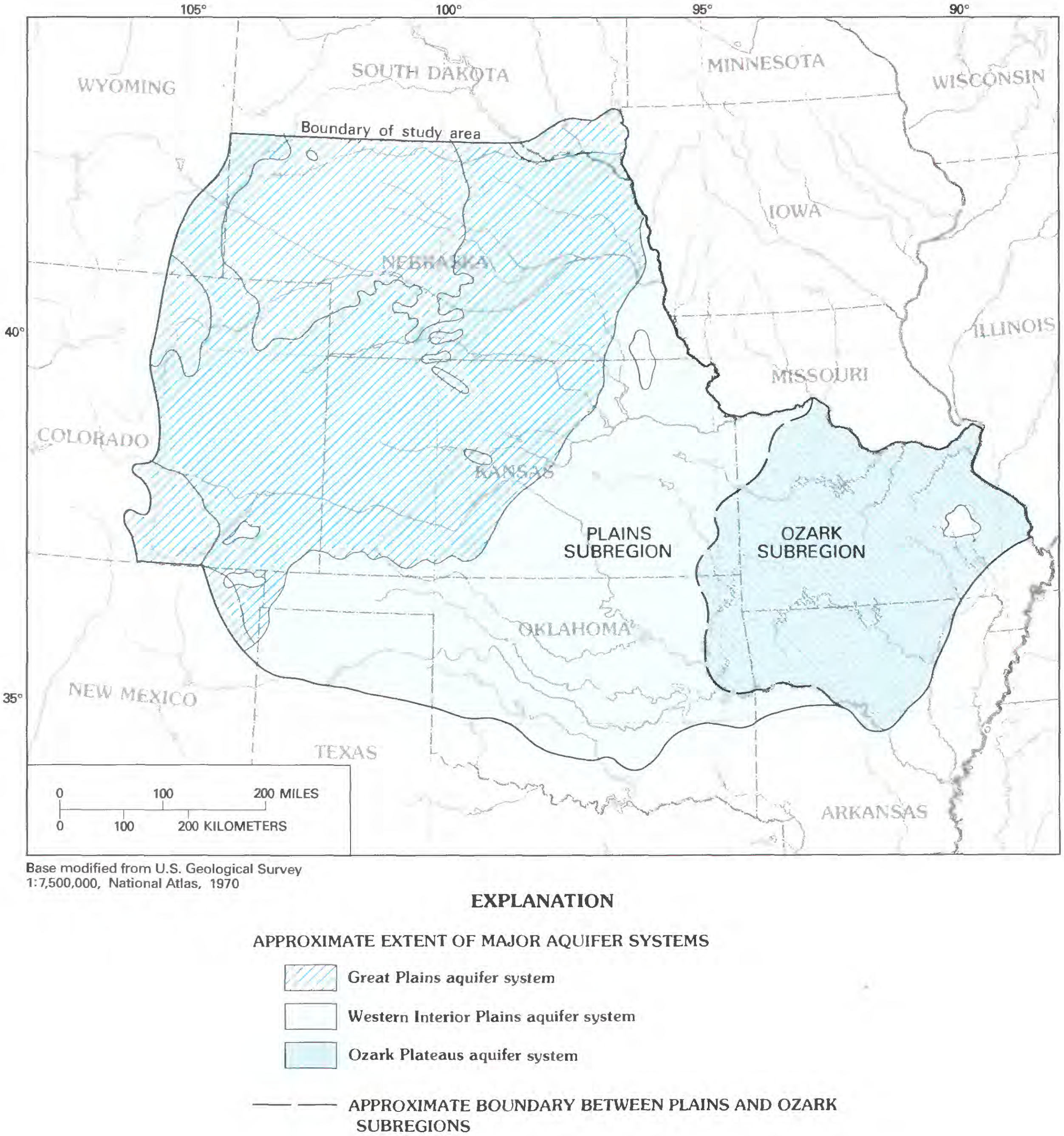


FIGURE 19.—Extent of major aquifer systems.

the Anadarko Basin is in part evidenced by the large equivalent- freshwater head in west-central Oklahoma shown in figure 16. Pressure from the overlying geopressure zone in the Morrowan sediment is attenuated downward into the aquifer system. However, because permeability is so slight, the pressure is not dissipated in the aquifer system by lateral flow. Permeability values are affected by depth as is indicated by the small permeability values in the Arkoma, Anadarko, and Denver Basins. In general, values of permeability less than $1x10^{-15}$ ft^2 are considered typical of confining material, not of aquifer material. However, the aquifer system is regionally distinct from the overlying confining system and the underlying basement confining unit.

Leakance through the confining unit that separates the lower units from the upper unit of the Western Interior Plains aquifer system varies directly with the

TABLE 1. *Generalized correlation of geohydrologic units to stratigraphic units in most of the Plains subregion*
[From Jorgensen and others, 1993]

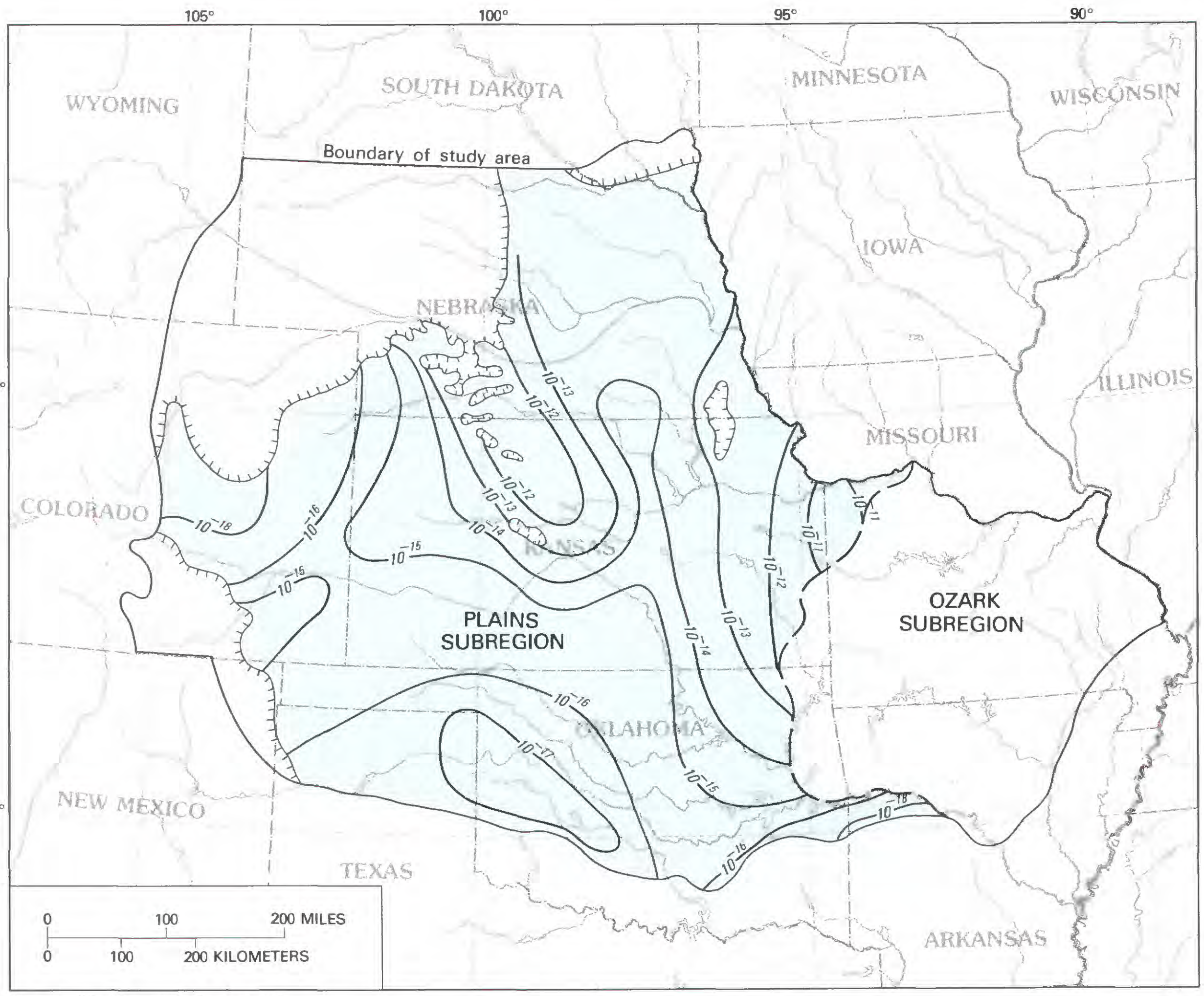
Geohydrologic unit		Principal rock-stratigraphic unit(s)	Time-stratigraphic unit
High Plains aquifer		Ogallala Formation and unconsolidated deposits	Quaternary and Tertiary
Great Plains confining system		Pierre Shale, Niobrara Formation, Carlile Shale, Greenhorn Limestone, Graneros Shale	Upper Cretaceous
Great Plains aquifer system	Maha aquifer	Dakota Sandstone, "D" sandstone, "J" sandstone, and equivalent of Newcastle Sandstone	Lower Cretaceous
	Apishapa confining unit	Kiowa Shale and equivalent of Skull Creek Shale	
	Apishapa aquifer	Cheyenne Sandstone and equivalent of Fall River Sandstone and Lakota Sandstone	
Western Interior Plains confining system		Morrison Formation, Sundance Formation, Entrada Sandstone, Dockum Formation, Elk City Sandstone, Doxey Shale, Big Basin Sandstone, Cloud Chief Formation, Day Creek Dolomite, Whitehorse Sandstone, Nippewalla Group, Sumner Group, Chase Group, Council Grove Group, Admire Group, Wabaunsee Group, Shawnee Group, Douglas Group, Lansing Group, Kansas City Group, Pleasanton Group, Marmaton Group, Cherokee Group, Atokan rocks, Morrowan rocks, and Springer Group	Jurassic through Upper Mississippian (Chesterian)
Western Interior Plains aquifer system	Upper aquifer unit	Meramecian, Osagean, and Kinderhookian rocks	Upper Mississippian through Upper Cambrian
	Confining unit	Chattanooga Shale and Woodford Shale	
	Lower aquifer units	Hunton Group, Sylvan Shale, Galena Dolomite, equivalent of Viola Limestone, Simpson Group, Arbuckle Group, and Reagan Group	
Basement confining unit		Mostly igneous and metamorphic rocks	Cambrian and Precambrian

vertical hydraulic conductivity and inversely with thickness. No measurements of vertical hydraulic conductivity are available; the thickness generally ranges from 0 to 300 ft.

MODEL ANALYSIS AND HYDROLOGIC BUDGET

A numerical ground-water flow model was developed and used to test conceptualization of flow in the regional aquifer systems of the study area (Signor and others, in press). In addition, two other numerical models were developed to simulate flow in more detail in the Great Plains and Ozark Plateaus aquifer systems as described in Helgesen and others (1993) and Imes and Emmett (1994). The regional model simulated the Western Interior Plains aquifer system, the Western Interior Plains confining system, the Great Plains aquifer system, and the Ozark Plateaus aquifer system. However, only the results for the regional model in simulating flow in the Western Interior Plains aquifer system will be described in this section.

The numerical model selected was a modular three-dimensional, finite-difference, ground-water flow model developed by McDonald and Harbaugh (1984). It is designed to simulate two- and three-dimensional movement of ground water of constant density through porous material. The model consists basically of a grid superimposed on each of the major geohydrologic units. The grid has 28 rows, 33 columns, and uniform cell size of 28 mi x 28 mi. The model row orientation was set to coincide with the principal directions of lineaments, North 35° West and North 55° East, which facilitated consideration of anisotropic hydraulic conductivity. Major geohydro-



Base modified from U.S. Geological Survey 1:7,500,000, National Atlas, 1970

EXPLANATION

10^{-12} LINE OF EQUAL ESTIMATED REGIONAL PERMEABILITY—Value is the thickness-weighted mean horizontal intrinsic permeability. Interval, in feet squared, is variable

EXTENT OF LOWER UNITS IN WESTERN INTERIOR PLAINS AQUIFER SYSTEM

APPROXIMATE BOUNDARY BETWEEN PLAINS AND OZARK SUBREGIONS

FIGURE 20.—Estimated regional intrinsic permeability of lower units in the Western Interior Plains aquifer system.

logic units in the study area are represented as layers in the model. From top to bottom the layers are:

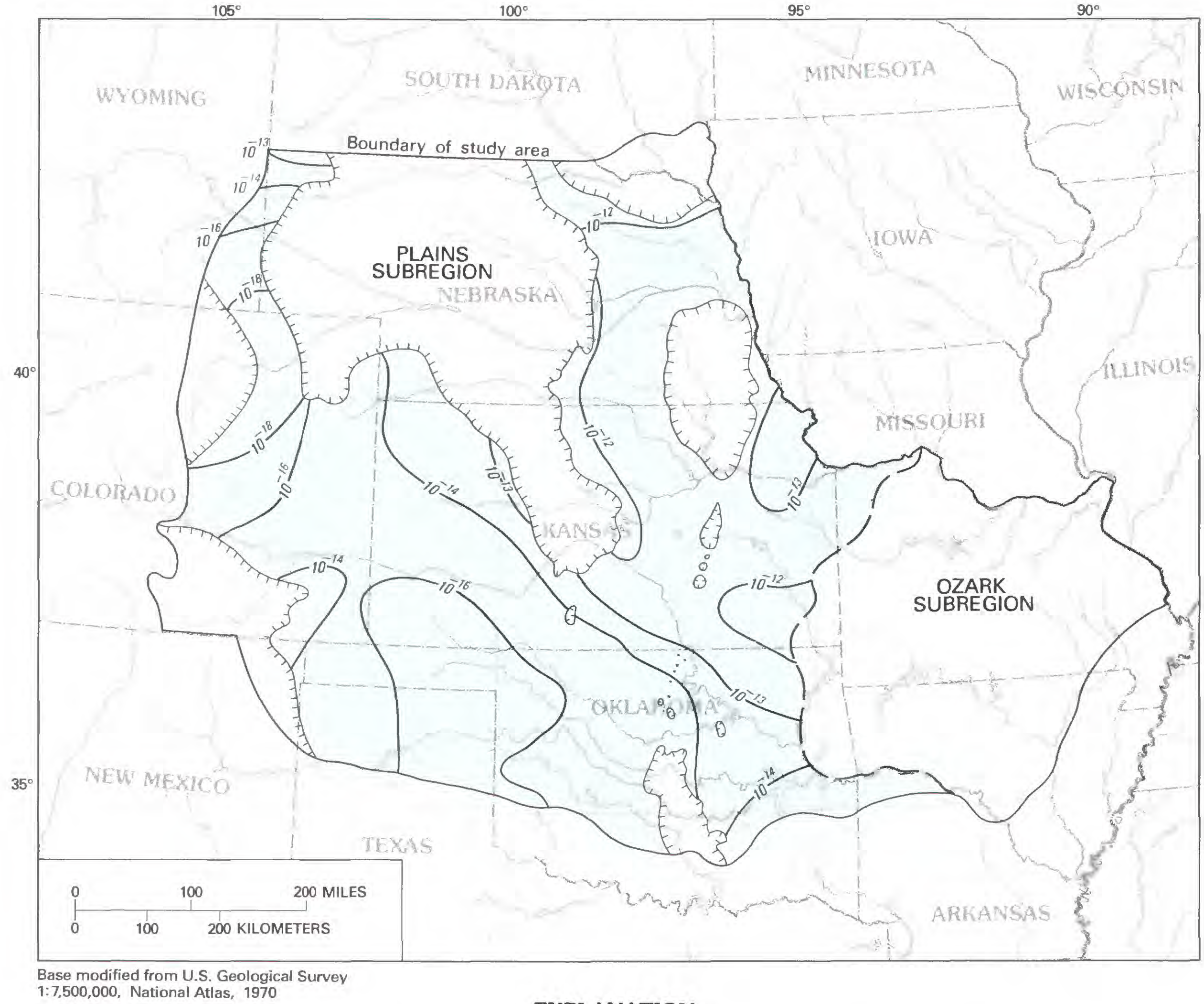
Layer 1—The surficial unit, which consists of the High Plains aquifer and the Great Plains confining system.

Layer 2—The Great Plains aquifer system.

Layer 3—The Western Interior Plains confining system.

Layer 4—The upper unit of the Western Interior Plains aquifer system in the Plains subregion and the Springfield Plateau aquifer in the Ozark subregion.

Layer 5—The lower units of the Western Interior Plains aquifer system in the Plains subregion and the combined Ozark aquifer, St. Francois confining unit, and the St. Francois aquifer in the Ozark Plateaus aquifer system in the Ozark subregion.



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EXPLANATION

10^{-13} LINE OF EQUAL ESTIMATED REGIONAL PERMEABILITY—Value is the thickness-weighted mean horizontal intrinsic permeability. Interval, in feet squared, is variable

EXTENT OF UPPER UNIT IN WESTERN INTERIOR PLAINS AQUIFER SYSTEM

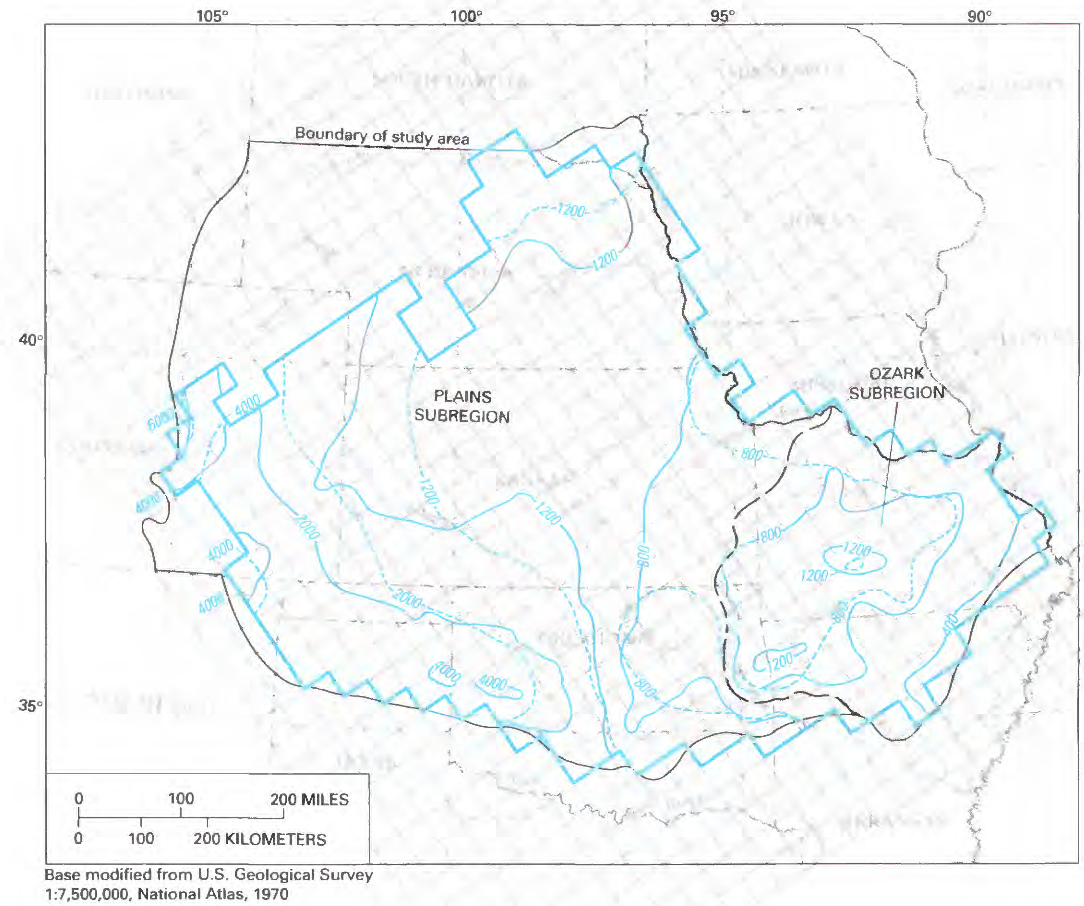
APPROXIMATE BOUNDARY BETWEEN PLAINS AND OZARK SUBREGIONS

FIGURE 21.—Estimated regional intrinsic permeability of upper unit in the Western Interior Plains aquifer system.

In general, data needed for simulation of ground-water flow in the model are water levels; altitude of geohydrologic units modeled; thicknesses, which can be determined by difference in altitudes of individual layers; intrinsic permeability (or hydraulic conductivity); and vertical leakance between centerlines of two vertically adjacent aquifer units or across confining-unit boundary conditions and source terms (vertical leakance is the effective vertical permeability divided by the thickness of the confining unit or distance between centerlines of two vertically adjacent model layers).

Boundary conditions for the model are no-flow, general-head, constant-head (specified head), and head-dependent boundaries (stream simulation). Source terms are water withdrawn or injected per model cell.

The model-calculated hydraulic head for layer 5 is shown in figure 22. In general, a comparison of model-calculated value correlates well with equivalent-



EXPLANATION

MODEL-LAYER BOUNDARY

MODEL-COMPUTED HYDRAULIC-HEAD CONTOUR—Interval, in feet, is variable. Datum is sea level

FIELD HYDRAULIC-HEAD CONTOUR—Interval, in feet, is variable. Datum is sea level

APPROXIMATE BOUNDARY BETWEEN THE PLAINS AND OZARK SUBREGIONS

FIGURE 22.—Model-computed and field hydraulic head for model layer 5 representing lower units in the Western Interior Plains aquifer system and the Ozark and St. Francois aquifers in the Ozark Plateaus aquifer system.

freshwater head, especially considering the variability of the results of drill-stem tests on which the equivalent-freshwater-head map was based. The Western Interior Plains aquifer system contains water of variable density and, thus, a direct comparison in all respects between model-calculated hydraulic head and equivalent head is not possible.

The velocity vectors of flow as calculated by the model for model layers 4 and 5 are shown in figures 23 and 24. The lengths of the arrow shafts in the figures are scaled logarithmically as to rate of movement. The arrowhead shows direction. Figures 23 and 24 show the extremely slow velocity of flow in the Western Interior Plains aquifer system. Both figures show flow outward from the geopressured zone in west-central Oklahoma. However, the velocities are extremely slow, confirming the slight permeability of the hydrologic units in that area. Accordingly, the quantity of flow outward from the geopressure zone is small. The transition zone between the Western Interior Plains and Ozark Plateaus aquifer systems is shown by the difference in direction of flow at the zone. Flow velocities in the Ozark Plateaus aquifer system are about five orders of magnitude greater than in the Western Interior Plains aquifer system.

USE AND POTENTIAL

Most of the water in the Western Interior Plains aquifer system is saline and could not be used as a potable water supply without treatment. However, the aquifer system contains a large quantity of water as listed in table 2. The accuracy of table 2 is based on assumptions stated later in the text. Oil and gas are produced from some zones within the aquifer system. Also, at some locations large quantities of brine produced with oil and gas from rocks above the aquifer system are being injected into the aquifer system.

Results of the flow simulation indicated that fluid velocities are very slow in the deeply buried units and that the aquifer system is nearly isolated from the overlying Great Plains aquifer system, especially in the area where halite and gypsum are present in the intervening confining system. Because of the degree of isolation, the slow velocity of flow, and the ambient water chemistry, the aquifer system has potential for material storage or waste disposal. For example, model results indicated that the velocity of water moving through pore spaces in the aquifer system in western Kansas is about $4x10^{-5}$ ft per year or about 40 ft in a million years. Even for a fluid velocity three orders of magnitude greater, the movement would be only about 7.6 mi in a million years. These rates assume that the integrity of the overlying confining system is maintained. Excess pore pressure, intensive drilling, or tectonic activity could result in loss of the integrity of the confining system. Evaluation of areas having pressure either greater than hydrostatic or less than hydrostatic would be useful in any evaluation of potential for storage or disposal of wastes. At some locations, such as near the uplifts that mark the boundaries of the CMRASA area, there has been considerable tectonic activity in the geologic past.

