REGIONAL AQUIFERS IN KANSAS, NEBRASKA, AND PARTS OF ARKANSAS, COLORADO, MISSOURI, NEW MEXICO, OKLAHOMA, SOUTH DAKOTA, TEXAS, AND WYOMING—GEOHYDROLOGIC FRAMEWORK

REGIONAL AQUIFER-SYSTEM ANALYSIS

U. S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1414-B

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Regional Aquifers in Kansas, Nebraska, and Parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming—Geohydrologic Framework

By DONALD G. JORGENSEN, JOHN O. HELGESEN, *and* JEFFREY L. IMES

REGIONAL AQUIFER-SYSTEM ANALYSIS—CENTRAL MIDWEST

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1414-B

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1993

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY

Robert M. Hirsch, *Acting Director*

Library of Congress Cataloging in Publication Data

Jorgensen, Donald G.
Regional aquifers in Kansas, Nebraska, and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming—Geohydrologic framework / by Donald G. Jorgensen, John O. Helgesen, and Jeffrey L. Imes.
p. cm. — (Regional aquifer-system analysis—Central Midwest) (U.S. Geological Survey professional paper ; 1414–B)
Includes bibliographical references.
Supt. of Docs. no.: I 19.16:1414-B
1. Aquifers—Middle West. I. Helgesen, John O. II. Imes, Jeffrey L. III. Title. IV. Series. V. Series: U.S. Geological Survey professional paper ; 1414–B.
GB1199.3.M54J67 1993 93-32495
551.49'0978—dc20 CIP

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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.

Robert M. Hirsch

Robert M. Hirsch
Acting Director

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[Plates are in separate volume]

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CONVERSION FACTORS

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
foot squared (ft^2)	0.09290	meter squared (m^2)
mile (mi)	1.609	kilometer (km)
mile squared (mi^2)	2.590	kilometer squared (km^2)
millidarcy (mD)	9.87×10^{-16}	meter squared (m^2)
gallon (gal)	3.785	liter (L)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
foot per second (ft/s)	0.3048	meter per second (m/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)

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 both the United States and Canada, formerly called "Sea Level Datum of 1929."

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ABSTRACT

Regional aquifers are described within a 370,000-square-mile area extending 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 of Arkansas and Oklahoma.

The present geohydrologic framework of aquifers and confining units in this area is controlled by topography, geologic structures, and hydraulic properties. All of these characteristics are the result of past geologic and hydrologic processes. From the end of the Precambrian to Late Cambrian time, the area was above sea level, and an uneven erosional surface had developed on the fractured crystalline rocks. From Late Cambrian through Middle Ordovician time, a transgressive but cyclic sea covered the area. The oldest deposits were mostly permeable sand followed by slightly permeable calcareous mud consisting of aragonite and algal remains.

During most of Silurian and Devonian time, nearly the entire area was above sea level, except for southern Oklahoma and northern Arkansas. Uplift diagenesis (diagenetic processes that occur during periods of uplift) greatly increased porosity and intrinsic permeability of the rocks. At the end of Devonian or the beginning of Early Mississippian time, a transgressing sea covered most of the area, and a very slightly permeable clay was deposited.

Calcareous mud was the dominant sediment deposited during much of Mississippian time. Tectonic activity increased as evidenced by uplifts, such as the Colorado–Wyoming uplift and the Nemaha uplift in Kansas. Subsiding basins, such as the Arkoma and Anadarko, received large quantities of sediment that covered the older rocks causing burial diagenesis of the calcareous muds, which in general, decreases primary porosity and permeability due to loading of sediments and selectively increases secondary porosity and permeability due to fracturing and dissolution.

Tectonic activity was at a maximum during Pennsylvanian time and decreased through the Permian. Uplifts, such as the Front Range, Apishapa, Criner, Amarillo, Wichita, Arbuckle, Ouachita, Ozark, Nemaha, and Cambridge–Central Kansas, were active. The Arkoma and Anadarko basins continued to subside and received as much as 20,000 feet of clay, calcareous mud, and sand. During the Permian, the eastern part of the area was tilted upward; the sea receded and regional ground-water flow commenced from east to west. In the Ozark uplift area, a small ground-water flow system began around the St. Francois Mountains.

During Triassic and Jurassic time, while the eastern part of the study area was above sea level, uplift diagenesis generally increased secondary porosity and permeability. However, during Early Cretaceous time, a transgressive but cyclic sea deposited permeable sand and very slightly permeable clay over the western and central parts of the study area. During Late Cretaceous time, clay was deposited in thick layers, and burial diagenesis occurred throughout most of the area. At the end of the Cretaceous and into Tertiary time, major uplifts, such as the Rocky Mountains, were formed as part of the Laramide orogeny. Uplifts in the west accompanied the regional tilting of the study area downward to the east. Regional ground-water flow changed to west to east in the Lower Cretaceous sandstones and in pre-Pennsylvanian rocks. The ground-water flow system near the St. Francois Mountains on the Ozark uplift continued to expand outward as Pennsylvanian and Permian rocks were removed by erosion.