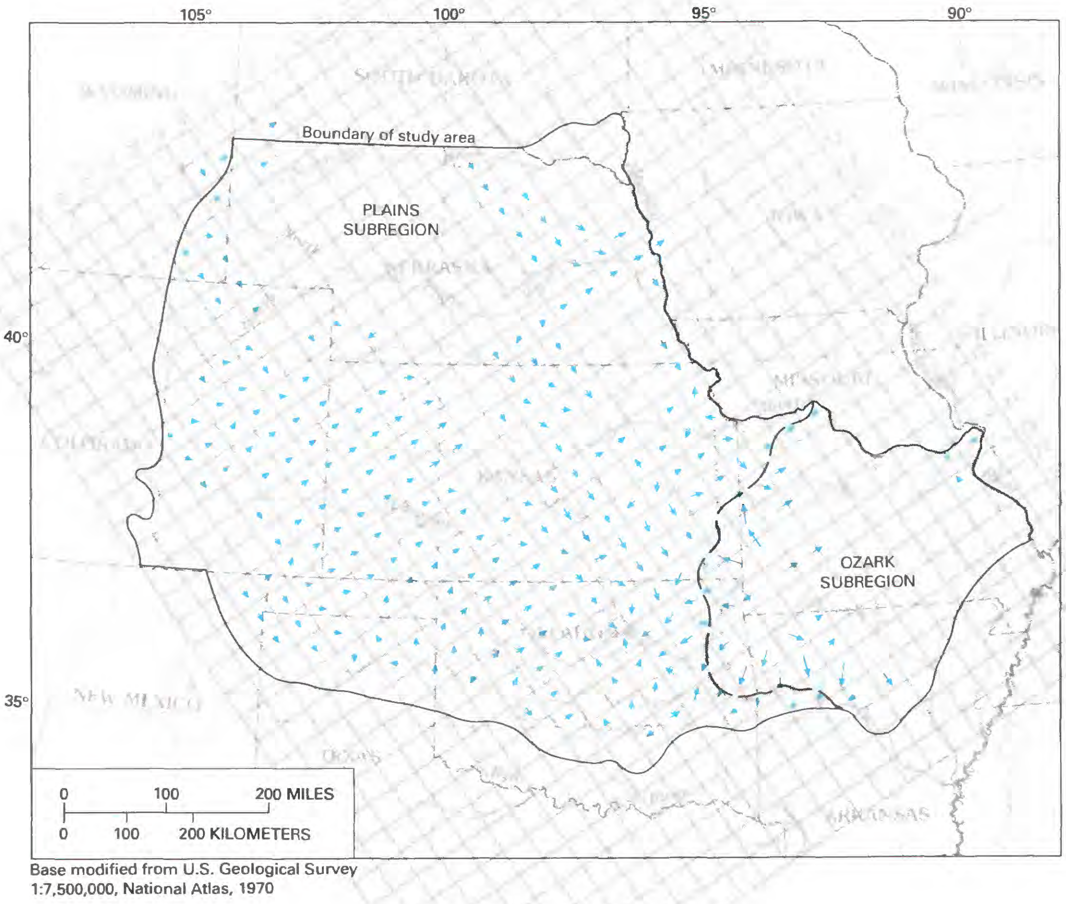
WESTERN INTERIOR PLAINS CONFINING SYSTEM

GEOLOGIC DEFINITION AND CORRELATION

The Western Interior Plains confining system consists of confining units separated by aquifers that are not in close hydraulic connection. That is, the aquifers are not in the same hydraulic system. Collectively, the confining units and the included aquifers restrict flow to and from the underlying Western Interior Plains aquifer system. The Western Interior Plains confining system is at land surface in much of the eastern part of the Plains subregion and in a significant part of the Ozark subregion. At some locations, the confining system is overlain directly by the High Plains aquifer system or, in small areas of eastern Nebraska and northeastern Kansas, by glacial till and loess. However, in much of the Plains subregion, the confining system is overlain by the Great Plains aquifer system.

Large pore pressures exist in a geopressured zone near the base of the confining system in the Anadarko Basin in Oklahoma. At this location, equivalent-freshwater hydraulic head exceeds 6,000 ft in sand and shale of Morrowan age. The pressure is transferred, but attenuated, into the underlying dolostone and limestone strata of the Western Interior Plains aquifer system (fig. 16) where equivalent-freshwater head exceeds 4,000 ft in the very slightly permeable rocks at the same location.

Formations of Pennsylvanian age form a major part of the confining system (Jorgensen and others, 1993, plate 2); they consist mostly of shale with limestone, sandstone, and some coal. In the deeper part of the Anadarko and Arkoma Basins, the ratio of limestone to sandstone decreases. In the shallower areas, the ratio of limestone to sandstone exceeds one. Adjacent to the Amarillo Uplift and Sierra Grande Arch (fig. 9), thick sections of permeable arkoses of Pennsylvanian and Permian age are present. These rocks are thought to have been derived from erosion of granitic rocks on the uplifts and to extend only a few tens of miles from the uplifts. The arkosic gravel, therefore, is not considered to be an important regional aquifer.

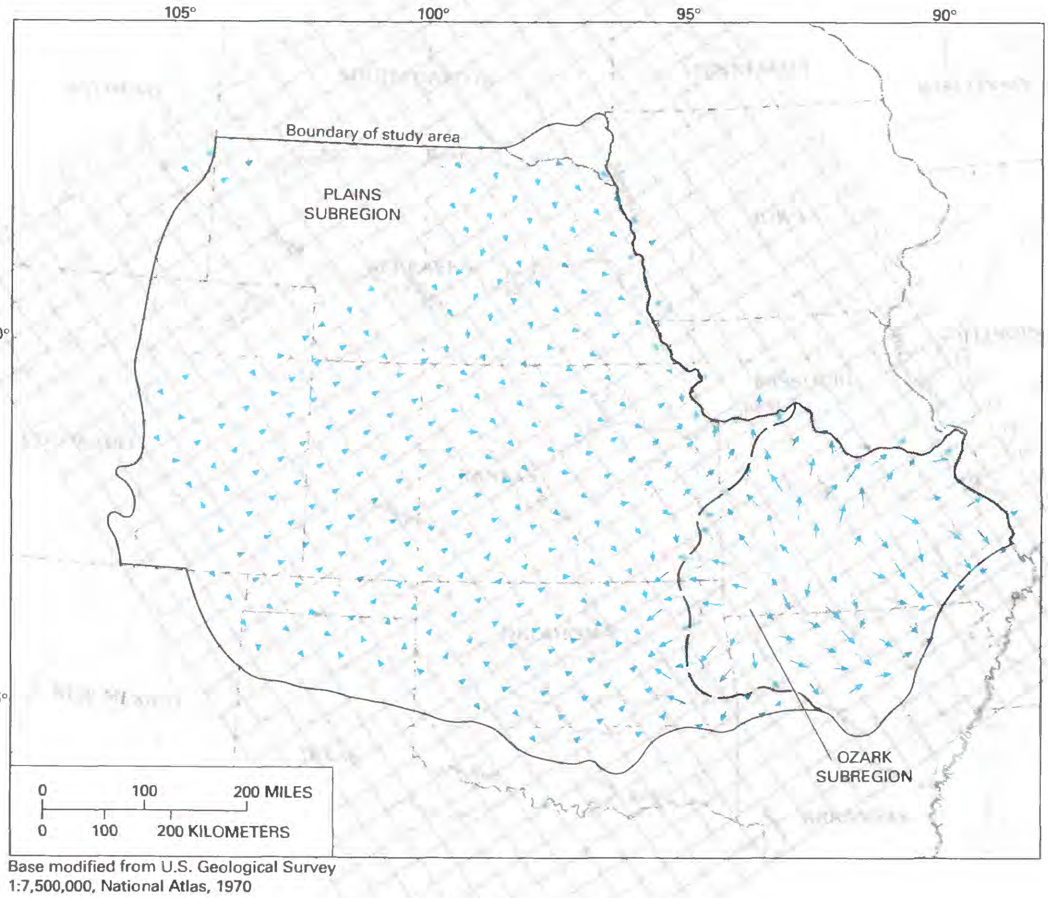


EXPLANATION

→ **LATERAL FLOW VECTOR—Length of shaft indicates relative magnitude**

— — **APPROXIMATE BOUNDARY BETWEEN THE PLAINS AND OZARK SUBREGIONS**

FIGURE 23.—Lateral flow-velocity vectors for model layer 4 representing upper unit in the Western Interior Plains aquifer system and the Springfield Plateau aquifer in the Ozark Plateaus aquifer system.



EXPLANATION

LATERAL FLOW VECTOR—Length of shaft indicates relative magnitude

APPROXIMATE BOUNDARY BETWEEN THE PLAINS AND OZARK SUBREGIONS

FIGURE 24.—Lateral flow-velocity vectors for model layer 5 representing lower units in the Western Interior Plains aquifer system and the combined Ozark aquifer, St. Francois confining unit, and St. Francois aquifer in the Ozark Plateaus aquifer system.

TABLE 2. *Water in storage in geohydrologic units in the CMRASA area*
[Data in millions of acre-feet; --, no data. Total ground water in storage. Drainable water would be less if nonyielding clay layers and specific yield of permeable units are taken into consideration]

State	Geohydrologic unit		
		Western Interior Plains aquifer system	
	Great Plains aquifer system	Upper unit	Lower units
	Plains subregion		
Arkansas	--	--	71
Colorado	1,553	188	223
Kansas	2,717	818	1,631
Missouri	--	29	121
Nebraska	7,035	174	766
New Mexico	54	8	9
South Dakota	190	--	8
Oklahoma	9	625	2,099
Texas	--	137	215
Wyoming	244	51	--
Total	11,802	2,030	5,143

State	Geohydrologic unit			
	Springfield aquifer[1]	Ozark aquifer	St. Francois aquifer	Combined St. Francois-Ozark aquifer[2]
		Ozark subregion[3]		
Arkansas[4]	30	1,775	51	1,825
Arkansas[5]	50	1,113	39	1,152
Kansas	25	127	7	134
Missouri	118	3,329	544	3,873
Oklahoma	45	445	8	454
Total	268	6,789	649	7,438

[1]Regional model layer 4. [2]Regional model layer 5.
[3]Leo F. Emmett, U.S. Geological Survey, written commun., 1987.
[4]Freshwater. [5]Saline water.

Permian-age formations in the Western Interior Plains confining system consist mostly of shale with evaporite deposits, sandstone, and limestone. Formations of Triassic and Jurassic age are mostly shale, sandstone, and limestone.

PROPERTIES

The areal extent and altitude of the top of the confining system are shown in Jorgensen and others (1993, plate 8). The altitude ranges from more than 6,000 ft above sea level in northeastern New Mexico to more than 3,000 ft below sea level in the Denver Basin. In general, the top of the exposed confining system slopes west to east toward a broad physiographic low near the outcrop area adjacent to the western perimeter of the Ozark subregion. The thickness of the confining system (Jorgensen and others, 1993, plate 9) ranges from more than 20,000 ft in the Anadarko Basin to 0 ft in northeastern Nebraska and in the Ozark subregion.

The estimated mean horizontal intrinsic permeability (weighted by thickness of different lithologies) of the confining system ranges from less than $1x10^{-16}$ to about $5x10^{-13}$ ft^2 (fig. 25). The aquifer units in the Western Interior Plains confining system in the deep basins are, in general, more permeable than aquifer units in the underlying Western Interior Plains aquifer system because permeability and porosity generally decrease with depth. However, leakage through the confining system at most locations is very small because the system includes thick layers of shale and extensive layers of nearly impermeable salt and other evaporite deposits that form effective confining units. The extent and thickness of the evaporite deposits is shown in figure 26.

The pressure of pore water in permeable units of the confining system is variable both vertically and horizontally because the units are not contained in a reasonably distinct hydraulic system. Large pore pressures exist in the previously described geopressured

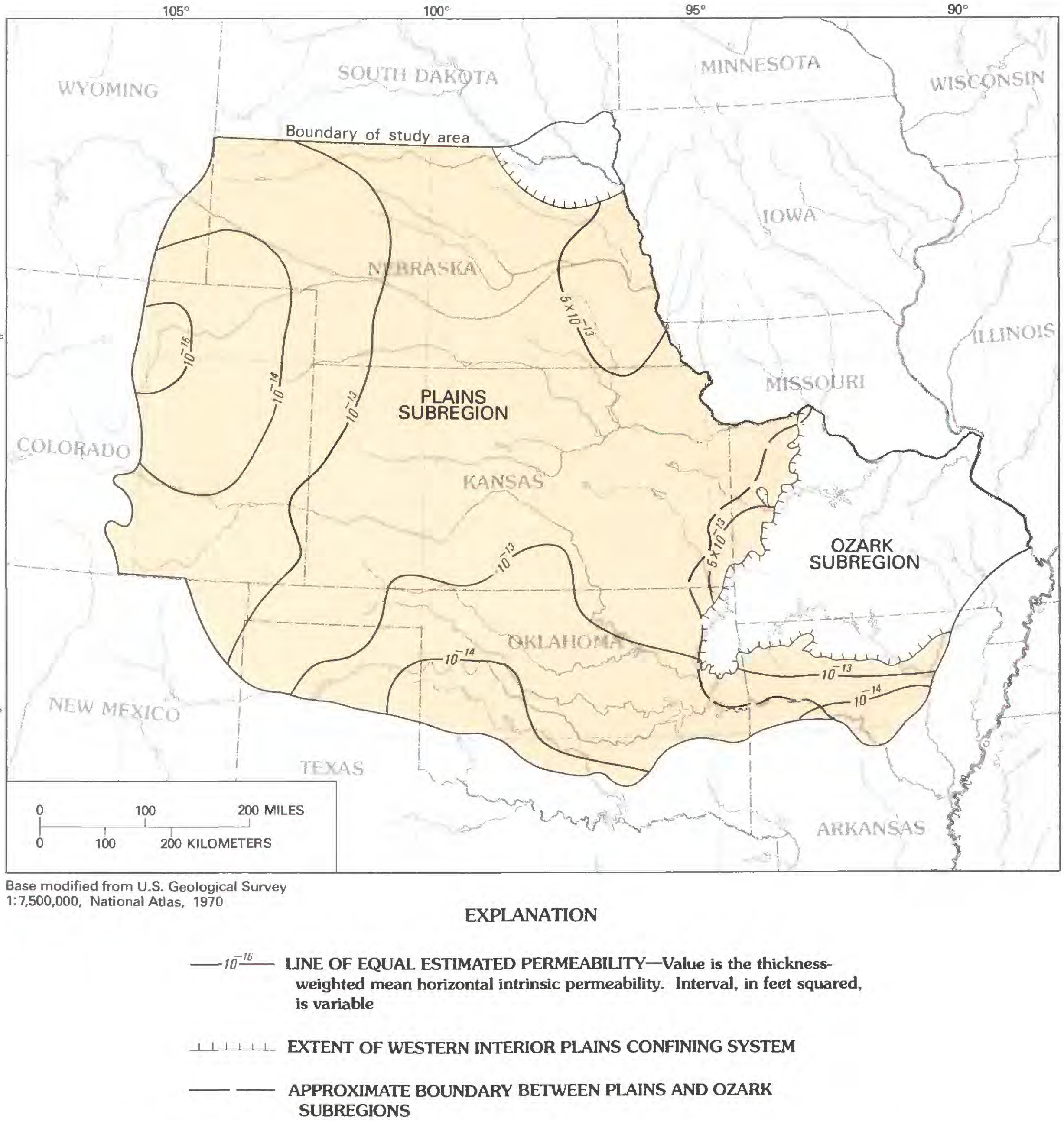
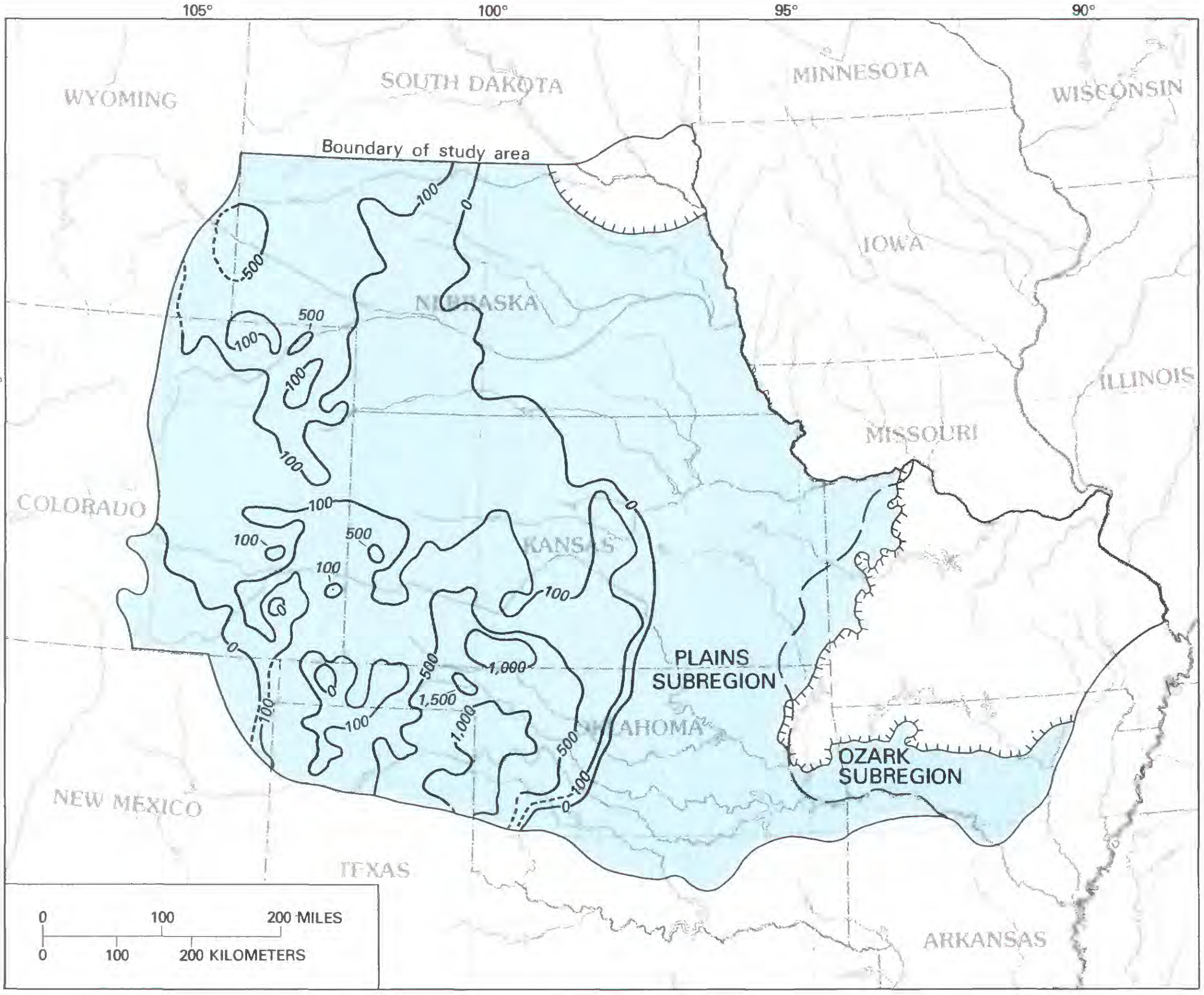


FIGURE 25.—Estimated regional intrinsic permeability of the Western Interior Plains confining system.

zone near the base of the confining system. However, pore pressure measured in drill-stem tests near the centerline of the confining system is below hydrostatic pressure in large areas, including the area over the geopressured zone. This occurrence of both overpressured and underpressured units reflects the confining nature of the system.

USE AND POTENTIAL

At some locations where the aquifer units crop out and, in general, at depths less than 500 ft, water from aquifer units in the Western Interior Plains confining system is fresh and suitable for domestic and other uses (fig. 27). However at other locations large quantities of oil and gas are produced from these same rocks,



Base modified from U.S. Geological Survey 1:7,500,000, National Atlas, 1970

EXPLANATION

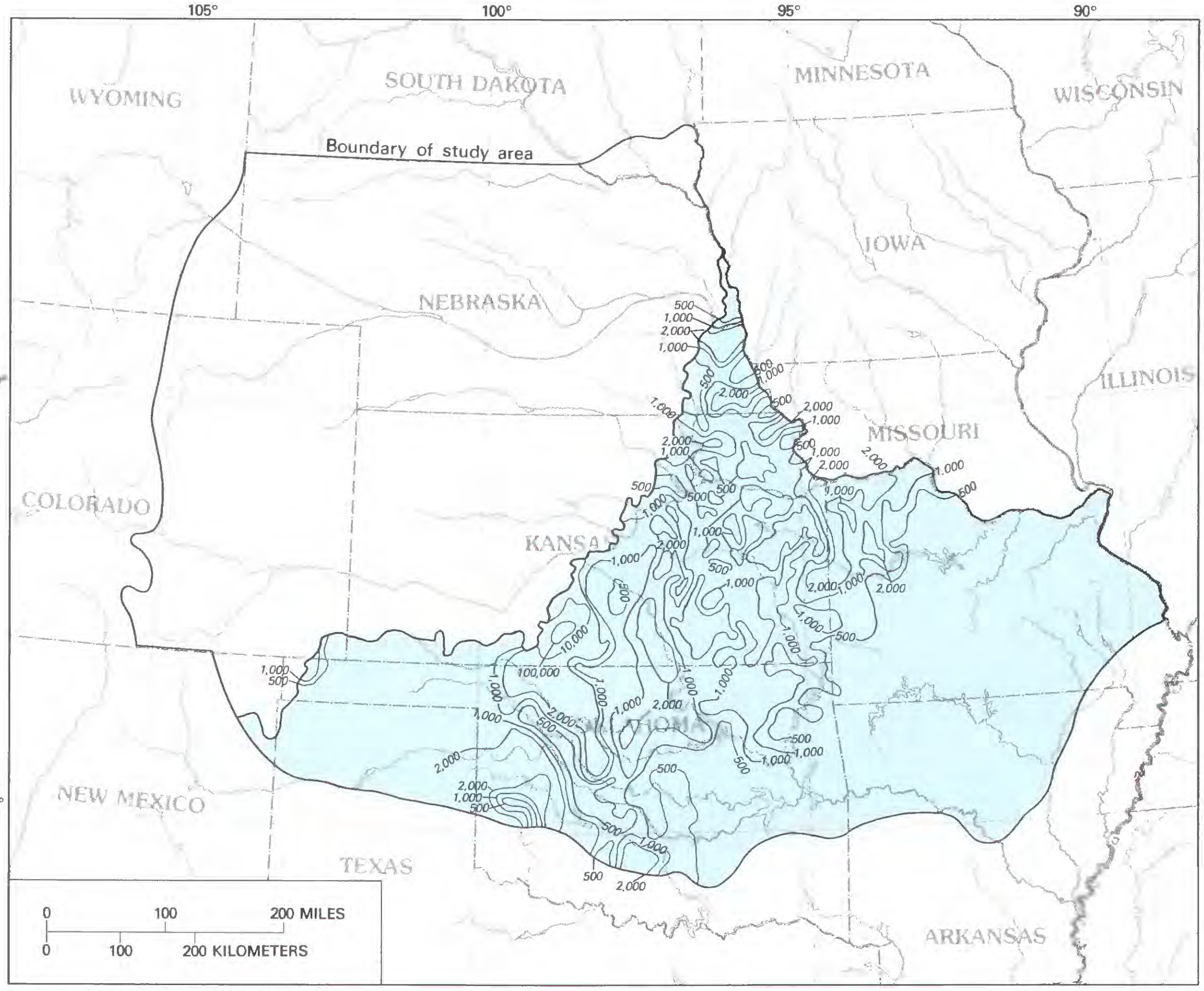
——100——— LINE OF EQUAL THICKNESS OF EVAPORITE DEPOSITS IN THE WESTERN INTERIOR PLAINS CONFINING SYSTEM—Dashed where approximate. Interval, in feet, is variable

LIMIT OF PENNSYLVANIAN ROCKS

— — — APPROXIMATE BOUNDARY BETWEEN PLAINS AND OZARK SUBREGIONS

FIGURE 26.—Thickness of evaporite deposits in the Western Interior Plains confining system.

such as in the Hugoton gas field. Halite beds are a salt resource, and manmade cavities within them are used for storage of natural gas and petroleum products. Because the confining system is thick and the permeability is small, confining units are candidates for storage of wastes or natural gas, petroleum and petroleum products, and saline or freshwater. However, many technical factors would have to be considered in evaluating the potential for storage or for disposal, including whether the candidate units are in a tectonically active area or if the area is adjacent to an area of abnormal pore pressures. There is potential for movement of fluids if the rocks are disturbed by natural causes, such as tectonics, or manmade causes, such as drilling and pressure injection of fluids.



Base modified from U.S. Geological Survey
1:7,500,000, National Atlas, 1970

EXPLANATION

——1,000—— **LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION FROM DEPTHS LESS THAN 500 FEET–Dashed where approximate. Interval, in milligrams per liter, is variable**

FIGURE 27.—Dissolved-solids concentrations in water from rocks older than those of the Great Plains aquifer system at depths less than 500 feet.

GREAT PLAINS AQUIFER SYSTEM

GEOHYDROLOGIC UNITS

The Great Plains aquifer system consists of two regional aquifers in the same hydraulic system separated in much of the area by a regional confining unit. The aquifers are found in regional water-bearing sandstone and other rocks, nearly all of which are of Early Cretaceous age. The Great Plains aquifer system is one of the most widespread in North America (Helgesen and others, 1982), extending from near the Arctic Circle in Canada to New Mexico (fig. 28).

The term Great Plains was chosen because, generally, the aquifer system is present at most locations in the Great Plains of North America. The Great Plains aquifer system includes the Apishapa (lower aquifer), the Maha (upper aquifer), and the intervening Apishapa confining unit (fig. 29). The altitude of the top of the Great Plains aquifer system (Helgesen and others, 1993, plate 4) ranges from more than 6,000 ft above sea level in northeastern New Mexico, a recharge area, to less than 1,000 ft above sea level in southeastern South Dakota, a discharge area, and to more than 4,000 ft below sea level in the Denver Basin.

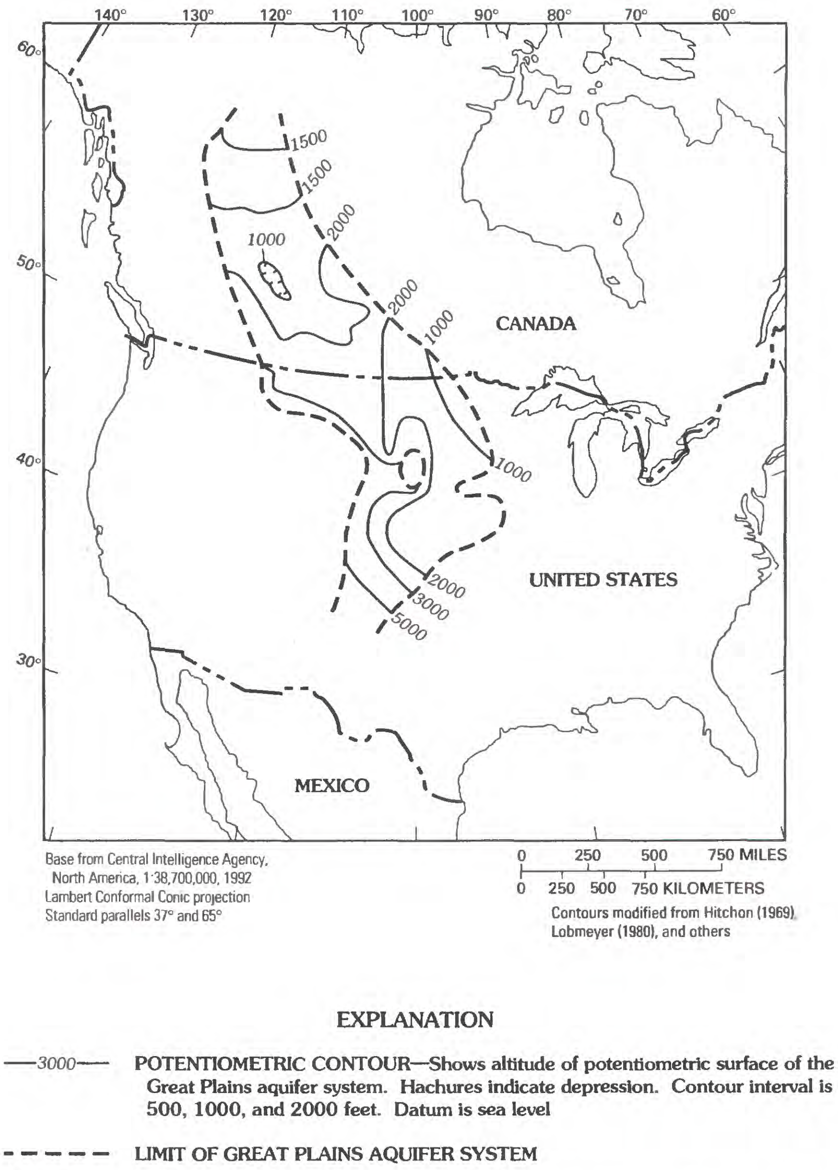


FIGURE 28.—Potentiometric surface and extent of the Great Plains aquifer system in North America (modified from Helgesen and others, 1982).

The correlation of aquifers to principal formations is shown in table 1. The two aquifers have been termed the "Dakota aquifer" or the "Dakota aquifer system" by various investigators. Others have restricted the term "Dakota aquifer" to either the upper (Maha) aquifer or the lower (Apishapa) aquifer. The name Dakota also has been used as a name for lithostratigraphic units as the Dakota Sandstone, the Dakota Formation, and the Dakota Group. The controversy as to correlation and terminology has been termed aptly the "Dakota controversy." Nearly all the items of the controversy relate to correlation of lithologic units and not to hydrology. The correlation of stratigraphic units and their correspondence with geohydrologic units is shown in Helgesen and others (1993, fig. 11).

The potentiometric surface of the Maha aquifer (fig. 30) probably is related closely to heads in the Apishapa aquifer because of leakage through the Apishapa confining unit. However, there may be considerable head difference in some areas. For example, in central South Dakota, just north of the CMRASA study area, a significant head difference exists between the two aquifers. The major recharge to the aquifer system in the study area is in southeastern Colorado and northeastern New Mexico (fig. 30). Most ground

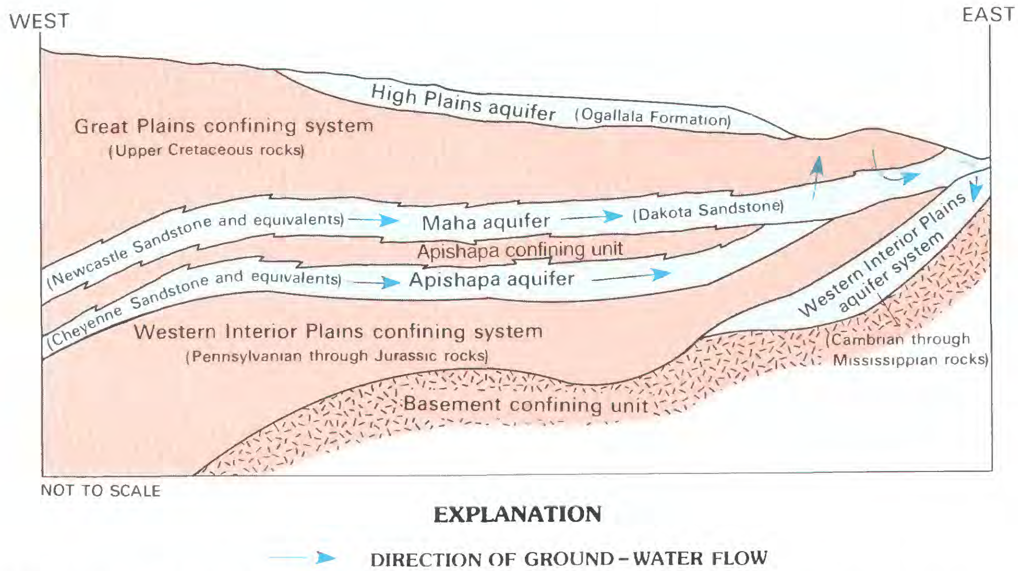


FIGURE 29.—Maha and Apishapa aquifers, Great Plains aquifer system. Section extends across Nebraska from the intersection of North Platte River and Wyoming-Nebraska boundary on the west to Missouri River at northernmost extent of Nebraska-Iowa boundary on the east.

water flows from the major recharge area east-northeast toward the eastern edge of the aquifer system in Kansas and eastern Nebraska. Near the southern and eastern extent of the aquifer system, the aquifers are close to land surface, and local recharge occurs (fig. 29).

At most locations, the Apishapa aquifer is composed of permeable, partially cemented, medium- to very fine-grained sandstone of the Cheyenne Sandstone and equivalents, such as the Fall River and Lakota Sandstones. The name Apishapa refers to water-bearing sandstones that crop out in the major recharge area in the vicinity of the Apishapa River and adjacent areas in southeastern Colorado, northeastern New Mexico, and southwestern Kansas.

The Apishapa confining unit separates and restricts water flow between the Apishapa aquifer and the overlying Maha aquifer at most locations. The confining unit is composed of slightly permeable shale layers, which at most locations consist of the Kiowa Shale and the equivalent Skull Creek Shale.

The Maha aquifer, which is the upper regional aquifer unit of the Great Plains aquifer system, is more extensive areally than the underlying Apishapa aquifer (fig. 29). The Maha aquifer at most locations consists of water-bearing, permeable, partially cemented, medium- to fine-grained sandstone of the Dakota Sandstone and equivalents, such as the Newcastle Sandstone and the "D" and "J" sandstone of informal usage. The aquifer was named from exposures of the water-yielding sandstone along bluffs of the Missouri River between Blair and Ponca, Nebraska. This is the location of the Maha (Omaha) Indians as reported by Lewis and Clark.

PROPERTIES

The altitude of the top of the Great Plains aquifer system is shown in Helgesen and others (1993, plate 4). The aquifer system is 200 to 800 ft thick throughout most of the area (fig. 31). The Apishapa aquifer is typically between 100 and 200 ft thick (Helgesen and others, 1993, plate 1). The Apishapa confining unit is generally less than 100 ft thick (Helgesen and others 1993, plate 2) and, similar to the Apishapa aquifer, is not as extensive as the overlying Maha aquifer. The Maha aquifer is the thickest and most areally extensive unit of the Great Plains aquifer system. Thickness of the Maha ranges from less than 100 ft in eastern Colorado to about 600 ft in northeastern Nebraska (Helgesen and others, plate 3). The maximum thickness exceeds 900 ft in two small areas in central Nebraska.

Permeability of both aquifers is mostly primary, except possibly in the Denver Basin, because the aquifers consist mostly of slightly cemented sandstone. Figure 32 shows the estimated thickness-weighted mean horizontal intrinsic permeability of the Great Plains aquifer system. Permeability generally decreases with depth, being greatest (10^{-10} ft^2) in the eastern part of the aquifer system and least (10^{-13} ft^2) in the Denver Basin.

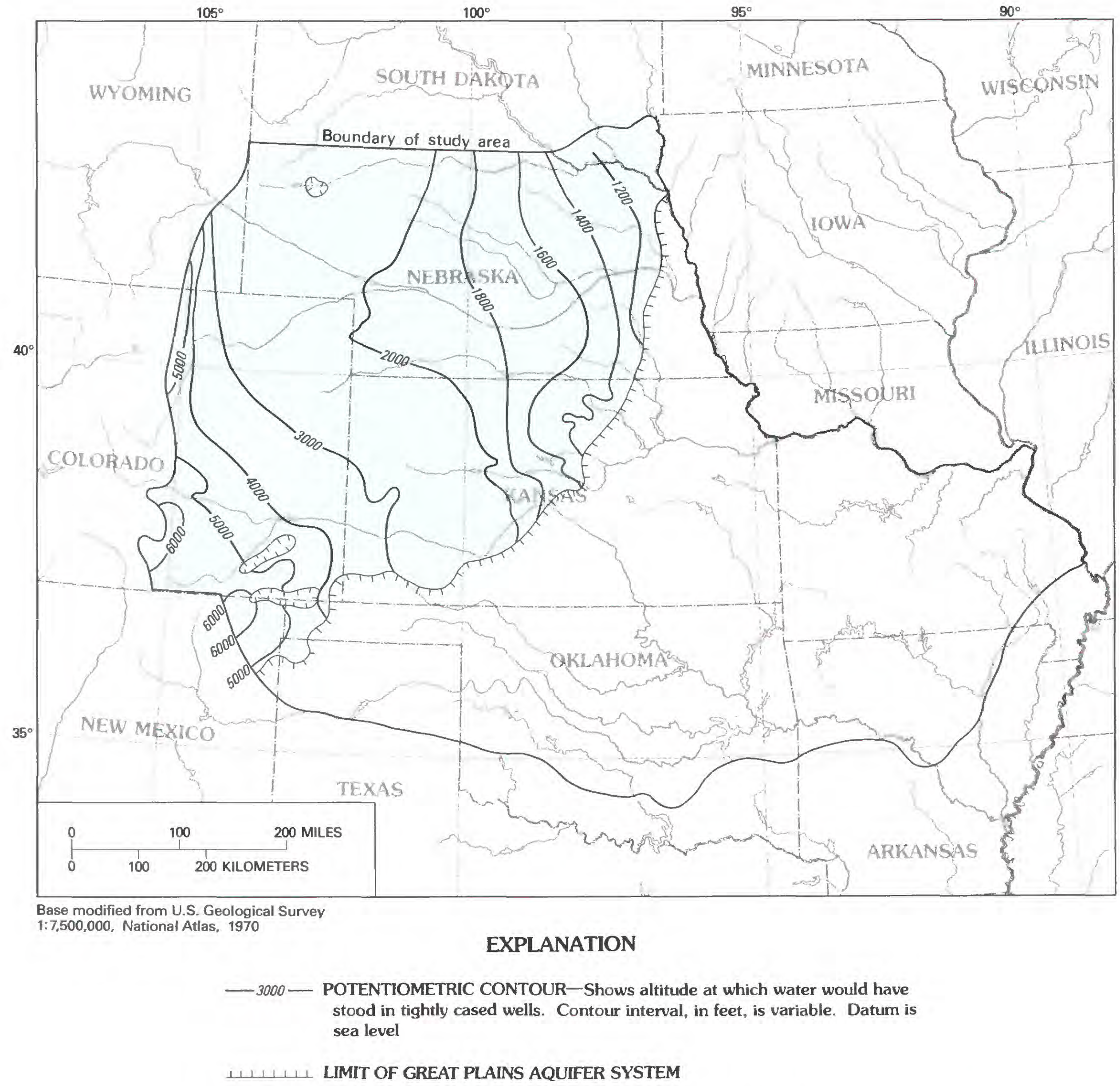


FIGURE 30.—Predevelopment potentiometric surface of the Maha aquifer, Great Plains aquifer system.

MODEL ANALYSIS AND HYDROLOGIC BUDGET

A computer model was used to test the conceptualization of flow in the Great Plains aquifer system, to improve definition of the hydrologic budget of the aquifer system, and to evaluate the aquifer system for potential use. The finite-difference ground-water flow model of McDonald and Harbaugh (1984) was chosen as being applicable to the Great Plains aquifer system with minor qualifications.

Horizontally, discretization is in the form of a uniform grid consisting of 46 rows and 35 columns (Helgesen and others, 1993). Each cell is 14 mi x 14 mi horizontally, for a grid density four times that of the regional CMRASA model. The model-grid orientation was North 35 ° West and North 55 ° East. This orientation approximately parallels the major bedrock joint patterns in the midcontinent region, and the orientation coincides with that of the regional model used for the entire CMRASA study area.

The system is discretized vertically into four model layers that generally correspond to the principal geohydrologic units. Layer 1 represents the Great Plains confining system in most places, or where it is not

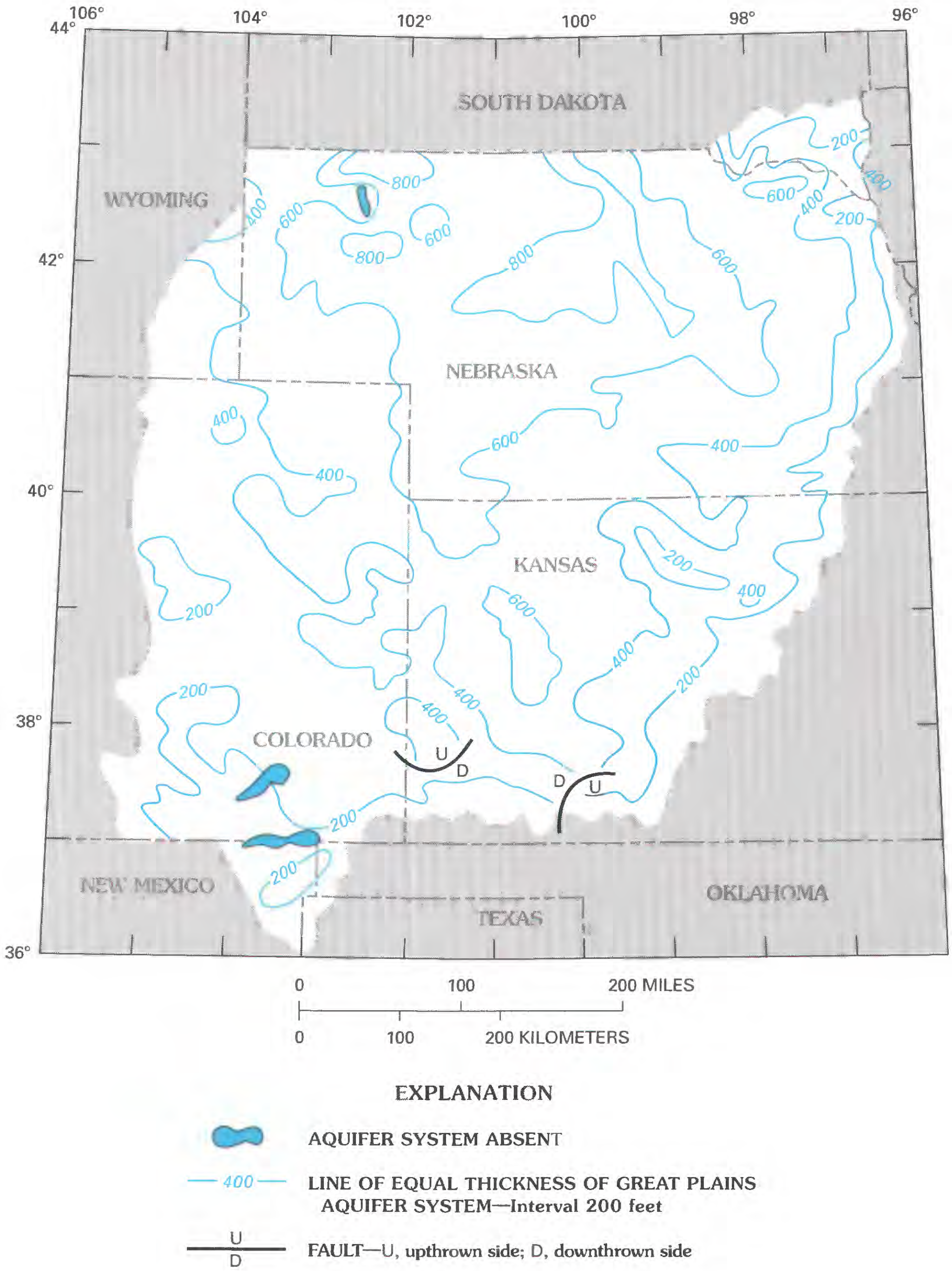
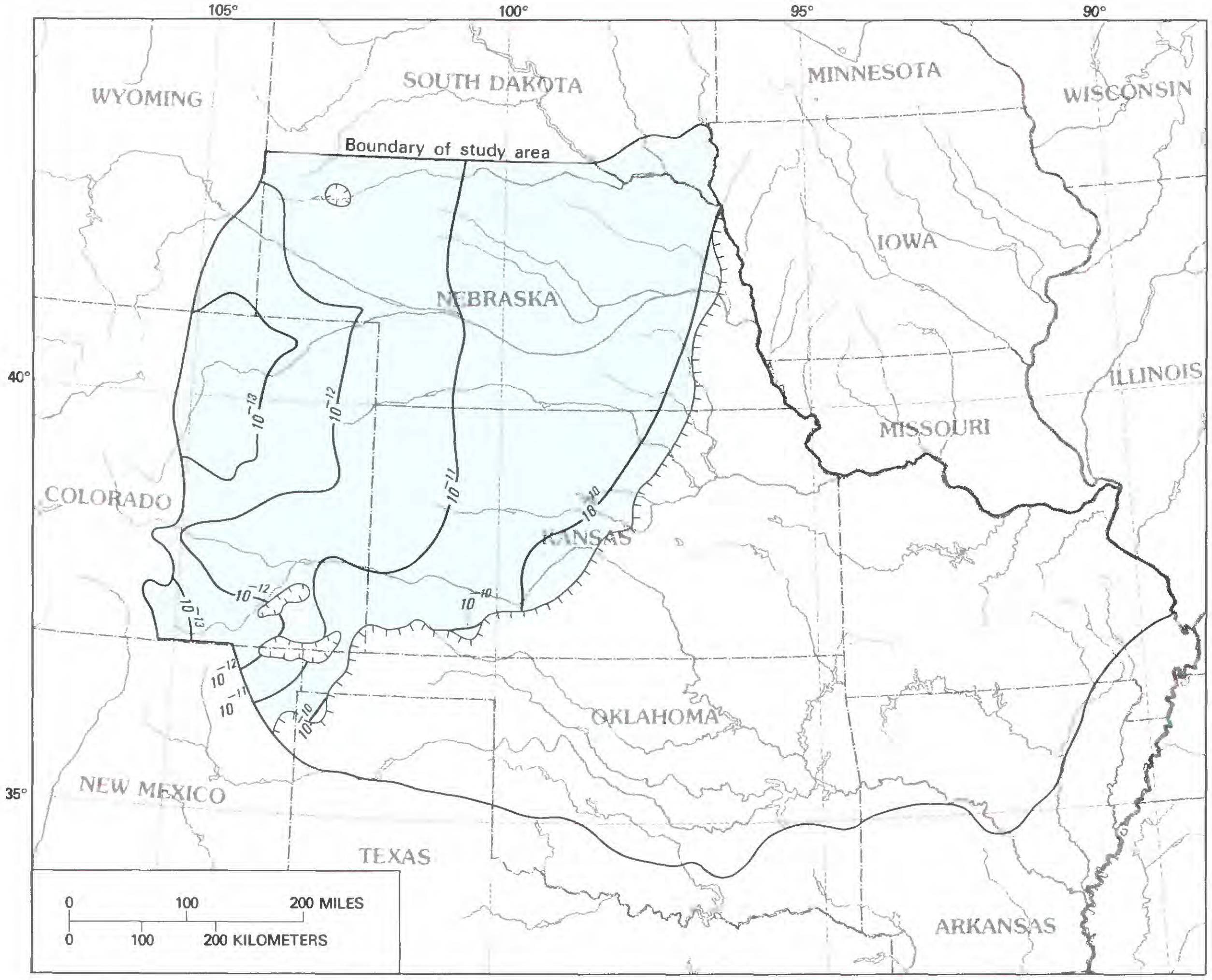


FIGURE 31.—Thickness of Great Plains aquifer system.

present, the layer represents the High Plains aquifer or unnamed Quaternary deposits, whichever directly overlies the Maha aquifer. Layers 2 and 3 represent the Maha and Apishapa aquifers, respectively. (The Apishapa confining unit, which separates the two aquifers, is not represented by a model layer.) Layer 4 represents the next 150 ft of strata beneath the Great Plains aquifer system, which is equivalent to the top part of the Western Interior Plains confining system in most of the area. In the northeastern part of the CMRASA study area, the Western Interior Plains confining system is absent, and layer 4 there represents the Western Interior Plains aquifer system. Farther northeast, the basement confining unit forms the lower boundary of the Great Plains aquifer system.



Base modified from U.S. Geological Survey 1:7,500,000, National Atlas, 1970

EXPLANATION

—— 10^{-13} —— **LINE OF EQUAL ESTIMATED PERMEABILITY—Value is the thickness-weighted mean horizontal intrinsic permeability. Interval, in feet squared, is variable**

⊥⊥⊥⊥⊥⊥⊥ **LIMIT OF GREAT PLAINS AQUIFER SYSTEM**

FIGURE 32.—Estimated regional intrinsic permeability of the Great Plains aquifer system.

Thickness values used in model calculations were based on the maps shown in Helgesen and others (1993, plates 1–3). Permeability values for layers 1 and 4 were assigned as fractions of the permeability of layer 2 (fig. 32). These fractions were applied uniformly within layers 1 and 4. Because the permeability of layer 2 is a function of depth, the permeability of layers 1 and 4 also were simulated as functions of depth.

Leakance values (effective vertical hydraulic conductivity divided by thickness) were determined by making effective vertical hydraulic conductivity a function of depth and a ratio of horizontal-to-vertical hydraulic conductivity. Where confined conditions prevail, storage coefficient was set equal to the product of estimated specific storage times thickness. To represent unconfined conditions, storage coefficient (specific yield) was set equal to 0.15.

Calibration of the model primarily entailed an effort to satisfactorily simulate flow in the aquifer system under natural predevelopment conditions. Inadequate information exists, however, to accurately define predevelopment conditions. Therefore, these conditions were surmised from field or estimated head data.

Calibration of the model to predevelopment conditions resulted in a steady-state head distribution that is in general agreement with the field or estimated predevelopment head distribution (fig. 33). Regionally, deviations in head were mostly within a contour interval of the predevelopment-head map. Areas of positive and negative deviations from field or estimated heads were somewhat irregularly distributed regionally.

The predevelopment, steady-state flow rate through the aquifer system was simulated as 342 ft^3/s, most of which is vertical leakage to or from adjacent units rather than lateral flow from or to outcrop areas. The distribution of rates of vertical interchange per grid cell between the Maha aquifer and the overlying units (fig. 34), shows a decrease of several orders of magnitude westward into the Denver Basin. Direction of the simulated vertical flow is everywhere downward into the aquifer system except along the eastern and southern edges. Vertical interchange at locations where the Great Plains aquifer system directly underlies the High Plains aquifer or the Missouri River alluvium constitutes about 60 percent of the simulated water budget. If recharge or discharge at outcrop areas is considered also, that proportion increases to more than 70 percent. Rates of simulated downward or upward flow at some individual grid cells (196 mi^2) exceeded 10 ft^3/s where direct connection with the High Plains aquifer or Missouri River alluvium exists. Simulated vertical interchange rates in the deepest part of the Denver Basin were less than 0.001 ft^3/s per grid cell.

Simulated vertical interchange between the Great Plains aquifer system and underlying units (fig. 35) was very small over most of the area, exceeding 0.1 ft^3/s per grid cell only along the eastern and southern edges. A general westward decrease in vertical flow rate per cell is again evident. Direction of the simulated vertical interchange is of interest and appears to be reasonable hydrologically. The predominantly upward flow along the Missouri River Valley is reasonable as simulated. Upward leakage has been cited by Schoon (1971) to explain calcium sulfate water in the aquifer system in southeastern South Dakota. Significant upward flow to the aquifer system is simulated in central Kansas. This upward flow occurs just west of the evaporite subcrop area, where flow may be diverted upward by these rocks of very slight permeability.

A simulation of transient conditions in the system was made for 1940–79 by adding fluid withdrawals to the predevelopment conditions defined by the model. Simulated withdrawal rates, by county and decade, were used to assign rates to cells corresponding with areas of development. All pumpage of oil, gas, and saline water, which is largely in the Denver Basin, was assigned to the Maha aquifer. Freshwater pumpage, which is largely near the outcrop in southwestern Kansas and associated with irrigation, was assigned to the Maha or Apishapa aquifers as appropriate. The simulation consisted of four 10-year periods with output recorded at the end of each period.

Simulated response to withdrawals of oil, gas, and saline water indicated cumulative head declines of 500 ft or more in the area of most intense development by the end of the 40-year period (fig. 36). Magnitude and extent of the simulated head declines generally resemble the differences between inferred predevelopment heads and current heads. Simulated head declines in response to freshwater pumpage are tens of feet, and exceed 100 ft locally, in parts of southern Colorado, southwestern Kansas, eastern Nebraska, and southeastern South Dakota (fig. 36). The observed and simulated water-level declines at selected locations are shown in figure 37.

Sensitivity of the model to changes in several variables was tested for the Great Plains aquifer-system model. Simulated hydraulic-head differences were most sensitive to changes in hydraulic conductivity and direct recharge to the aquifer in outcrop areas. Simulated discharge to streams was most sensitive to changes in hydraulic conductivity.

USE AND POTENTIAL

The diverse character of the Great Plains aquifer system makes it suitable for a wide range of uses. Resources of the aquifer system that have been developed are (1) oil and natural gas; (2) freshwater for irrigation, municipal, industrial, domestic, stock, or other purposes; and (3) saline water produced mainly in association with oil, much of which is reinjected to maintain reservoir pressure (secondary-recovery procedures).

Assessment of the oil and gas resources is not within the scope of this study. Other uses are addressed herein based on the current understanding of the regional hydrology. This assessment cannot incorporate the local variations in geohydrologic conditions that need to be considered.

The total amount of water stored in the Great Plains aquifer system is nearly 12 billion acre-ft (table 2). However, about half of that amount is stored in confining-unit material. Assuming specific yield is half of porosity, approximately 3 billion acre-ft is in drainable storage. More than half of the water in storage is in Nebraska.

EXPLANATION

— 1800 — **POTENTIOMETRIC CONTOUR—Shows altitude of approximate predevelopment potentiometric surface, based on field or estimated data. Interval, in feet of head, is variable. Datum is sea level**

- - 1800 - - **SIMULATED POTENTIOMETRIC CONTOUR—Shows model-calculated altitude of predevelopment potentiometric surface. Interval, in feet of head, is variable. Datum is sea level**

LIMIT OF MAHA AQUIFER WITHIN STUDY AREA—Screened toward aquifer

FIGURE 33.—Comparison of field or estimated and simulated predevelopment hydraulic-head distributions for Maha aquifer.

EXPLANATION

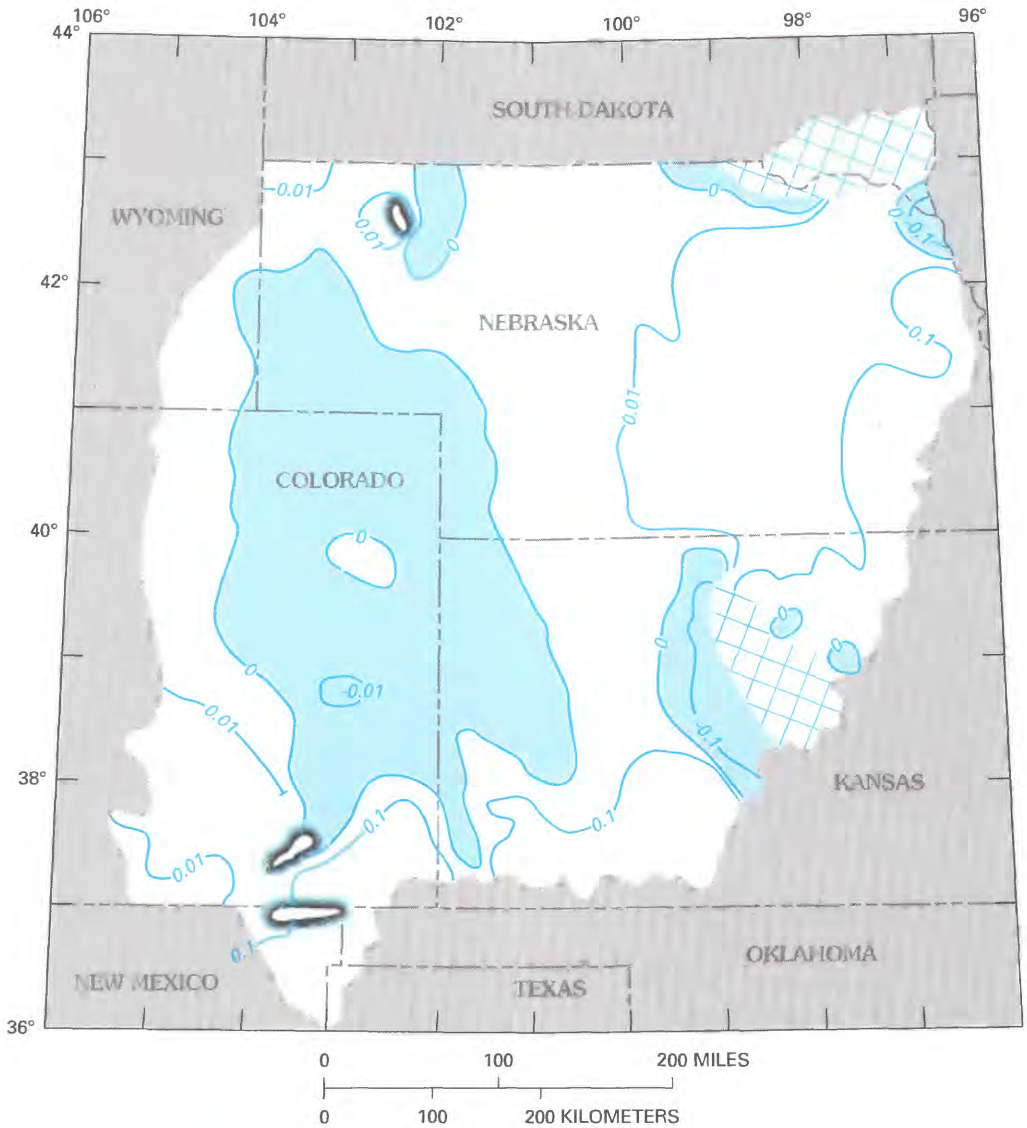
AREA OF SIMULATED UPWARD DISCHARGE

OUTCROP AREA OF MAHA AQUIFER

— 0.1 — LINE OF EQUAL SIMULATED VERTICAL VOLUMETRIC FLOW PER MODEL CELL TO OR FROM OVERLYING LAYER—Negative value denotes upward discharge. Interval, in cubic feet per second, is variable

LIMIT OF MAHA AQUIFER WITHIN STUDY AREA—Screened toward aquifer

FIGURE 34.—Simulated vertical volumetric flow between Maha aquifer and overlying units.



EXPLANATION

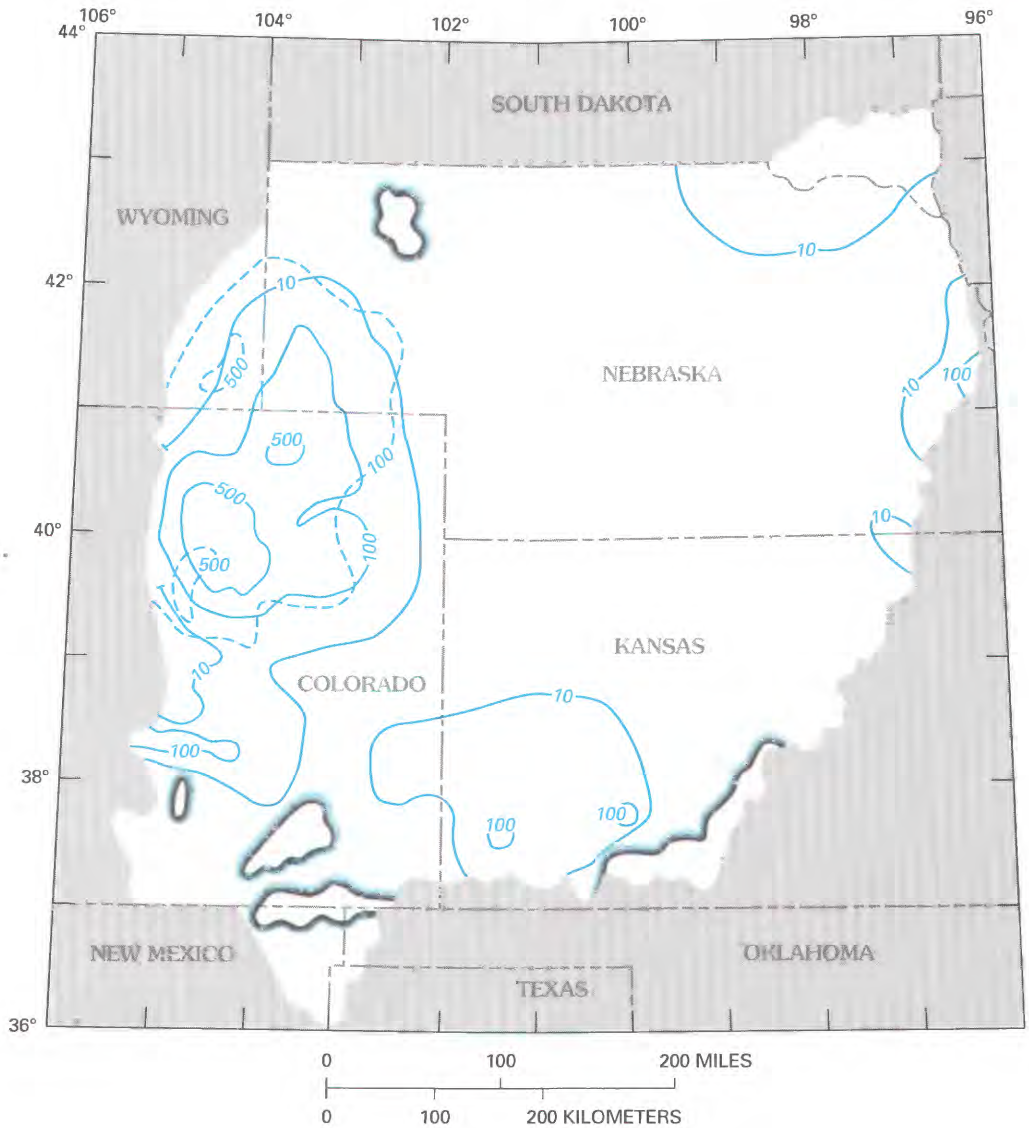
AREA OF SIMULATED UPWARD FROM UNDERLYING ROCK UNIT TO GREAT PLAINS AQUIFER SYSTEM

AREA OF ZERO SIMULATED VERTICAL VOLUMETRIC FLOW—In areas where the Great Plains aquifer system is directly underlain by basement confining unit (in northeastern part of the study area) or by evaporite deposits (in central Kansas)

— 0.1 — LINE OF EQUAL SIMULATED VERTICAL VOLUMETRIC FLOW PER MODEL CELL TO OR FROM OVERLYING LAYER—Negative value indicates upward flow from underlying layer. Interval, in cubic feet per second, is variable

LIMIT OF AQUIFER SYSTEM WITHIN STUDY AREA—Screened toward aquifer

FIGURE 35.—Simulated vertical volumetric flow between the Great Plains aquifer system and underlying units.



EXPLANATION

—100— LINE OF EQUAL SIMULATED HEAD DECLINE, 1940-79—Interval, in feet of head, is variable

-- 100 -- LINE OF EQUAL HEAD DECLINE IN DENVER BASIN, AS ESTIMATED FROM INFERRED PREDEVELOPMENT CONDITIONS—Interval, in feet of head, is variable

LIMIT OF MAHA AQUIFER WITHIN STUDY AREA—Screened toward aquifer

FIGURE 36.—Inferred hydraulic-head declines in Denver Basin and simulated hydraulic-head declines in response to development of Great Plains aquifer system.

Long-term water-yielding capability relates to the response of the system and to what degree it can adjust to sustain newly imposed rates of withdrawal. Withdrawals imposed on the natural system affect the system's storage, recharge, and discharge, depending on rates and location of the withdrawals.

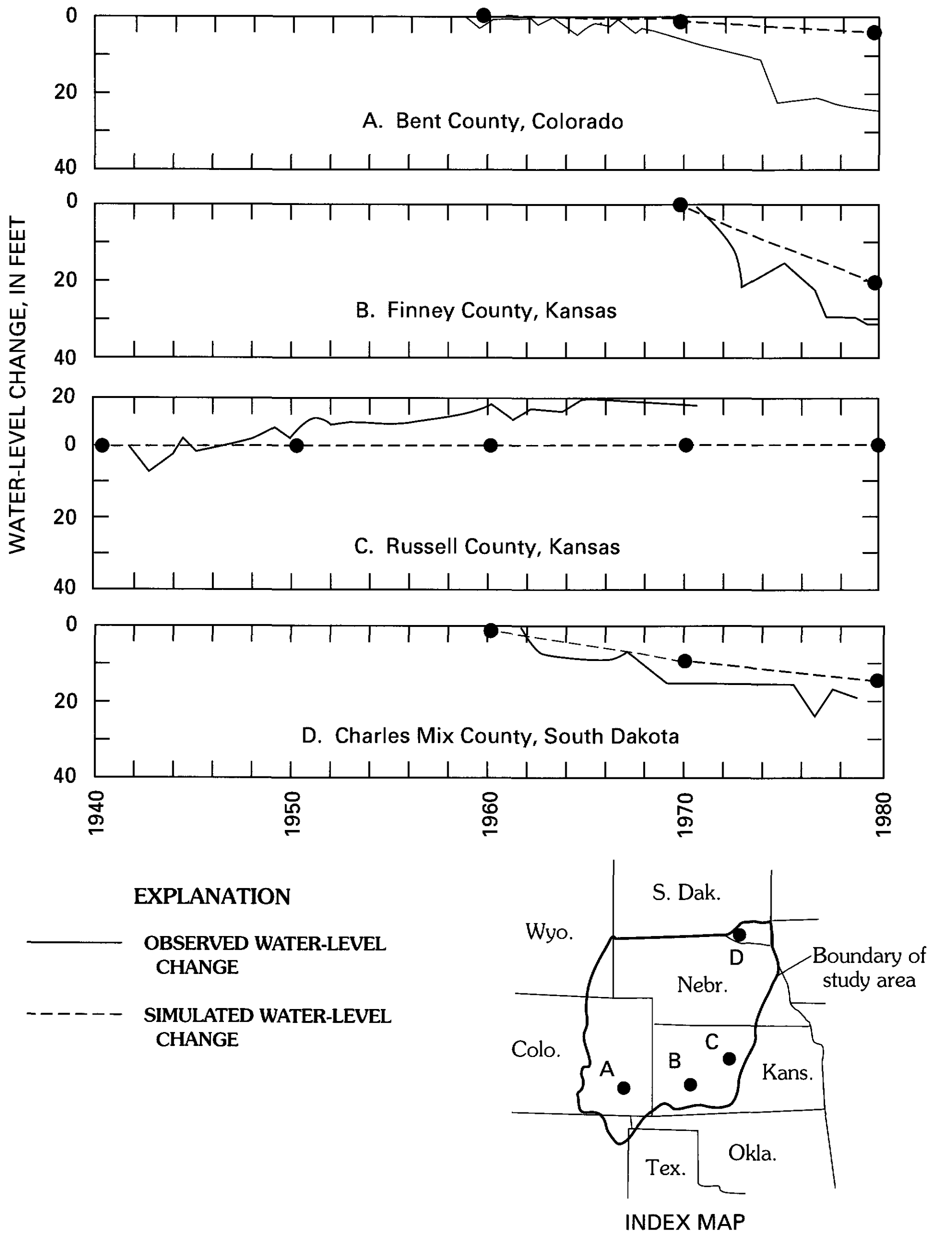


FIGURE 37.—Observed and simulated water-level changes at selected locations in Great Plains aquifer system.

Considering only the Great Plains aquifer system itself, withdrawals from the system may do one or more of the following:

1. Intercept water that would have discharged upward to overlying units;
2. Intercept water that would have discharged downward to underlying units;
3. Intercept water that would have discharged to streams or to evapotranspiration in aquifer-system outcrop areas;
4. Remove water from aquifer-system storage.

Withdrawals also may induce flow from sources of water in hydraulic connection with the aquifer system. These sources are (1) the High Plains aquifer, (2) other adjacent units, and (3) streams in aquifer- system outcrop areas.

Evaluation of the water budget and its changes through the simulation of 1940–79 conditions allows quantification of effects on the recharge, discharge, and storage components of the budget (fig. 38). (Oil and gas withdrawals are a very small part of total

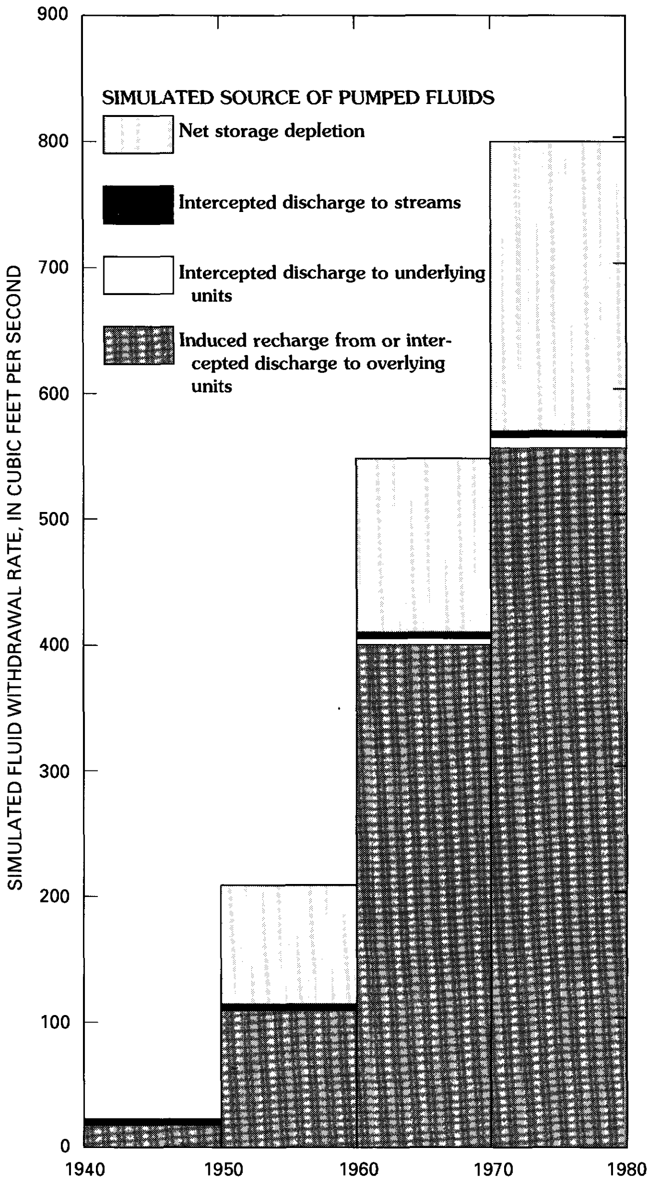


FIGURE 38.—Simulated changes in recharge, discharge, and storage in response to 1940–79 pumpage from Great Plains aquifer system.

withdrawals). Note that the 1970–79 rate of withdrawal was about 800 ft^3/s, which greatly exceeded the predevelopment recharge rate of 340 ft^3/s. The simulated source of pumped fluids was mostly induced recharge from or intercepted discharge to overlying units. Nearly one-third of the withdrawal is derived from storage depletion. Large-scale withdrawals from the Great Plains aquifer system would be accompanied by severe depletion of storage because of the limited natural recharge (Helgesen and others, 1993).

Some parts of the Great Plains aquifer system possess hydrologic characteristics potentially favorable for accepting liquid wastes. Successful and safe subsurface disposal of liquid wastes requires an aquifer with porosity and hydraulic conductivity sufficient to accept the wastes, and hydrogeologic conditions that would prevent movement of the wastes into areas where water quality is suitable for development.

Capability for accepting wastes as affected by hydraulic properties generally decreases with increases in depth of burial. As shown by extensive injection of oil-field brine, the strata commonly are capable of accepting waste, despite relatively large depths of burial. Garbarini and Veal (1968) identified the southern flank of the Denver Basin as potentially suitable for waste disposal at depths exceeding 1,000 ft. As discussed earlier, flow approaches stagnation in most of the Denver Basin, a favorable characteristic for waste disposal. Presuming that flow of solutes would be principally advective (that is, with the flow of water), flow velocities of the waste would be equally slow. The overlying confining system would restrict flow upward from the aquifer system, although its integrity may be reduced by improperly abandoned wells. A large downward hydraulic-head gradient prevails in most of the area, which creates favorable potential to keep the injected wastes in the aquifer system in the Denver Basin.

GREAT PLAINS CONFINING SYSTEM AND RELATED HYDROLOGIC UNITS

The Great Plains aquifer system is directly overlain by the Great Plains confining system in most places (fig. 39). The Great Plains confining system is as much as 8,000 ft thick (fig. 40). The confining units within this system are composed of shale, which include the Upper Cretaceous Graneros, Carlile, and Pierre Shales, and slightly permeable Tertiary clay and silt. The confining system also includes two extensive but minor aquifers. These aquifers are in the Greenhorn Limestone and the Niobrara Chalk. The confining system, at most locations, effectively restricts flow to and from the Great Plains aquifer system and the surficial High Plains aquifer if present, or to and from the water table in the soil zone.

The High Plains aquifer (fig. 2) mainly consists of permeable sand and gravel deposits of Tertiary and Quaternary age (Gutentag and others, 1984). Where present, its character permits hydraulic connection with adjacent units.

The glacial drift, which is mostly a till, consists of heterogeneous clay, silt, sand, and gravel and has a

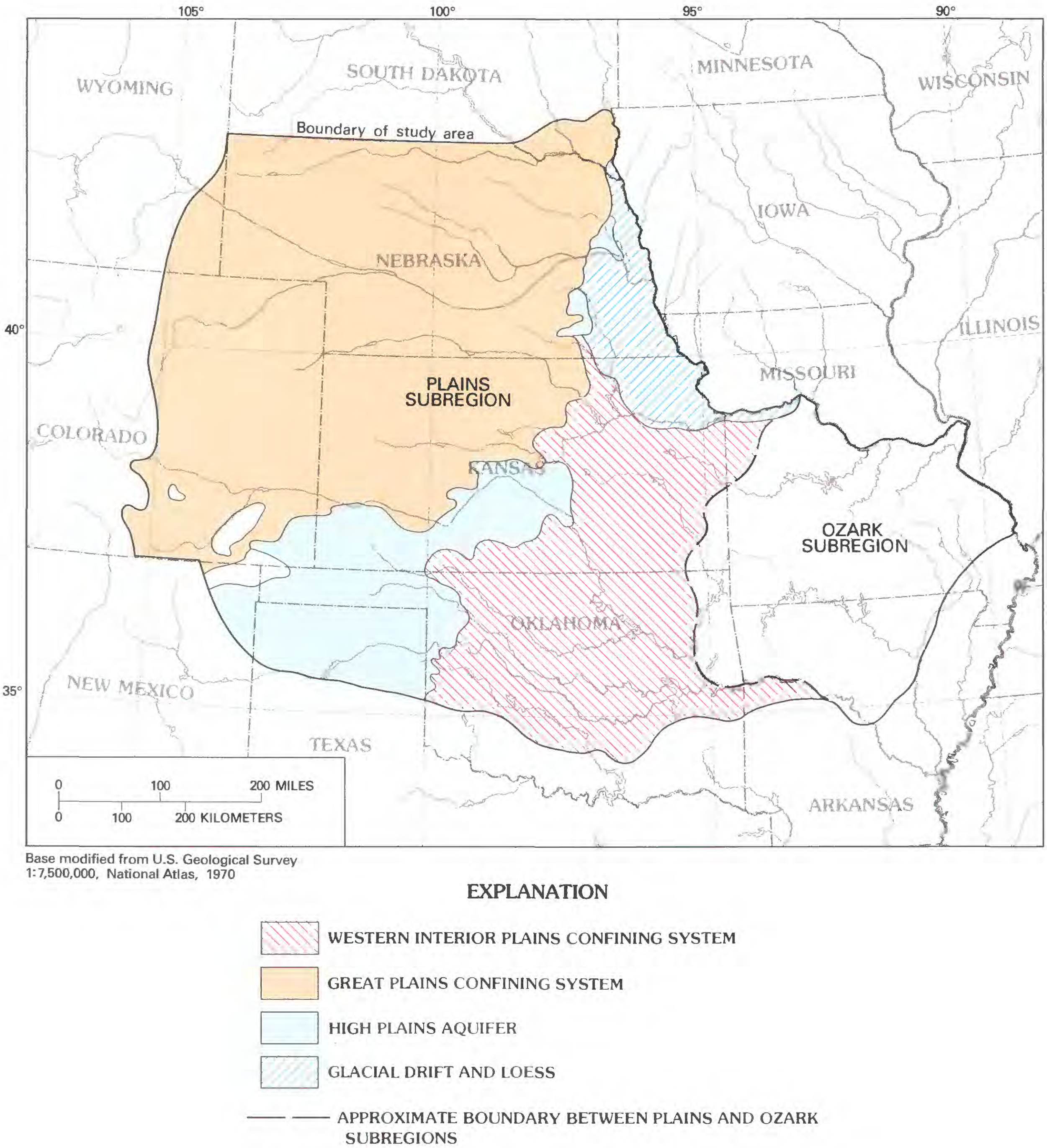
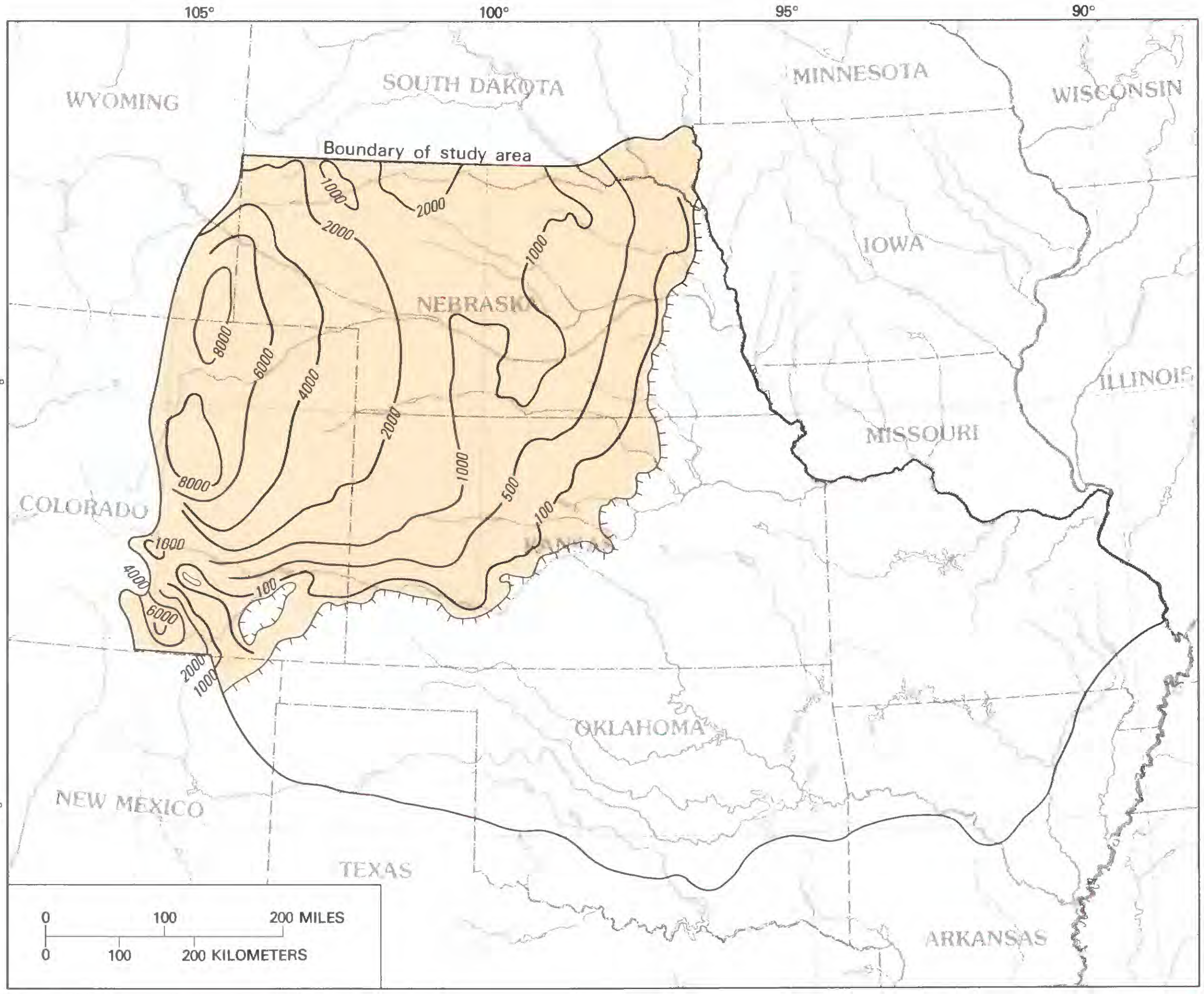


FIGURE 39.—Geohydrologic units overlying regional aquifer systems in the Plains subregion.

variable hydraulic character. Loess, which consists of uniform silt-size material, overlies the Great Plains aquifer system and the Western Interior Plains confining system at different locations and has moderate vertical permeability. The glacial drift and loess probably are a leaky confining system for the underlying aquifer units (fig. 39).

OZARK SUBREGION

The Ozark subregion (fig. 41) corresponds to the Ozark Plateaus physiographic province and the Ouachita physiographic province north of the Arkansas River. The subregion is bounded by the Missouri River, the Mississippi River, the Mississippi Alluvial Plain, the Arkansas River, and the broad and very



Base modified from U.S. Geological Survey 1:7,500,000, National Atlas, 1970

EXPLANATION

—2000— LINE OF EQUAL THICKNESS OF GREAT PLAINS CONFINING SYSTEM—Interval, in feet, is variable

LIMIT OF GREAT PLAINS CONFINING SYSTEM

FIGURE 40.—Thickness of Great Plains confining system.

gentle regional topographic low extending from northeastern Oklahoma to the Missouri River in central Missouri.

Ground-water flow is, in general, regionally outward from a topographic high along an axis from the St. Francois Mountains in southeastern Missouri to the tristate corner of Missouri, Arkansas, and Oklahoma. Locally, flow generally is toward the deep stream valleys. Flow in the three regional aquifers of the Ozark Plateaus aquifer system (table 3) also is outward from a topographic ridge of the Boston Mountains in northwestern Arkansas towards the Arkansas Valley. The Ozark Plateaus aquifer system is underlain by the basement confining unit that is composed mostly of igneous and metamorphic crystalline rocks. The basement rocks are fractured and locally water bearing, such as in the St. Francois Mountains (fig. 41), but on a regional basis they are assumed to form the base of the regional flow system.

OZARK PLATEAUS AQUIFER SYSTEM

Nearly all ground water used in the Ozark subregion, either well water or spring water, is from three regional aquifers that are within a distinct hydraulic system. These three aquifers and two intervening con-

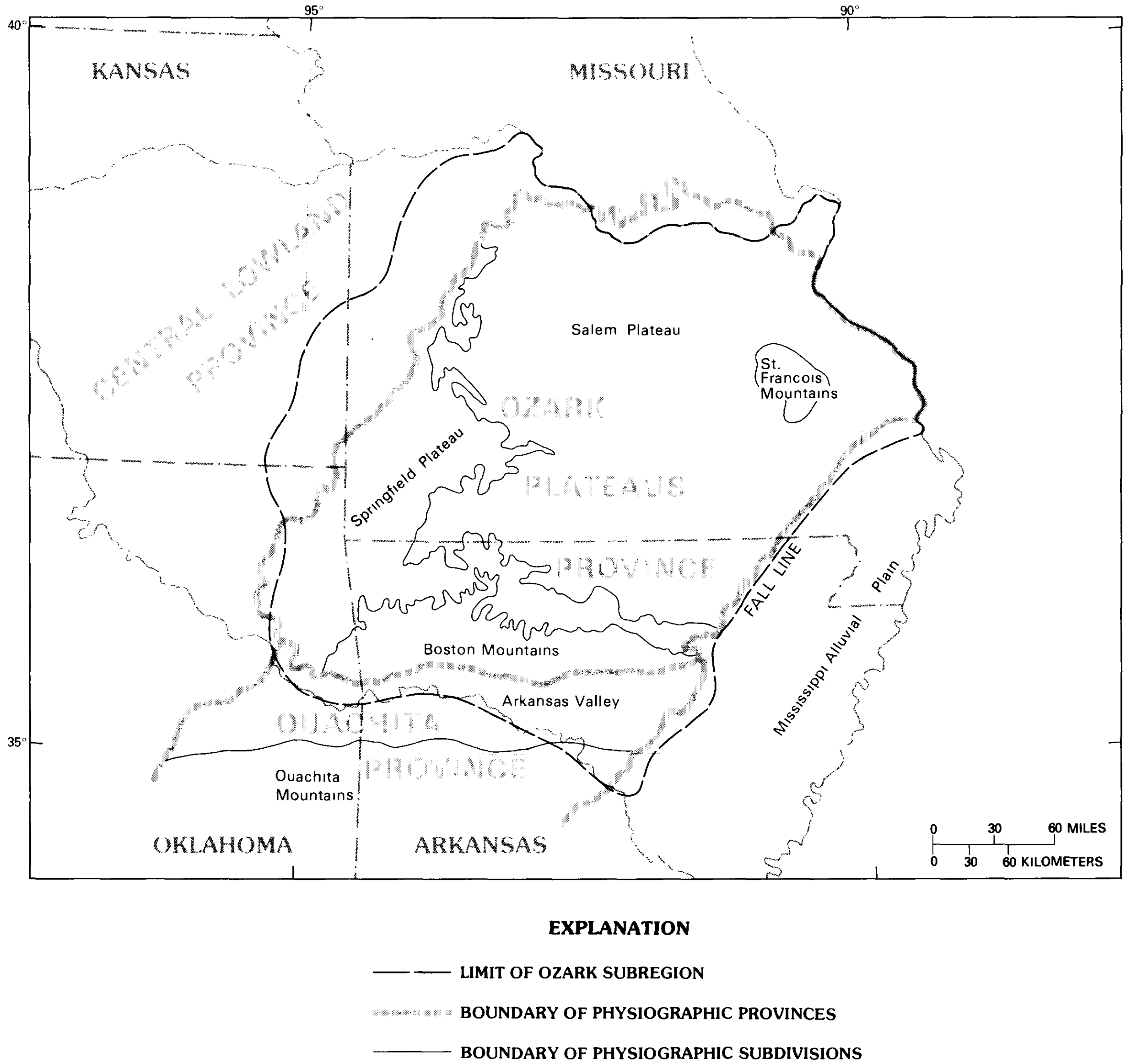


FIGURE 41.—Physiographic features of the Ozark subregion.

fining units are termed the Ozark Plateaus aquifer system because of their widespread occurrence in the Ozark Plateaus physiographic province. The aquifer system overlies the basement confining unit and has an extensive outcrop area. The aquifer system is overlain by the Western Interior Plains confining system in a band that extends along the western and southern boundaries of the subregion and by similar rocks along the eastern boundary.

GEOHYDROLOGIC UNITS

The Ozark Plateaus aquifer system consists of five units, which, from lower to upper, are the St. Francois aquifer, St. Francois confining unit, Ozark aquifer, Ozark confining unit, and Springfield Plateau aquifer.

The geohydrologic units of the Ozark Plateaus aquifer system are composed of sedimentary rocks that range in age from Cambrian through Mississippian (table 3). Boundaries between the geohydrologic units do not always conform to geologic-time divisions or to formation boundaries, but delineate groups of rocks having similar hydrologic properties. All of the geohydrologic units that comprise the Ozark Plateaus aquifer system crop out in the Ozark Plateaus (fig. 42).

The lateral boundaries of each of the three regional aquifers generally are the same as those of the Ozark

TABLE 3. *Generalized correlation of geohydrologic units to stratigraphic units in most of the Ozark subregion*
[From Jorgensen and others, 1993]

Geohydrologic uuit		Principal rock-stratigraphic uuit(s)	Time- stratigraphic unit
Western Interior Plains confining system		Marmaton Group, Cherokee Group, Atokan rocks, Bloyd Shale, Hale Formation, Morrowan rocks, Pitkin Limestone, Fayetteville Shale, and Batesville Sandstone	Middle Pennsylvanian through Upper Mississippian (Chesterian)
Ozark Plateaus aquifer system	Springfield Plateau aquifer	Moorefield Formation, St. Louis Limestone, Salem Limestone, Warsaw Limestone, Boone Formation, St. Joe Limestone Member of Boone Formation, Keokuk Limestone, Burlington Limestone, and Fern Glen Limestone	Mississippian
	Ozark confining unit	Chouteau Group[1] and Chattanooga Shale, Northview Shale, and Hannibal Shale	Lower Mississippian and Upper Devonian
	Ozark aquifer	Clifty Limestone, Penters Chert, Lafferty Limestone, St. Clair Limestone, Brassfield Limestone, Cason Shale, Fernvale Limestone, Kimmswick Limestone, Plattin Limestone, Joachim Dolomite, St. Peter Sandstone, Everton Formation, Smithville Formation, Powell Dolomite, Cotter Dolomite, Jefferson City Dolomite, Roubidoux Formation, Gasconade Dolomite, Gunter Sandstone Member of Gasconade Dolomite, Eminence Dolomite, and Potosi Formation	Middle Devonian through uppermost Cambrian
	St. Francois confining unit	Elvins Group, Derby and Doe Run Dolomite, Davis Formation	Upper Cambrian
	St. Francois aquifer	Bonneterre Dolomite, Lamotte Sandstone, and Reagan Sandstone	
Basement confining unit		Mostly igneous and metamorphic rocks	Precambrian

[1]Designated Chouteau Limestone by U.S. Geological Survey.

subregion. The extent of the ground-water flow along the western boundary of the Ozark Plateaus aquifer system also is controlled by the thickness and permeability of the Western Interior Plains confining system. In general ground water flowing westward moves laterally down the hydraulic gradient and downdip in the aquifer below the land surface and confining system to below the broad topographic low that extends from northeastern Oklahoma into central Missouri, and then leaks upward (fig. 17). The downdip flow extends to a depth of about 500 ft. The Western Interior Plains aquifer system is laterally adjacent to the western boundary of the Ozark Plateaus aquifer system. In general, both aquifer systems discharge water vertically upward through the thin (and therefore leaky) confining system to the streams or water table in the area of the broad topographic low. The flow system extends to about the Fall Line of northeastern Arkansas and the bootheel of southeastern Missouri. In general, flow across the Fall Line is intercepted by streams, marshes, and drainage canals in the Mississippi Alluvial Plain.

The St. Francois aquifer, the lowermost geohydrologic unit of the Ozark Plateaus aquifer system, consists of water-bearing sandstone and dolomite that rests on the basement confining unit. The aquifer crops out around the St. Francois Mountains (fig. 42) for which it is named and is overlain by the St. Francois confining unit.

The hydraulic head of the St. Francois aquifer is mostly topographically controlled. The aquifer is recharged by infiltration of precipitation through the

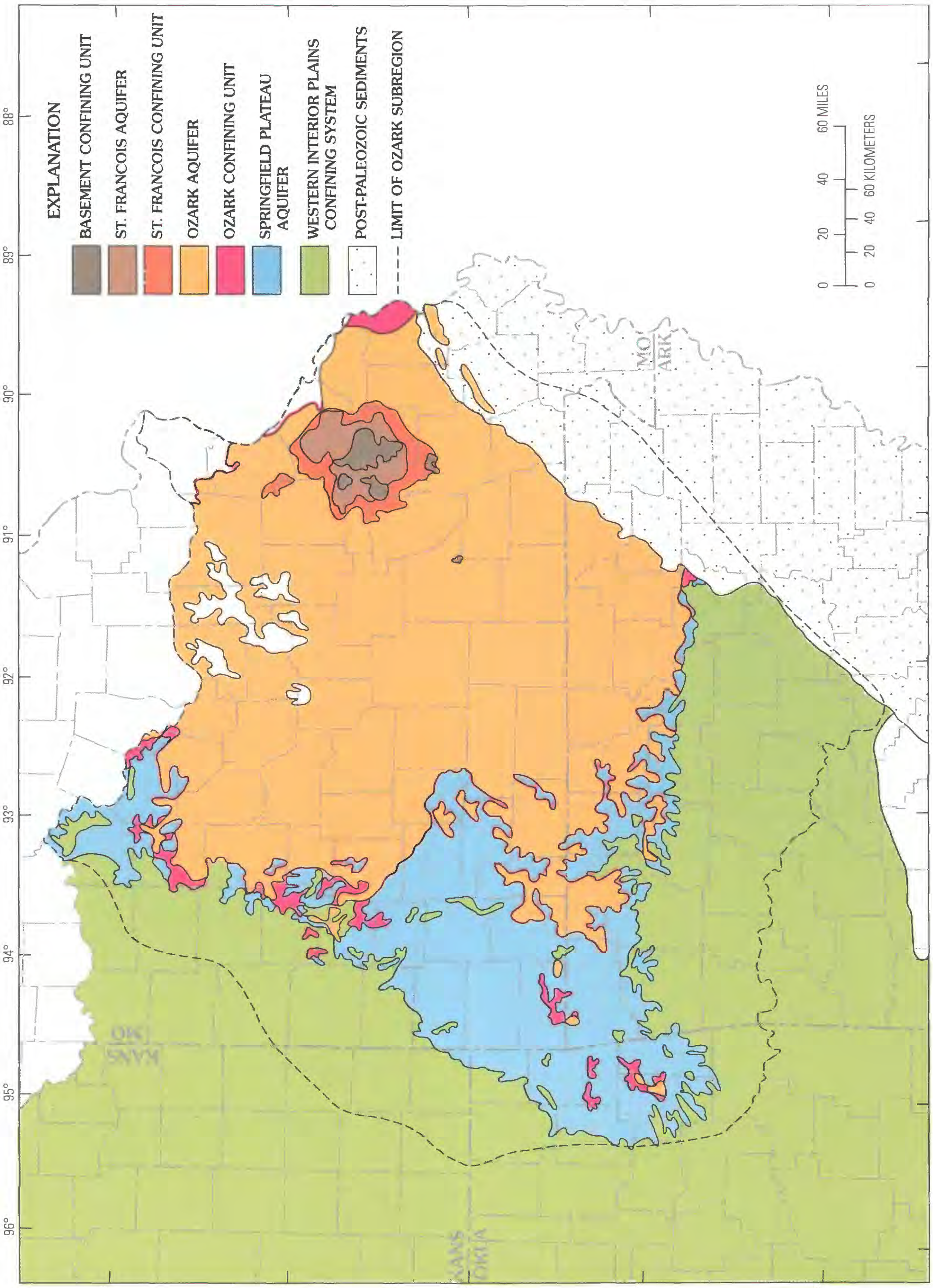


FIGURE 42.—Outcrop areas of regional geohydrologic units in and adjacent to the Ozark Plateaus physiographic province.

soil zone at the outcrops. The aquifer also is recharged by flow from the fractured Precambrian rocks of the basement confining unit near the outcrop area. Beyond the outcrop area, ground-water movement is restricted by the overlying confining unit. The aquifer discharges upward through the confining unit to overlying aquifers in areas downdip from the outcrop. However, exact areas of this discharge are not known because the hydraulic head in the aquifer is known only in the outcrop area.

The St. Francois confining unit, the lower of the two confining units in the Ozark Plateaus aquifer system, restricts flow between the St. Francois aquifer and the overlying Ozark aquifer at most locations. The leaky confining unit is composed of very slightly permeable shale, and slightly permeable siltstone, dolostone, and limestone. The rocks are part of three Upper Cambrian geologic units—the Davis Formation, the Derby Dolomite, and the Doe Run Dolomite (table 3).

The Ozark aquifer is composed mostly of water-bearing dolostone and is the most permeable and the most extensively used aquifer in the Ozark subregion. The aquifer, except in the St. Francois Mountains area, is at land surface throughout the area that generally is termed the "Ozark area" or the "Ozarks." The aquifer accordingly is termed the Ozark aquifer because of the close association with the Ozarks. The aquifer consists of fractured and solutioned dolostone with some limestone, sandstone, chert, and shale. Sandstone, where it exists as massive bodies, generally is clean, well sorted, and permeable; however, in northern Arkansas, it is well cemented, slightly fractured, and much less permeable. The aquifer, at most locations, is underlain by the St. Francois confining unit and overlain by the Ozark confining unit. The aquifer crops out in a large area over the Ozark Uplift and is a greatly dissected karst terrain with numerous streams and springs.

Water in most of the Ozark aquifer is unconfined, and its occurrence and flow are controlled by topographic relief. Throughout the outcrop area, ground water moves toward the major rivers and their tributaries (fig. 43), and hundreds of springs have developed. Typically, flow to these springs is local because most recharge to the springs is in the upland intervalley areas and is discharged in nearby stream valleys. The Mississippi and Missouri River Valleys are major discharge areas for regional flow from the Ozark aquifer.

The Ozark confining unit, the uppermost confining unit of the Ozark Plateaus aquifer system, restricts flow between the underlying Ozark aquifer and the overlying Springfield Plateau aquifer. The Ozark confining unit is named for its position relative to the underlying Ozark aquifer, which it confines. The leaky confining unit is composed mostly of shale, shaley limestone, and limestone.

The Springfield Plateau aquifer is composed of water-bearing limestone and is exposed at many locations on the Springfield Plateau, from which its name is taken, in southwestern Missouri. The aquifer, except along the Fall Line, extends outward from the outcrop area to the periphery of the Ozark subregion and dips into the subsurface along the west and south boundaries of the subregion, where it is overlain by nearly impermeable shale layers of the Western Interior Plains confining system. The aquifer is the uppermost unit of the Ozark Plateaus aquifer system and, at most locations, overlies the Ozark confining unit.

The Springfield Plateau aquifer also is present in the subsurface south of the Boston Mountains in Arkansas. In that area, water in the aquifer contains in excess of 1,000 mg/L dissolved solids, probably because near-surface permeability has not been developed, and thus, the slowly moving water probably dissolves minerals as it passes through the overlying Western Interior Plains confining system. The aquifer south of the Boston Mountains is unused because of greater dissolved-solids concentrations and small well yields.

Hydraulic-conductivity values for the Springfield Plateau aquifer are not available. Estimates of hydraulic conductivity based on specific capacity generally are not available because nearly all wells of sufficient diameter to permit measurement of drawdown are open to both the Springfield Plateau aquifer and the underlying Ozark aquifer.

The Springfield Plateau aquifer is recharged mostly at its outcrop areas. In general, water moves locally from high intervalley recharge areas to low discharge areas along the streams that dissect the area. Regionally, lateral flow in the Springfield Plateau aquifer is believed to be similar to that in the underlying Ozark aquifer.

The Springfield Plateau aquifer is overlain along the western and southern borders by rock that restricts or confines flow to and from the aquifer. The overlying confining material is the eastern edge of the Western Interior Plains confining system, which is composed of layers of very slightly permeable shale and of moderately permeable limestone, sandstone, and coal. The limestone is slightly fractured and has a small permeability, except near land surface where dissolution has markedly increased permeability. The same geologic formations comprising the Springfield Plateau aquifer exist near St. Louis in the northeast corner of the subregion near the confluence of the

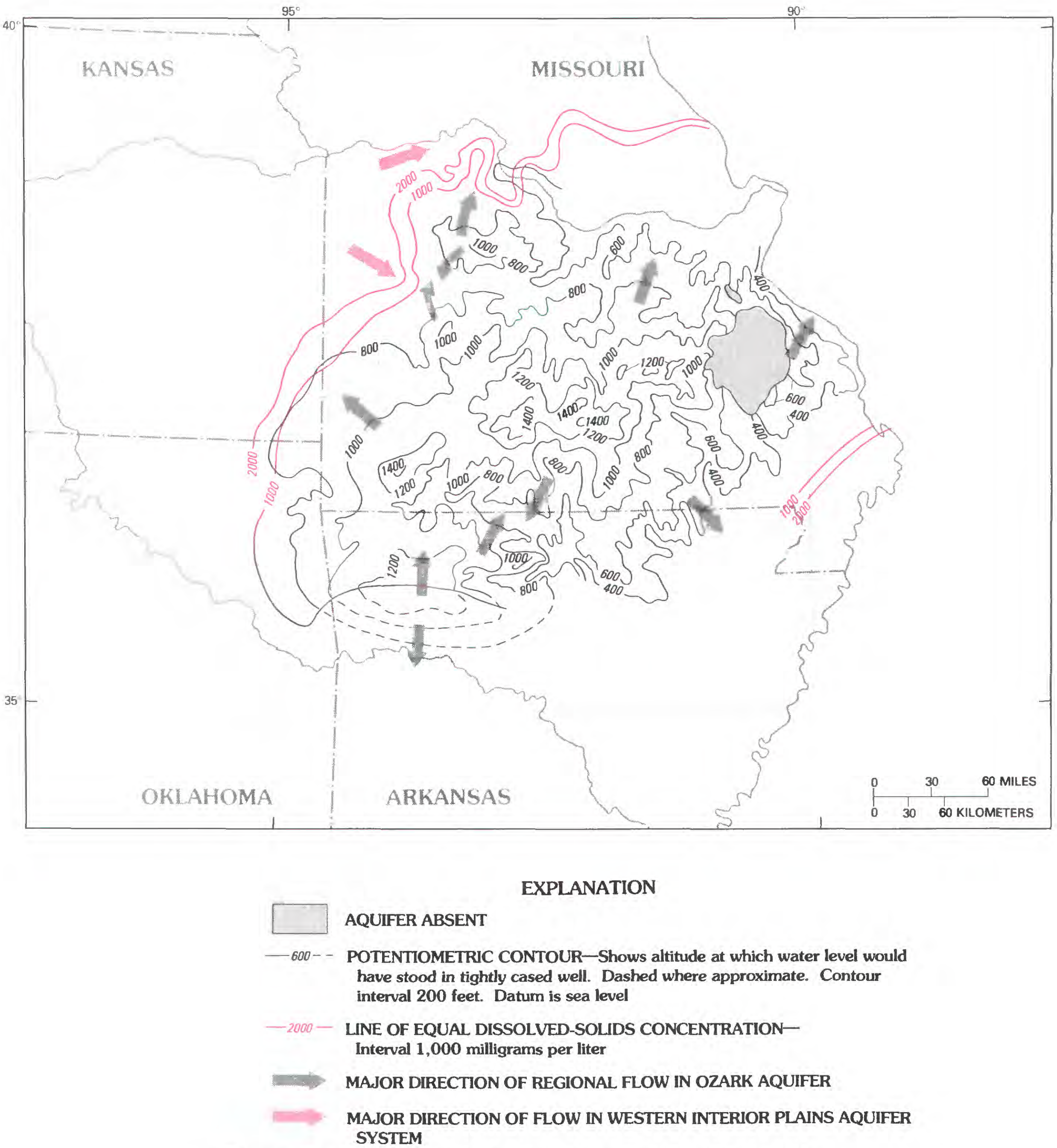


FIGURE 43.—Predevelopment potentiometric surface of the Ozark aquifer.

Missouri and Mississippi Rivers. These rocks are not in the Springfield Plateau aquifer flow system; they form two local and isolated flow systems. The rocks have hydraulic characteristics that are similar to the Springfield Plateau aquifer. The rocks at this location are about 900 ft thick and thicken abruptly to the east, attaining a thickness of more than 1,500 ft within a few miles.

PROPERTIES

The altitude and thickness of the aquifers and confining units are shown in Imes and Emmett (1994). The St. Francois aquifer generally is between 200 and 500 ft thick. The Ozark aquifer is the thickest (commonly about 1,000 ft) geohydrologic unit in the Ozark subregion; its thickness is shown in figure 44. The Springfield Plateau aquifer is between 100 and 400 ft thick throughout much of the subregion.

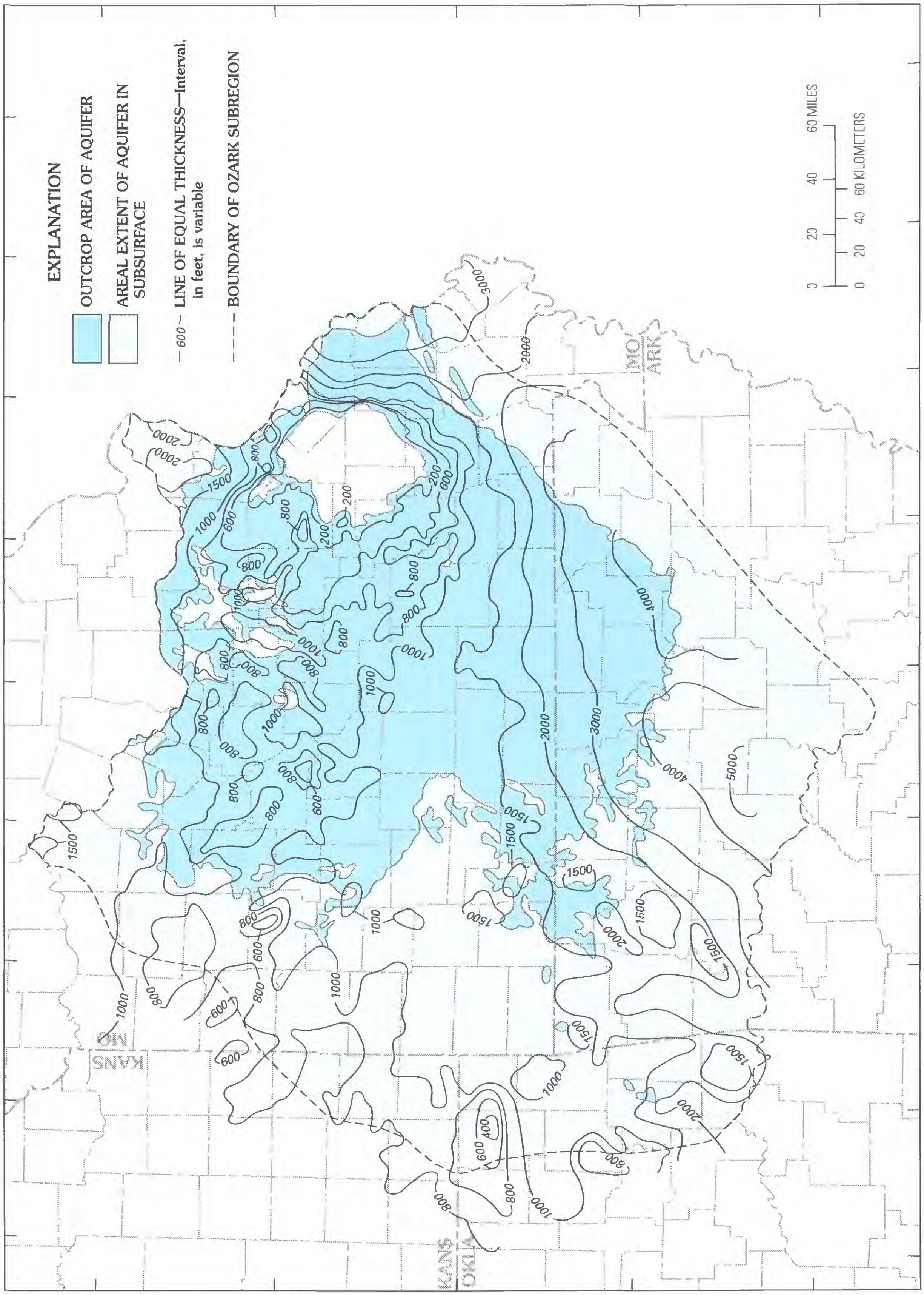


FIGURE 44.—Thickness of Ozark aquifer.

Estimated hydraulic conductivity of the St. Francois aquifer, based on specific capacity of wells, ranges from $1x10^{-4}$ to $1x10^{-6}$ ft/s in outcrop areas near the St. Francois Mountains and tends to decrease away from the outcrop areas. Little data are available elsewhere because the rocks become more deeply buried and strata that are more water yielding overlie the St. Francois aquifer. The St. Francois confining unit is, of course, less permeable than the aquifer. The vertical hydraulic conductivity of the confining unit decreases with increasing shale content. Percentage of shale ranges from 0 to more than 40 percent and generally is less than 30 percent.

The hydraulic conductivity of the Ozark aquifer has been estimated from specific-capacity data and inferred from the density of fractures and the degree of development of solution openings. The areas of greatest hydraulic conductivity are concentrated along an east-west line passing through the St. Francois Mountains where the hydraulic conductivity may be as much as $1x10^{-3}$ ft/s. In areas where dissolution has occurred and springs are numerous, the hydraulic conductivity exceeds $1x10^{-1}$ ft/s. Hydraulic conductivity of the aquifer decreases to the south to as little as $1x10^{-8}$ ft/s near the southern boundary of the subregion. The hydraulic conductivity of the Ozark confining unit decreases with increasing shale content. Shale content ranges from 0 to 100 percent, and shale contents greater than 50 percent are typical.

Values of hydraulic conductivity of the Springfield Plateau aquifer from aquifer or specific-capacity tests are not available. Hydraulic conductivity is highly variable, being large where karst terrain has developed and much smaller in nonkarstic areas and at greater depths.

MODEL ANALYSIS AND HYDROLOGIC BUDGET

A finite-difference digital model of the Ozark Plateaus aquifer system was made to analyze flow quantities in the hydrologic system (Imes and Emmett, 1994). The model was constructed to simulate natural flow conditions prior to development of water supplies from the aquifer system. An ancillary purpose was to evaluate the accuracy of estimates of hydraulic properties. The model of McDonald and Harbaugh (1984) was used. The model grid consists of 22 rows and 28 columns, with uniform cell size of 14 mi x 14 mi. The axes of the grid network are aligned North 35° West and North 55° East, generally coinciding with the prevailing directions of the significant lineaments and known fault and fracture traces; it is the same alignment that was used in the regional model.

The three-dimensional model contains four layers that are, from top to bottom: the Western Interior Plains confining system (layer 1), the Springfield Plateau aquifer (layer 2), the Ozark aquifer (layer 3), and the St. Francois aquifer (layer 4). The Western Interior Plains confining system is not part of the Ozark Plateaus aquifer system and is incorporated into the model only as a passive layer that forms the necessary restriction to the exchange of water between the water table or streams near land surface and the Springfield Plateau aquifer. Potentiometric heads are simulated only for the three aquifers that are part of the Ozark Plateaus aquifer system. The intervening Ozark confining unit and St. Francois confining unit are not treated as model layers.

A transient-state model was not developed for the Ozark Plateaus aquifer system because of the insignificant amount of regional drawdown in any of the three aquifers that are part of the Ozark Plateaus aquifer system. Drawdown cones associated with municipal pumpage generally are localized and not interconnected regionally because, historically, ground-water use in most of the Ozarks has been small. Many of the large-capacity wells withdraw water from unconfined parts of the aquifers where large quantities of stored water inhibit development of large drawdown cones.

The exception to these general statements occurs in the tristate lead-mining district located in the vicinity of the Missouri, Kansas, and Oklahoma borders. Here, large-capacity pumps were used to dewater large areas of the Springfield Plateau aquifer during the early part of the 20th century. The mining pumpage along with municipal pumpage in the area lowered water levels several hundred feet throughout the mining district and surrounding area. Many of the mines have been closed since World War II, and water levels have recovered to predevelopment altitudes except where municipal pumpage, most notably in Ottawa County, Oklahoma, is continuing.

Accurate modeling of the boundary condition of recharge to the water table and stream-aquifer interchange is extremely important because recharge to the aquifer from precipitation is the dominant source of water to the aquifer system. Stream-aquifer interaction is the dominant discharge of water from the aquifer system. The quantity of recharge to the water table per model cell was estimated from results of an investigation by Dugan and Peckenpaugh (1985). That investigation considered soil slope, permeability, depth to water table, land use, and 30 years of climate record. However, it is not possible to use these recharge values directly. Due to the coarse grid of the finite-difference flow model, all ground-water flow is not simulated. The model only simulates intercell (regional) flow; it does not simulate intercell flow that results from recharge to and discharge from the same cell. The recharge rate specified in the model must be adjusted downward to represent only that component of recharge that becomes intercell (regional) flow. For this purpose, a method proposed by Jorgensen and others (1989a, 1989b) was used. The application of that method and the design, assumptions, boundary conditions, and simulation results of the flow model of the Ozark Plateaus aquifer system are described by Imes and Emmett (1994). The reduced rate of recharge used in the model and the total recharge rate (estimated by Dugan and Peckenpaugh, 1985) are shown in figure 45.

The independently derived and model-cell adjusted values of recharge to the water table and stream-aquifer interchange were used in the model to calculate hydraulic heads; during calibration, these heads were compared to water levels measured in wells. The model was tested for sensitivity to changes in recharge to the water table, hydraulic conductivity of layers 2, 3, and 4 (aquifer layers), and vertical leakance between layers 1 and 2, layers 2 and 3, and layers 3 and 4. The model was found to be sensitive to all aquifer properties tested, but it was dominantly sensitive to changes in recharge to the water table.

The hydraulic-conductivity and transmissivity values of layers 2, 3, and 4 (Springfield Plateau, Ozark, and St. Francois aquifers) of the calibrated model (simulated water levels matched well with predevelopment water levels) are shown in figures 46, 47, and 48. These maps show effective values for the entire thickness of each unit and do not show the large variations that occur locally within each aquifer. Rocks affected by surficial karst or paleokarst possess very large hydraulic conductivity.

A water budget for the Ozark Plateaus aquifer system shows that prior to development only 6 percent of the mean annual precipitation in the aquifer system outcrop area contributed to the deeper regional ground-water flow that is simulated. About 25 percent of the 127,187 ft^3/s precipitation on the aquifer system outcrop area percolated to the water table. Of the water that entered the water table, about 78 percent was intracell flow that discharged into nearby streams and springs. This water is not simulated in the flow model. The remaining 7,091 ft^3/s (6 percent of precipitation) became regional ground-water flow and is simulated. Of this regional flow, 4,035 ft^3/s of water discharged to regional sinks (large streams and lakes) inside the study area, and 3,056 ft^3/s of water discharged as boundary flow to the Mississippi, Missouri, and other major rivers, aquifers of the Mississippi Embayment, and the water table in the Western Interior Plains confining system (fig. 49). Because pumping rates are small compared to the large natural rates of recharge and discharge, the regional ground-water budget prior to development probably is similar to the present-day budget.

USE AND POTENTIAL

About 200 Mgal of ground water is withdrawn daily from wells completed in the Ozark Plateaus aquifer system for public supply, industrial use, domestic and stock supplies, and supplemental irrigation. In addition, large withdrawals for dewatering of underground mines were common around the turn of the century. The Ozark Plateaus aquifer system unquestionably supports the largest yields to wells of any of the aquifer systems in the CMRASA study area.

Wells completed in the St. Francois aquifer yield as much as 500 gal/min in areas where a significant thickness of Lamotte Sandstone is penetrated. Yields of wells penetrating only the Bonneterre Dolomite typically are less. However, withdrawals for dewatering mines in the Bonneterre Dolomite in the "Old Lead Belt" in southeastern Missouri reportedly ranged from 13 to 17 Mgal per day in the early 1900's (Buckley, 1908). These mines mostly were closed by the 1960's. Mines in the "New Lead Belt," also in the Bonneterre Dolomite in southeastern Missouri, reportedly were dewatered at an average rate of 26 Mgal per day in 1971 (Warner and others, 1974). Withdrawals at individual mines were as much as 4,900 gal/min. The St. Francois aquifer, therefore, obviously has the potential to support large withdrawals from wells.

The Ozark aquifer is the primary source of water to large-yield public-supply, industrial, and irrigation wells throughout the Ozarks and adjacent areas (Imes and Emmett, 1994). Wells that penetrate all the most-permeable units of the aquifer underlying the Salem Plateau (fig. 41) yield as much as 1,000 gal/min in places. Formations in the Ozark aquifer that yield the largest amounts of water to wells are the St. Peter Sandstone, the Roubidoux Formation, the Gunter Sandstone Member of the Gasconade Dolomite, and the Potosi Dolomite. Individual formations, such as the Roubidoux and Gasconade, yield 500 gal/min to wells locally. The potentiometric surface of the Ozark aquifer was lowered as much as 400 ft by large-scale municipal and industrial withdrawals near Miami, Oklahoma, 200 ft by industrial withdrawals near Springfield, Missouri, and 100 ft by municipal withdrawals for Pittsburg, Kansas. Nevertheless, the potential for additional development of water supplies

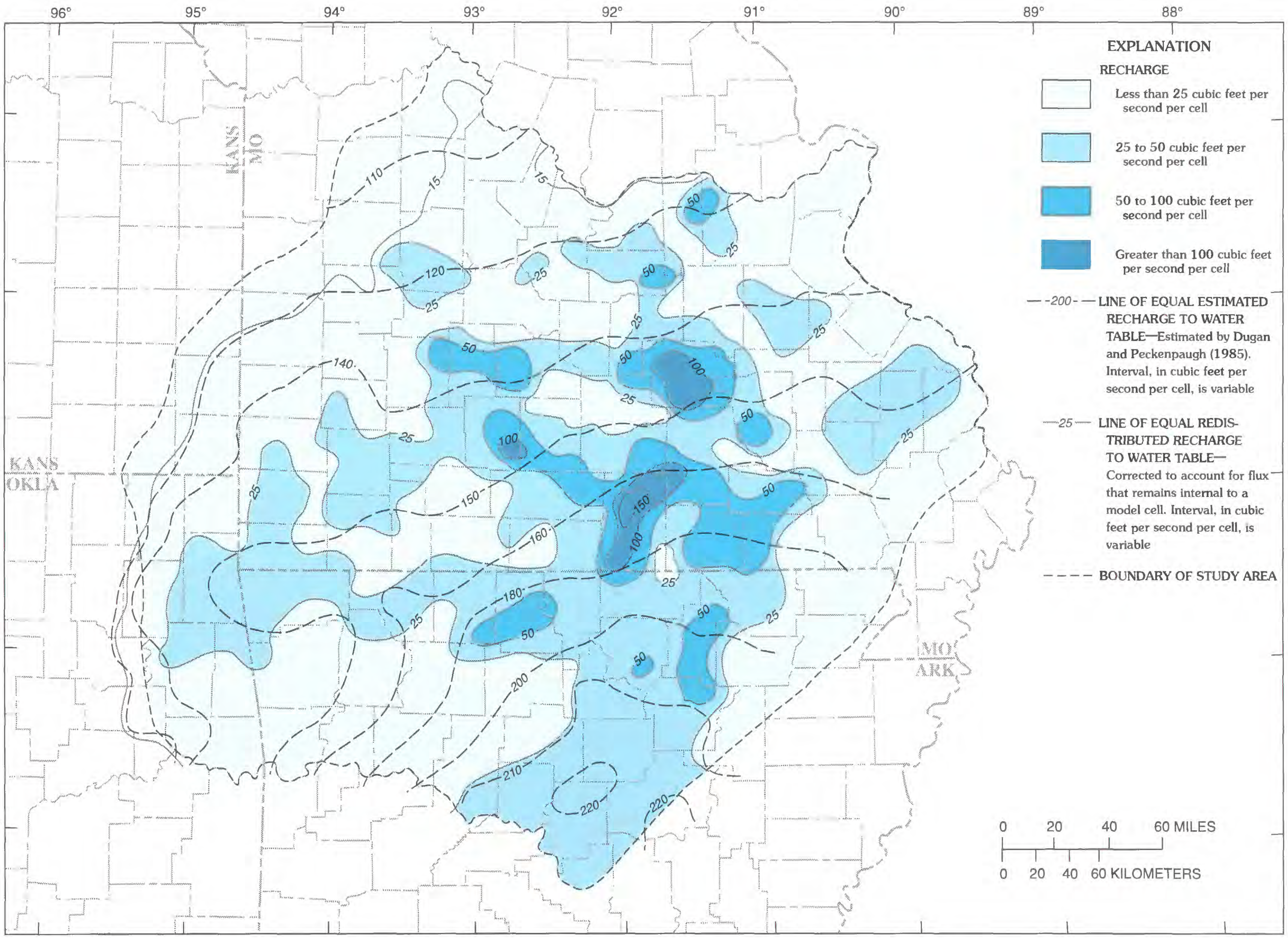


FIGURE 45.—Recharge to water table as estimated by Dugan and Peckenpaugh (1985) and redistributed recharge to account for water that remains internal to a cell of the Ozark model.

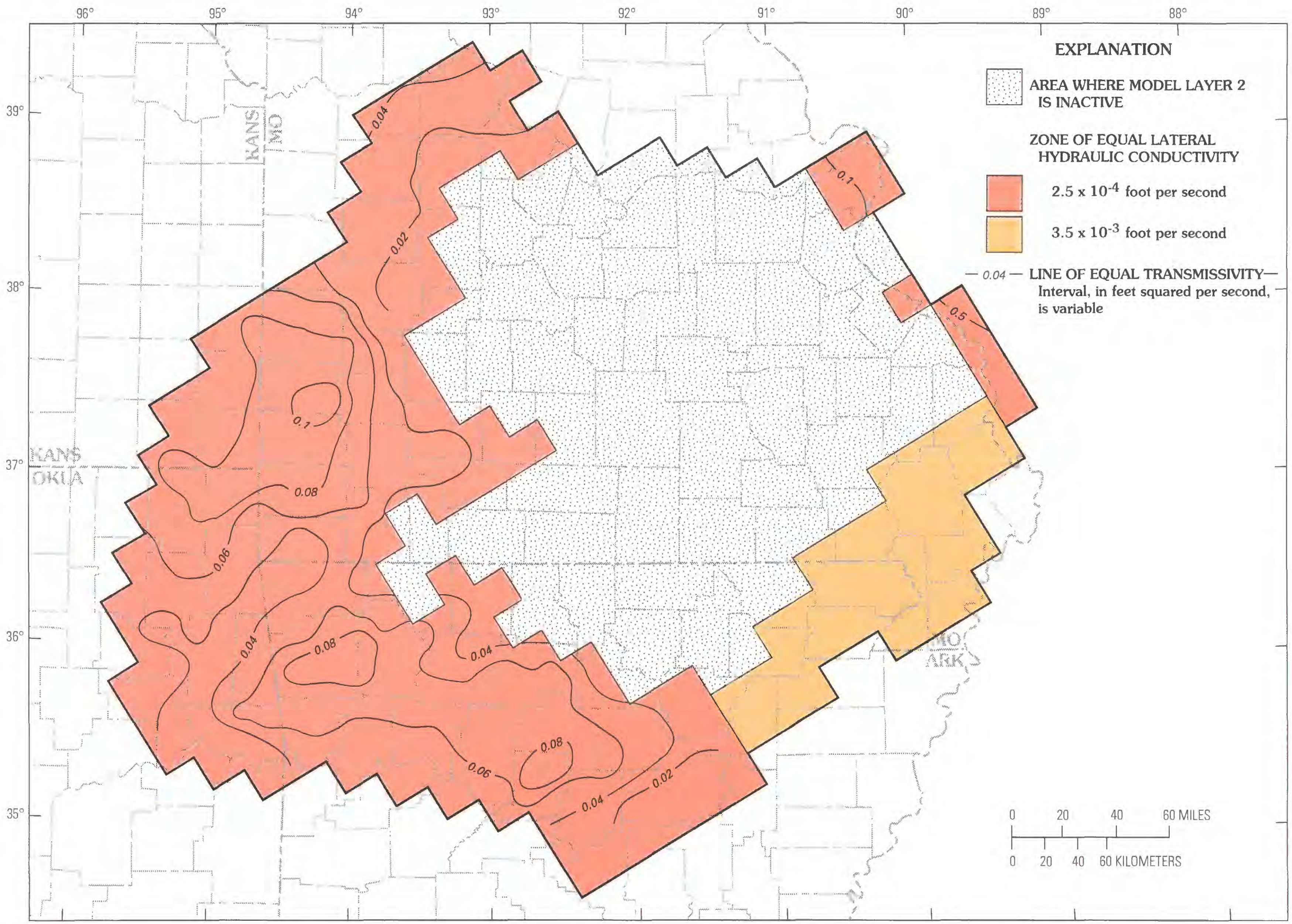


FIGURE 46.—Distribution of lateral hydraulic conductivity and transmissivity for Ozark model layer 2.

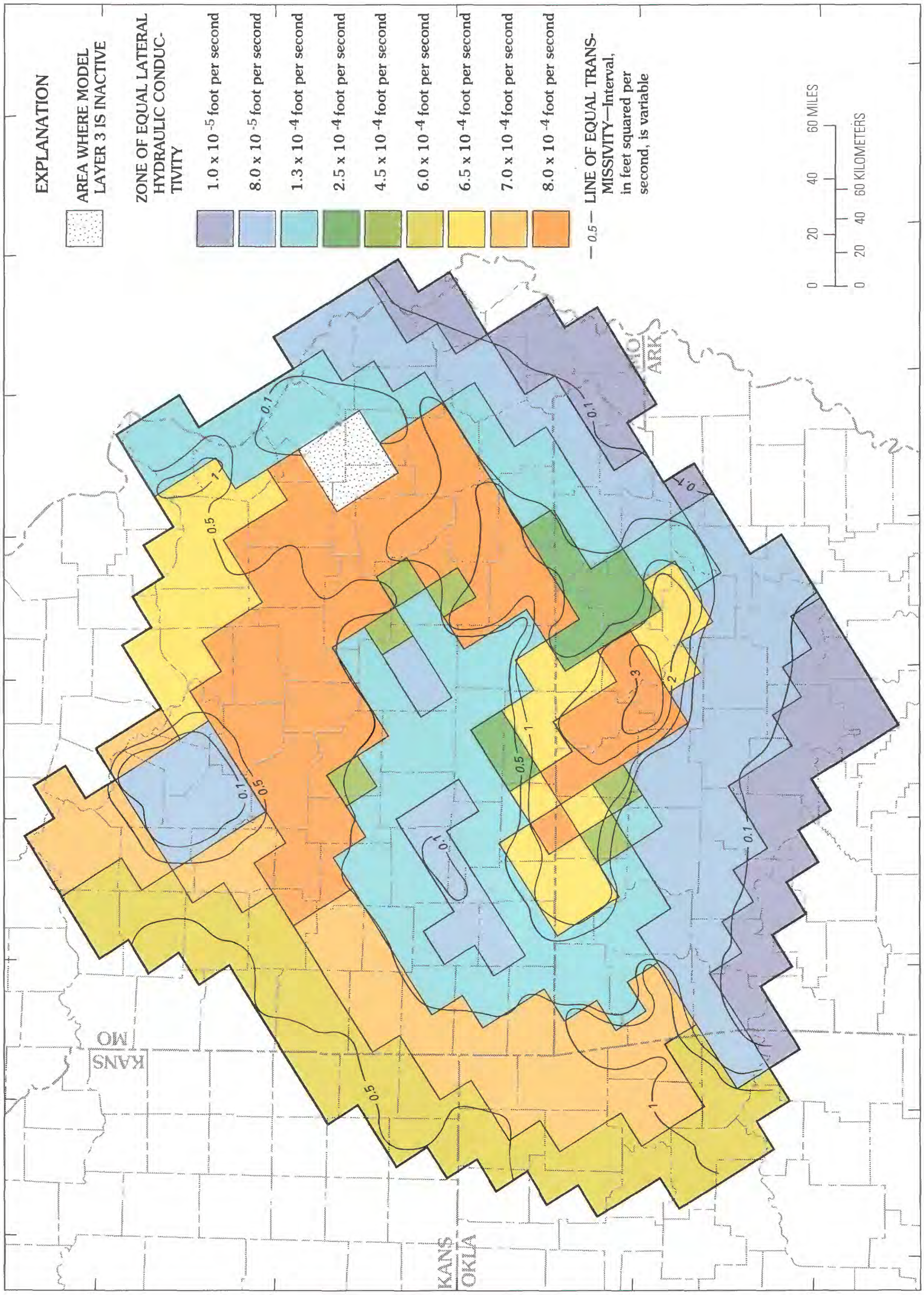


FIGURE 47.—Distribution of lateral hydraulic conductivity and transmissivity for Ozark model layer 3.

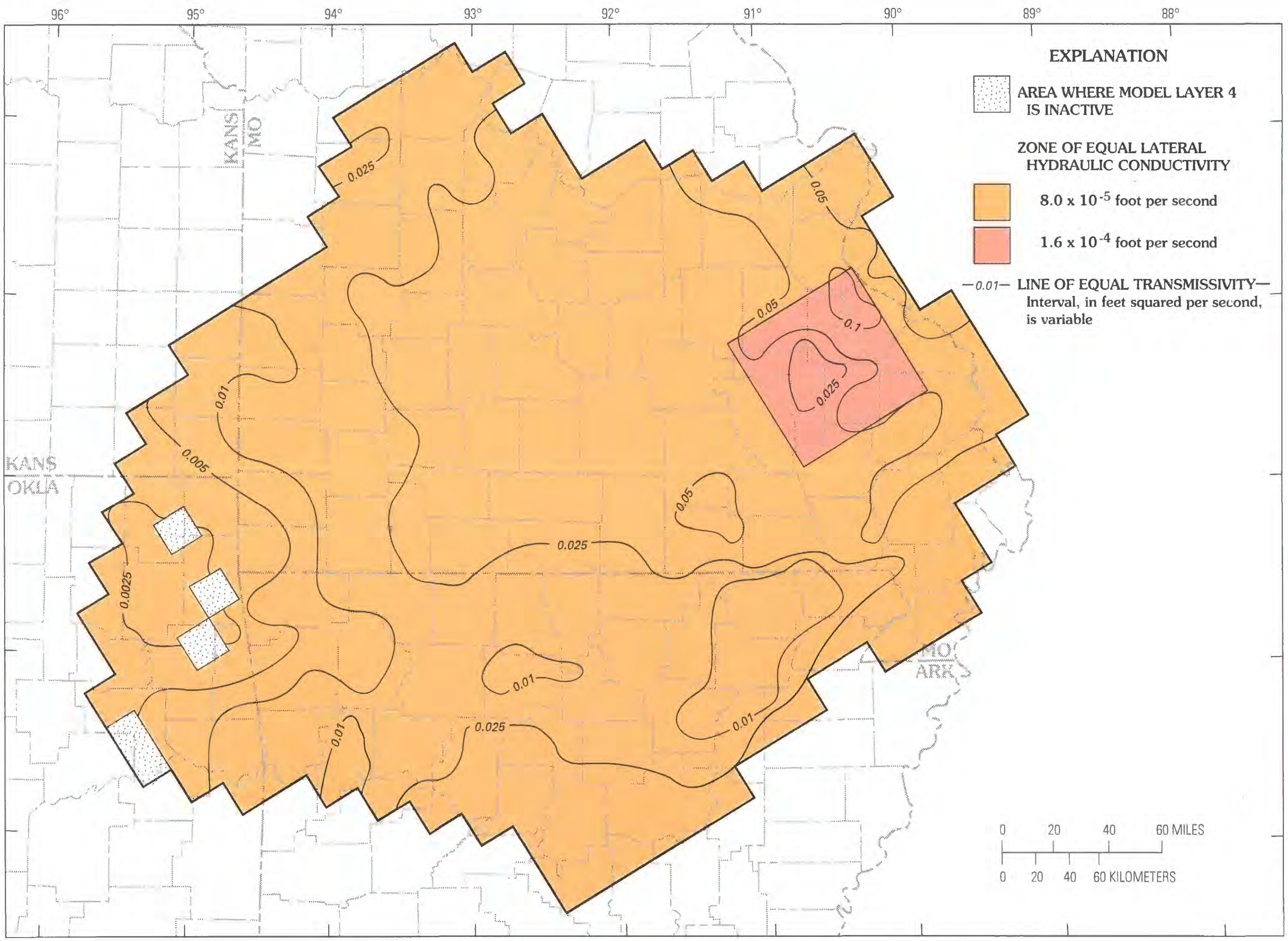


FIGURE 48.—Distribution of lateral hydraulic conductivity and transmissivity for Ozark model layer 4.

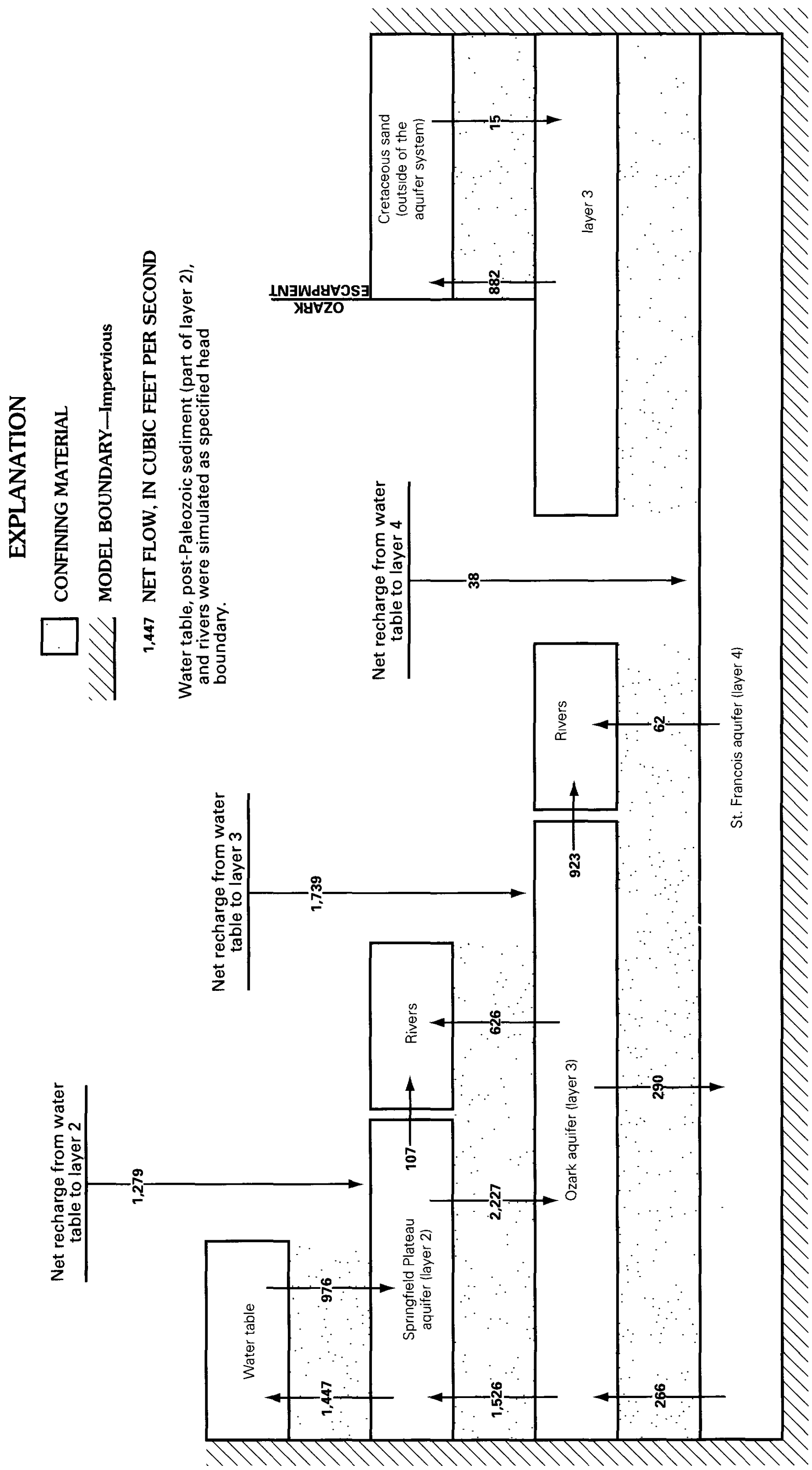


FIGURE 49.—Ground-water budget of the Ozark Plateaus aquifer system based on simulation.

from the Ozark aquifer is large, particularly in areas removed from municipal and industrial well fields.

Wells completed in the Springfield Plateau aquifer generally have smaller yields than wells in the Ozark aquifer. Most wells completed entirely in the Springfield Plateau aquifer are for domestic and stock use and yield less than 25 gal/min. Some industrial wells in Jasper County, Missouri, however, yield as much as 400 gal/min from fractured zones in the aquifer. Large amounts of water were pumped for dewatering mines and processing ore in the tristate lead-zinc mining district of southwest Missouri, southeast Kansas, and northeast Oklahoma. The pumpage indicates that large yields can be obtained in places. Abernathy (1941, p. 234) states that as much as 2 Mgal of water were pumped daily to dewater some of the mines.

GEOCHEMISTRY OF REGIONAL AQUIFERS

The chemistry of water in each of the aquifer systems in the CMRASA area is distinct and is described separately below, starting with the Western Interior Plains aquifer system.

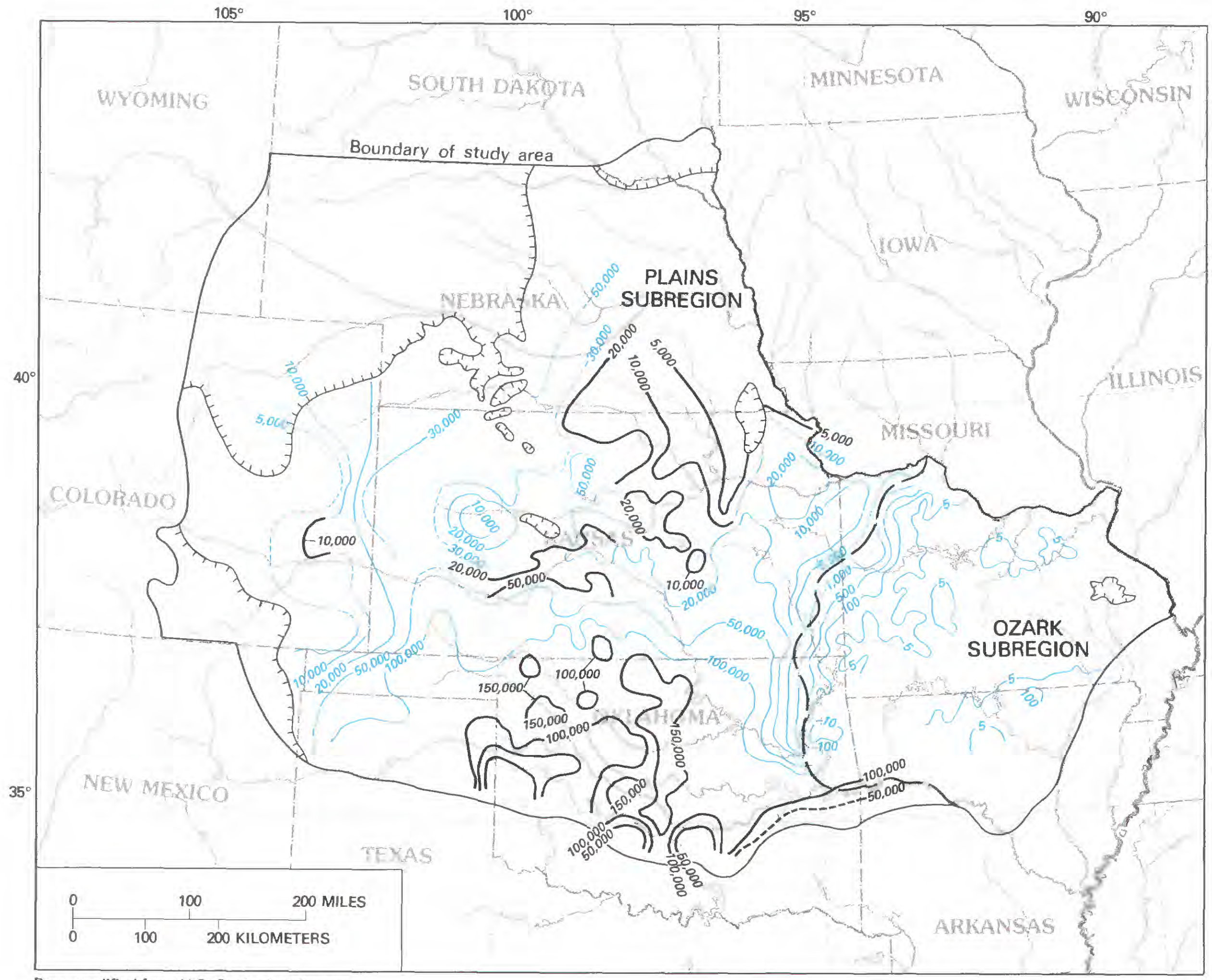
The Western Interior Plains aquifer system includes water-bearing lower units, a confining unit, and a water-bearing upper unit. Water from the lower units of the Western Interior Plains aquifer system contains less than 10,000 mg/L dissolved solids in only a few areas; locally and in the eastern part of the Anadarko Basin in Oklahoma, dissolved-solids concentrations exceed 300,000 mg/L (fig. 18). Movement of ground water, as indicated by lateral differences in density and pressure, is highly complex. In the western part of the area, flow is toward the southeast, changing to east-southeast along the Central Kansas Uplift. In the southern part of the area underlain by lower units, water moves radially outward from the Anadarko Basin. Virtually all water from the lower units is of the sodium chloride type, with chloride concentrations as large as 190,000 mg/L in the Anadarko Basin (fig. 50). Sodium-to-chloride ratios generally are similar to those of seawater, and calcium-to-magnesium ratios commonly are about 2.5. Chloride-to-sulfate ratios, however, typically are much larger than that of seawater, suggesting loss of sulfate during concentration of the original connate waters (Baker and Leonard, 1995).

The formations that constitute the confining unit and the upper aquifer unit in the Western Interior Plains aquifer system were removed from large parts of the area by erosion in Mississippian time. Ground-water flow patterns in the upper unit generally are similar to those in the underlying rocks. Where the upper unit is present, the water is somewhat fresher than water in the lower aquifer units. However, the distribution of dissolved-solids concentrations is broadly similar to that of the lower units; maximum concentrations typically are less than 250,000 mg/L (fig. 27). Nearly all the water is a sodium chloride type, with chloride concentrations locally as large as 180,000 mg/L (fig. 51). Sodium-to-chloride ratios in the upper unit typically are smaller than ratios in the lower units, generally ranging from about 0.65 to 0.8. Ratios of calcium to magnesium are larger, reflecting the presence of more limestone and less dolomite in the upper unit. Chloride-to-sulfate ratios tend to be smaller than ratios in water from the lower units, but typically much larger than ratios in seawater (Baker and Leonard, 1995).

Although the Western Interior Plains confining system functions as a regional confining unit, the areally extensive limestone and sandstone formations in the older part of the section are permeable, especially at shallow depths, and locally are water bearing or contain prolific reservoirs of oil. Water from the confining system at depths below 500 ft generally contains large concentrations of dissolved solids, locally as great as 300,000 mg/L. Dissolved-solids concentrations tend to be very large in rocks above and below evaporite deposits in the upper part of the confining system. At depths greater than 500 ft, most water samples are a sodium chloride type, and chloride concentrations of 50,000 mg/L or greater are common (Baker and Leonard, 1995).

In the southeastern two-thirds of the study area, rocks of the confining system have been exposed to a long period of erosion and subaerial weathering. Increased permeability of many of these rocks, due to weathering and dissolution, together with the incursion of meteoric water, has altered the chemical character of the shallow (less than 500 ft deep) ground water, which now bears little resemblance to water in the regional flow systems. Concentrations of dissolved solids range from a few hundred to more than 100,000 mg/L and vary widely over short distances (Baker and Leonard, 1995), reflecting the variability of the rock materials both laterally and vertically. The more dilute water generally is a calcium bicarbonate type; water with large concentrations of dissolved solids is a sodium chloride or calcium sulfate type and generally is associated with the presence of evaporite deposits.

In the northwestern part of the study area, the Western Interior Plains confining system is overlain by rocks of Cretaceous age that contain the Great Plains aquifer system. This system consists of two



Base modified from U.S. Geological Survey 1:7,500,000, National Atlas, 1970

EXPLANATION

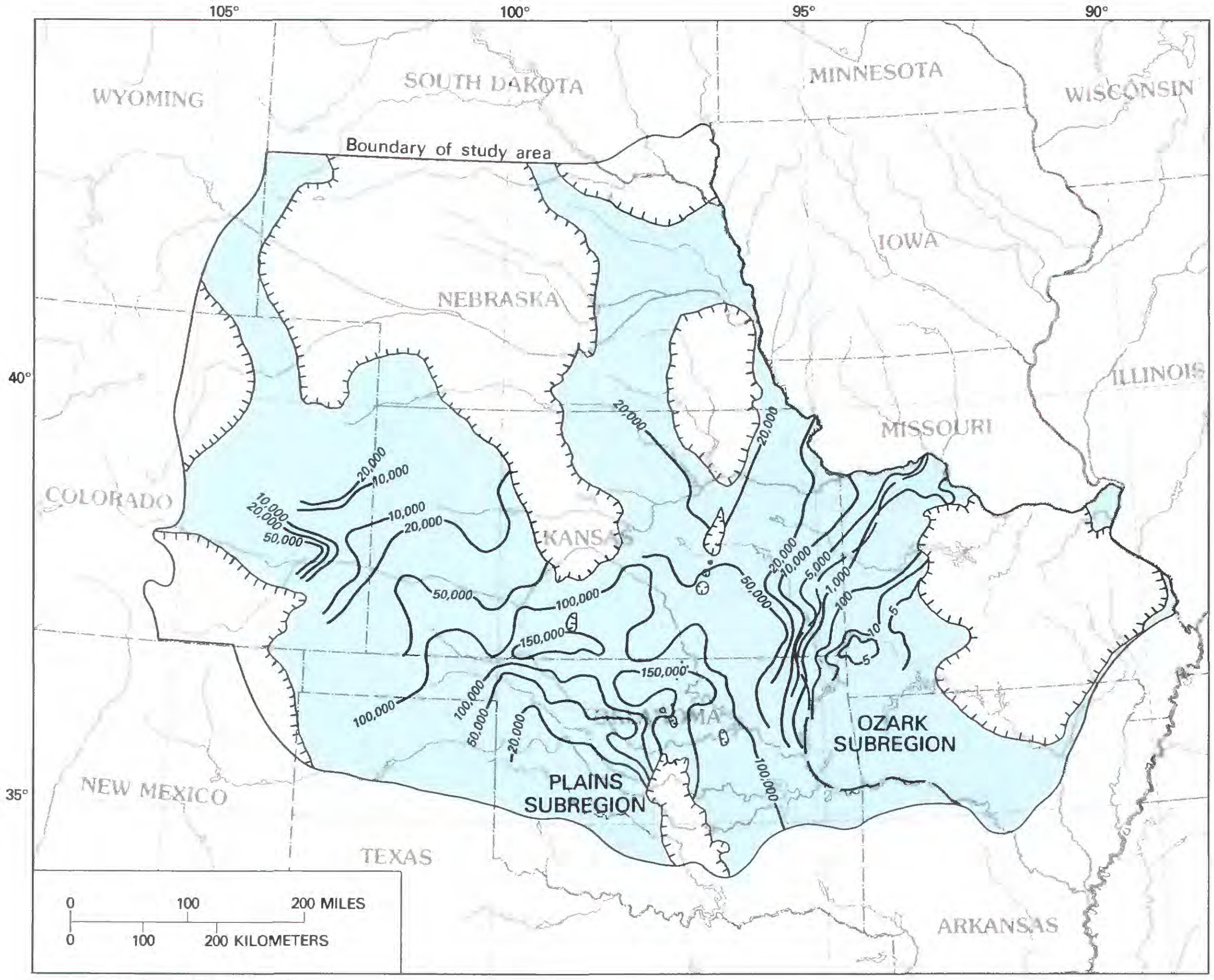
—1,000— — — LINE OF EQUAL CHLORIDE CONCENTRATION IN WATER MOSTLY FROM MIDDLE ORDOVICIAN UPPER ORDOVICIAN, SILURIAN, AND DEVONIAN ROCKS—Dashed where approximately located. Interval, in milligrams per liter, is variable

—1,000— — LINE OF EQUAL CHLORIDE CONCENTRATION IN WATER MOSTLY FROM UPPER CAMBRIAN AND LOWER ORDVICIAN ROCKS—Dashed where approximately located. Interval, in milligrams per liter, is variable

LIMIT OF LOWER UNITS IN THE WESTERN INTERIOR PLAINS AND OZARK PLATEAUS AQUIFER SYSTEMS

— — — APPROXIMATE BOUNDARY BETWEEN PLAINS AND OZARK SUBREGIONS

FIGURE 50.—Chloride concentrations in water from lower units in the Western Interior Plains aquifer system and the Ozark and St. Francois aquifers in the Ozark Plateaus aquifer system.



Base modified from U.S. Geological Survey 1:7,500,000, National Atlas, 1970

EXPLANATION

—1,000— LINE OF EQUAL CHLORIDE CONCENTRATION IN WATER MOSTLY FROM UPPER UNITS IN THE WESTERN INTERIOR PLAINS AND OZARK PLATEAUS AQUIFER SYSTEMS—Dashed where approximately located. Interval, in milligrams per liter, is variable

LIMIT OF UPPER UNITS IN THE WESTERN INTERIOR PLAINS AND OZARK PLATEAUS AQUIFER SYSTEMS

— — — APPROXIMATE BOUNDARY BETWEEN PLAINS AND OZARK SUBREGIONS

FIGURE 51.—Chloride concentrations in water from upper unit in the Western Interior Plains aquifer system and the Springfield Plateau aquifer in the Ozark Plateaus aquifer system.

aquifer units, both composed primarily of slightly cemented water-bearing sandstone deposits, that are separated by a thin, discontinuous shale confining unit (fig. 29). The direction of ground-water flow and the chemistry of the water generally are similar in both aquifer units. Water generally moves from west to east through the system. Concentrations of dissolved solids exceed 5,000 mg/L in most water from the interior part of the system and are as large as 125,000 mg/L locally in western Nebraska (Helgesen and others, 1993, plate 6). Outside the Denver Basin, very large concentrations of dissolved solids seem to be related to evaporite deposits in the underlying confining system (figs. 17 and 26). Around the southern and eastern boundaries of the system, the aquifers are at or near land surface, and concentrations of dissolved solids less than 1,000 mg/L result from addition of meteoric water or freshwater from overlying aquifers (Leonard and others, 1983).

Water types in the Great Plains aquifer system differ greatly. The more concentrated water (more than 5,000 mg/L) generally is a sodium chloride type, but fresher water is a sodium sulfate, sodium bicarbonate, or calcium bicarbonate type (Helgesen and others, 1993, plates 6 and 7). Calcium sulfate water in northeastern Nebraska and in small areas near the eastern boundary of the system in Kansas probably are related to solution of gypsum or to upward leakage of water from the underlying rocks of Permian age. Chloride concentrations in water from most parts of the system (Helgesen and others, 1993, plate 8) are considerably less than in modern seawater, indicating that the sediment was deposited in brackish (rather than saline) water or that there has been some flushing and dilution of connate water. Sodium-to-chloride ratios in water from most of the system also are less than ratios in modern seawater (Helgesen and others, 1993, plate 9); however, near the outcrop area, sodium-to-chloride ratios as great as 10 suggest the addition of sodium-rich water. Calcium-to-magnesium ratios in most of the aquifer system range from about 0.2 to 3.5 and are associated with a wide variety of water types and concentrations (Baker and Leonard, 1995). Ratios of chloride to sulfate vary widely and, generally, seem to relate to chloride concentrations.

The Ozark Plateaus aquifer system consists of three aquifer units separated by two confining units (table 3). The lowermost aquifer unit, the St. Francois aquifer, is separated from the overlying Ozark aquifer by the St. Francois confining unit. The confining unit generally is leaky and locally is absent, and the hydrochemistry of the two aquifer units is similar. Water in these aquifers commonly contains less than 500 mg/L dissolved solids (fig. 18) and is a calcium magnesium carbonate type. Sodium, sulfate, and chloride concentrations in most samples are only a few milligrams per liter. Calcium-to-magnesium ratios typically are near 1, consistent with the predominantly dolomitic rocks (Baker and Leonard, 1995). Overall, the water chemistry represents meteoric water charged with carbon dioxide approaching equilibrium with the carbonate rocks through which it is moving.

The upper aquifer unit, the Springfield Plateau aquifer, is at or near land surface over most of its areal extent and generally is unconfined. As in the underlying aquifers, the chemical character of the water is the result of the solution of aquifer materials by meteoric water. Dissolved-solids concentrations commonly are less than 300 mg/L (fig. 52), and virtually all water samples are a calcium bicarbonate type. Calcium-to-magnesium ratios generally are greater than 5, reflecting the preponderance of limestone over dolostone in the rocks of this unit (Baker and Leonard, 1995).

REFERENCES CITED

Abernathy, G.E., 1941, Ground-water resources of Mississippian and older rocks in Bourbon, Crawford, Cherokee, and Labette Counties, southeastern Kansas: Kansas Geological Survey Bulletin 38, Reports Studies 1941, pt. 8, p. 221–236.

Baker, C.H., and Leonard, R.B., 1995, Hydrochemistry of aquifer systems in Cretaceous and older rocks underlying Kansas, Nebraska, and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Water-Resources Investigations Report 94–4144, 53 p.

Bennison, A.P., and Chenoweth, P.A., compilers, 1984, Geologic highway map of northern Great Plains region: American Association of Petroleum Geologists Map 12, 1 sheet, scale 1:1,875,000.

Buckley, E.R., 1908, Geology of the disseminated lead deposits of St. Francois and Washington Counties, Missouri: Rolla, Missouri Division of Geology and Land Survey, v. 9, pt. 1, 259 p.

Busby, M.W., 1966, Annual runoff in the conterminous United States: U.S. Geological Survey Hydrologic Investigations Atlas HA–212, 1 sheet, scale 1:7,500,000.

Carlson, M.P., 1963, Lithostratigraphy and correlation of the Mississippian system in Nebraska: Nebraska Geological Survey Bulletin 21, 46 p.

Craig, L.C., and Varnes, K.L., 1979, History of the Mississippian System—An interpretive summary: U.S. Geological Survey Professional Paper 1010–R, p. 371–405.

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

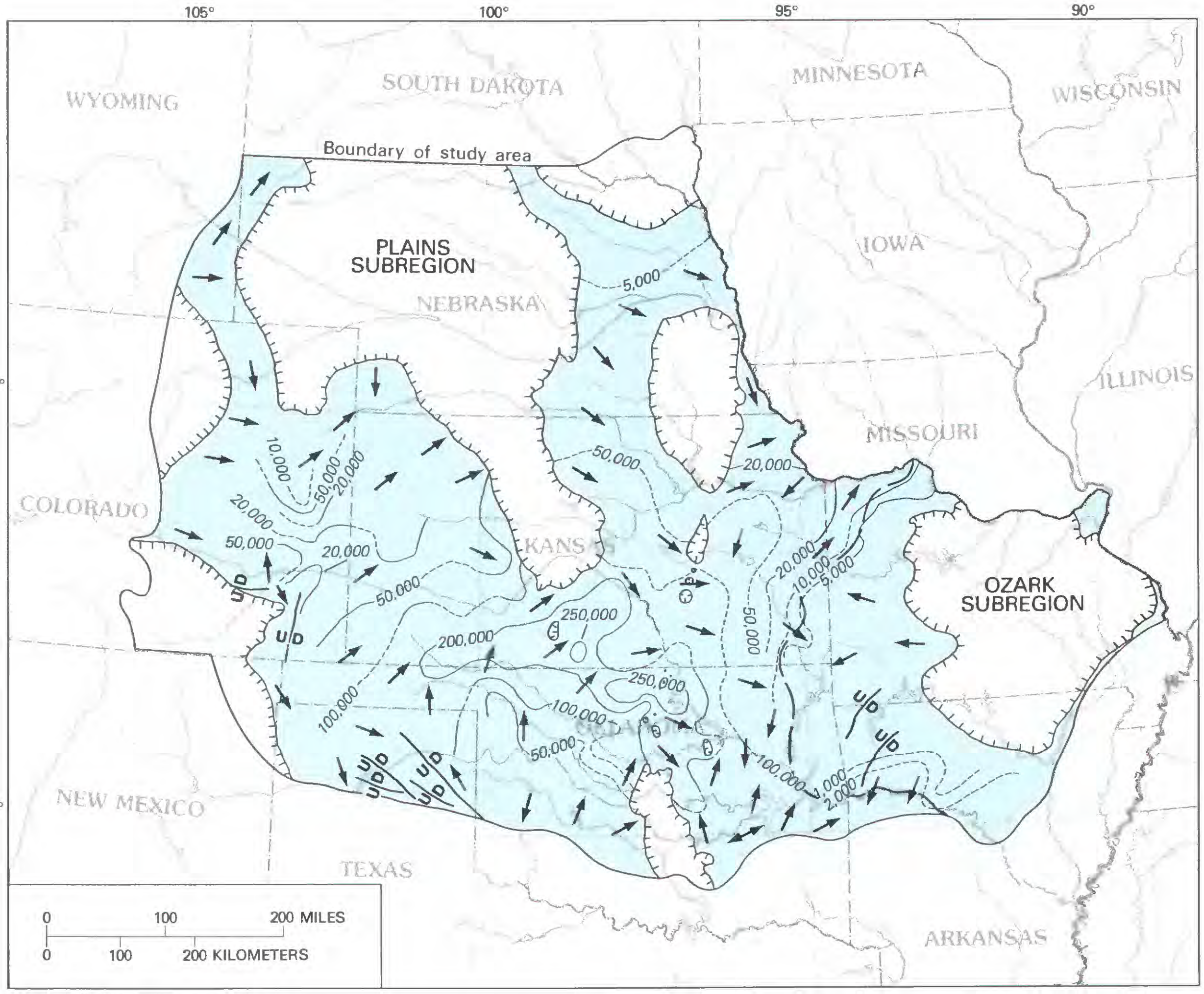
Dugan, J.T., 1986, Hydrologic characteristics of soils in parts of Arkansas, Colorado, Kansas, Missouri, Nebraska, New Mexico, Oklahoma, South Dakota, and Texas: U.S. Geological Survey Hydrologic Investigations Atlas HA–678, 1 sheet, scale 1:1,500,000.

Dugan, J.T., and Peckenpaugh, J.M., 1985, Effects of climate, soils, and land use on consumptive water use and ground-water recharge to the Central Midwest regional aquifer system, mid-continent United States: U.S. Geological Survey Water-Resources Investigations Report 85–4236, 78 p.

Eagleman, J.R., 1976, Visualization of climate: Lawrence, University of Kansas Press, 142 p.

Fenneman, N.M., 1946, Physical divisions of the United States [map]: U.S. Geological Survey, 1 sheet, scale 1:7,000,000.

Garbarini, G.S., and Veal, H.K., 1968, Potential of Denver basin for disposal of liquid wastes, *in* Galley, J.E., ed., Subsurface disposal in geologic basins—A study of reservoir strata: American Association of Petroleum Geologists Memoir 10, p. 165–185.



Base modified from U.S. Geological Survey 1:7,500,000, National Atlas, 1970

EXPLANATION

-----5,000—— LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION IN WATER FROM UPPER UNITS OF THE WESTERN INTERIOR PLAINS AQUIFER SYSTEM AND THE SPRINGFIELD PLATEAU AQUIFER IN THE OZARK PLATEAUS AQUIFER SYSTEM—Dashed where approximate. Interval, in milligrams per liter, is variable

→ APPARENT DIRECTION OF LATERAL FLOW—Based on pressure and density near the center line of the geohydrologic unit

LIMIT OF UPPER UNITS OF THE WESTERN INTERIOR PLAINS AQUIFER SYSTEM AND OF SPRINGFIELD PLATEAU AQUIFER

APPROXIMATE BOUNDARY BETWEEN PLAINS AND OZARK SUBREGIONS

U/D FAULT—U, upthrown side; D, downthrown side

FIGURE 52.—Dissolved-solids concentrations in water from upper unit in the Western Interior Plains aquifer system and the Springfield Plateau aquifer in the Ozark Plateaus aquifer system.

Grubb, H.F., in press, Summary of hydrology of the regional aquifer systems, Gulf of Mexico Coastal Plain, south-central United States: U.S. Geological Survey Professional Paper 1416–A.

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

Hayes, W.C., 1962, Precambrian surface showing major lineaments: Missouri Geological Survey map, 1 sheet, scale 1:500,000.

Hedman, E.R., and Engel, G.B., 1989, Flow characteristics for selected streams in the Great Plains subregion of Central Midwest regional aquifer system and selected adjacent areas—Kansas and Nebraska, and parts of Colorado, Iowa, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–708, 3 sheets, scale 1:1,000,000.

Hedman, E.R., and Jorgensen, D.G., 1990, Surface- and ground-water interaction and hydrologic budget of the Missouri River Valley aquifer between Yankton, South Dakota, and St. Louis, Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA–721, 1 sheet, scale 1:1,500,000.

Hedman, E.R., Skelton, John, and Freiwald, D.A., 1987, Flow characteristics for selected springs and streams in the Ozark subregion, Arkansas, Kansas, Missouri, and Oklahoma: U.S. Geological Survey Hydrologic Investigations Atlas HA–688, 4 sheets, scale 1:750,000.

Helgesen, J.O., and Hansen, C.V., 1989, Description of data files compiled for the Central Midwest Regional Aquifer-System Analysis: U.S. Geological Survey Open-File Report 89–42, 37 p.

Helgesen, J.O., Jorgensen, D.G., Leonard, R.B., and Signor, D.C., 1982, Regional study of the Dakota aquifer (Darton's Dakota revisited): Ground Water, v. 20, no. 4, p. 410–414.

Helgesen, J.O., Leonard, R.B., and Wolf, R.J., 1993, Hydrology of the Great Plains aquifer system in Nebraska, Colorado, Kansas, and adjacent areas: U.S. Geological Survey Professional Paper 1414–E, 80 p., 10 plates.

Imes, J.L., and Emmett, L.F., 1994, Geohydrology of the Ozark Plateaus aquifer system in parts of Missouri, Arkansas, Oklahoma, and Kansas: U.S. Geological Survey Professional Paper 1414–D, 127 p.

Jorgensen, D.G., 1989, Some uses of geophysical logs to estimate porosity, water resistivity and intrinsic permeability: U.S. Geological Survey Water-Supply Paper 2321, 24 p.

———1993, Paleohydrology of the Central United States: U.S. Geological Survey Bulletin 1989–D, 32 p.

Jorgensen, D.G., Gogel, Tony, and Signor, D.C., 1982, Determination of flow in aquifers containing variable density water: Ground Water Monitoring Review, v. 2, no. 2, p. 40–45.

Jorgensen, D.G., Helgesen, J.O., and Imes, J.L., 1993, Regional aquifers in Kansas and Nebraska, and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming—Geohydrologic framework: U.S. Geological Survey Professional Paper 1414–B, 72 p., 25 plates.

Jorgensen, D.G., and Signor, D.C., 1981, Plan of study for the Central Midwest regional aquifer-system analysis in parts of Arkansas, Colorado, Kansas, Missouri, Nebraska, New Mexico, Oklahoma, South Dakota, and Texas: U.S. Geological Survey Water-Resources Investigations Report 81–206, 28 p.

Jorgensen, D.G., Signor, D.C., and Imes, J.L., 1989a, Accounting for intracell flow in models with special emphasis on water-table recharge and stream aquifer interaction—Part 1, problems and concepts: Water Resources Research, v. 25, no. 4, p. 669–676.

———1989b, Accounting for intracell flow in models with emphasis on water-table recharge and stream-aquifer interaction—Part 2, a procedure: Water Resources Research, v. 25, no. 4, p. 677–684.

King, P.B., compiler, 1968, Tectonic map of North America, *in* National Atlas: U.S. Geological Survey, 1 sheet, scale 1:7,500,000.

Kinney, D.M., compiler, 1966, Geologic map of the United States: U.S. Geological Survey, National Atlas of the United States of America, p. 74–75, scale 1:7,500,000.

Krueger, J.M., and Keller, G.R., 1986, Interpretation of crustal structure from regional gravity anomalies, Ouachita Mountains area and adjacent Gulf Coastal Plain: American Association of Petroleum Geologists Bulletin, v. 70, no. 6, p. 667–689.

Leonard, R.B., Signor, D.C., Jorgensen, D.G., and Helgesen, J.O., 1983, Geohydrology and hydrochemistry of the Dakota aquifer, central United States: Water Resources Bulletin, v. 19, no. 6, p. 903–911.

McDonald, M.G., and Harbaugh, A.W., 1984, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 83–875, 528 p.

McKee, E.D., and others, 1967, Paleotectonic maps of the Permian System: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–450, 164 p.

McKee, E.D., Oriel, S.S., Ketner, K.B., MacLachlan, M.E., Goldsmith, J.W., MacLachlan, J.C., and Mudge, M.R., 1959, Paleotectonic maps of the Triassic System: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–300, 33 p., 9 sheets, scale 1:5,000,000.

Merriam, D.F., 1963, Geologic history of Kansas: Kansas Geological Survey Bulletin 162, 317 p.

Oetking, Philip, Feray, D.E., and Renfro, H.B., compilers, 1966, Geological highway map of the mid-continent region, Kansas, Missouri, Oklahoma, and Arkansas: American Association of Petroleum Geologists Map 1, 1 sheet, scale 1:1,900,800.

———1967, Geological highway map of southern Rocky Mountain region, Utah, Colorado, Arizona, and New Mexico: American Association of Petroleum Geologists Map 2, 1 sheet, scale 1:1,900,800.

Renfro, H.B., compiler, (no date), Geological highway map of Texas: American Association of Petroleum Geologists Map 7, 1 sheet, scale 1:1,900,800.

Schoon, R.A., 1971, Geology and hydrology of the Dakota Formation in South Dakota: South Dakota Geological Survey Report of Investigations 104, 55 p.

Signor, D.C., Helgesen, J.O., Jorgensen, D.G., and Leonard, R.B., 1996, Geohydrology and simulation of steady-state flow conditions in regional aquifer systems in Cretaceous and older rocks underlying Kansas, Nebraska, and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1414–C, 109 p., 2 plates.

Sims, P.K., compiler, 1985, Precambrian basement map of northern midcontinent, U.S.A.: U.S. Geological Survey Open-File Report 85–0604, 16 p., 1 sheet, scale 1:1,000,000.

Warner, D.L., Fletcher, C.S., and Cesare, J.A., 1974, Effect of mining operations on ground-water levels in the New Lead Belt, Missouri: Colombia, Missouri, Water Resources Research Center, Completion Report A–060, 85 p.

Warner, L.Q., 1980, Colorado limeament, *in* Kent, H.C., and Porter, K.W., eds., Colorado geology: Rocky Mountain Association of Geologists, Symposium on Colorado, p. 11–21.

Weeks, J.B., Gutentag, E.D., Heimes, F.J., and Luckey, R.R., 1988, Summary of the High Plains regional aquifer-system analysis in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming; U.S. Geological Survey Professional Paper 1400–A, 30 p.

Young, H.L., 1992, Summary of ground-water hydrology of the Cambrian-Ordovician aquifer system in the Northern Midwest: U.S. Geological Survey Professional Paper 1405–A, 55 p.

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