Three major regional aquifer systems are identified in the area—the Western Interior Plains aquifer system, the Great Plains aquifer system, and the Ozark Plateaus aquifer system. The Western Interior Plains aquifer system and the overlying Great Plains aquifer system are in the western part of the Interior Plains physiographic division. The Western Interior Plains aquifer system, the Western Interior Plains confining system, and the overlying Great Plains aquifer system, all overlie the basement. Overlying these geohydrologic systems are the Great Plains confining system and the High Plains aquifer. Water in both aquifer systems flows mostly west to east. The Ozark Plateaus aquifer system is in the Interior Highlands physiographic division, mostly in the Ozark Plateaus. In this area, water flows outward from the axis of the Ozark Plateaus. A transition zone in western Missouri, southeastern Kansas, and northeastern Oklahoma marks the location where the flow from the Western Interior Plains aquifer system and the Ozark Plateaus aquifer system meet and move vertically upward to the streams and the near-surface water table.

Rocks of the Western Interior Plains aquifer system consist mostly of dolostone, limestone, and shale of Cambrian through Mississippian age. At most locations, the aquifer units are permeable and water yielding except in deep basins where permeability is markedly decreased. The aquifer system is several thousand feet thick in the Anadarko basin. The aquifer system contains saline water with dissolved-solids concentrations ranging from about 10,000 to more than 200,000 milligrams per liter. Intrinsic permeability is small, ranging from 10^{-17} to 10^{-11} feet squared.

The Western Interior Plains confining system restricts water flow between the Western Interior Plains aquifer system and the overlying Great Plains aquifer system at nearly all locations including the deep basins. The thick confining system consists mostly of layered shale, limestone, sandstone, and evaporite

deposits of Late Mississippian through Jurassic age. The thickness of the confining system decreases from about 20,000 feet in the Anadarko basin to about zero along the periphery of the Ozark Plateaus, where it crops out.

The Great Plains aquifer system overlies the Western Interior Plains confining system and contains two regional aquifers and one confining unit. Both aquifers are composed predominantly of permeable Lower Cretaceous sandstone and are separated at most locations by a shale confining unit. Most recharge occurs in southeastern Colorado and northeastern New Mexico. Ground water flows east-northeast from these western recharge areas to discharge areas in central Kansas and eastern Nebraska.

Intrinsic permeability in the Great Plains aquifer system ranges from 10^{-13} feet squared in the Denver basin to more than 10^{-10} feet squared near the eastern outcrops. The Maha aquifer (mostly Dakota Sandstone and equivalents) is the upper of the two major regional aquifer units and is more extensive than the underlying Apishapa aquifer (mostly Cheyenne Sandstone and equivalents). The Apishapa confining unit (mostly Kiowa Shale) separates the Apishapa and Maha aquifers. Dissolved-solids concentrations of water in the Great Plains aquifer system decrease from more than 20,000 milligrams per liter in western Nebraska to less than 1,000 milligrams per liter along outcrops in southeast Colorado, central Kansas, and eastern Nebraska.

The Ozark Plateaus aquifer system is within the Ozark Plateaus area. The aquifer system includes three regional aquifers and two confining units. They are in ascending order, the St. Francois aquifer, the St. Francois confining unit, the Ozark aquifer, the Ozark confining unit, and the Springfield Plateau aquifer. The St. Francois aquifer, which is the lowest geohydrologic unit of the Ozark Plateaus aquifer system, is composed of mostly Upper Cambrian sandstone, and lies on the basement. The aquifer is more than 1,000 feet thick near the Mississippi River Alluvial Plain, but typically is 200 to 500 feet thick. The St. Francois confining unit, which overlies and confines the St. Francois aquifer, is composed of Upper Cambrian shale, siltstone, dolostone, and limestone and is leaky because it transmits a considerable quantity of water.

The Ozark aquifer, the largest and most extensively used aquifer in the Ozark Plateaus area, is composed mostly of Upper Cambrian through Middle Ordovician fractured and permeable dolomitic rocks. The aquifer is typically about 1,000 feet thick and is the thickest unit in the Ozark Plateaus aquifer system. The Ozark confining unit restricts the movement of water between the Ozark aquifer and the overlying Springfield Plateau aquifer. The confining unit includes Upper Devonian through Lower Mississippian shale.

The Springfield Plateau aquifer is composed of fractured and permeable Mississippian limestone. Aquifer thickness is as much as 1,500 feet, but thicknesses of 100 to 400 feet are typical. The aquifer is overlain to the west by beds of very slightly permeable shale of Pennsylvanian age.

INTRODUCTION

The study area of the Central Midwest regional aquifer-system analysis (Central Midwest RASA) 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 of Arkansas and Oklahoma. The strata of interest are from Cambrian to Cretaceous age and are thousands to tens of thousands of feet thick in some areas. Several important regional aquifer systems that contains both freshwater and saline water (greater than 7,000 milligrams per liter dissolved solids) are included in the study area. In much of the area, little was previously known about the regional flow and hydrochemistry within the aquifer systems or about relations among them.

Within the central United States, three other regional aquifer-system analyses (RASA) (fig. 2), which in places share geographic or hydrologic boundaries with Central Midwest RASA, were completed prior to this study. These RASA were the High Plains RASA (Weeks, 1978), the Northern Great Plains RASA (Dinwiddie, 1979), and the Northern Midwest RASA (Steinhilber and Young, 1979). The Gulf Coast RASA (fig. 2) is still being conducted in 1987 as this report is being written (Grubb, 1984).

PURPOSE AND SCOPE

The background, purpose, scope, objectives, and approach of the Central Midwest RASA are described in the project-planning report by Jorgensen and Signor (1981). The findings of the Central Midwest RASA are reported in five chapters: Chapter A is the summary chapter, which will collate the important findings reported in other chapters; chapter B (this report) 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.

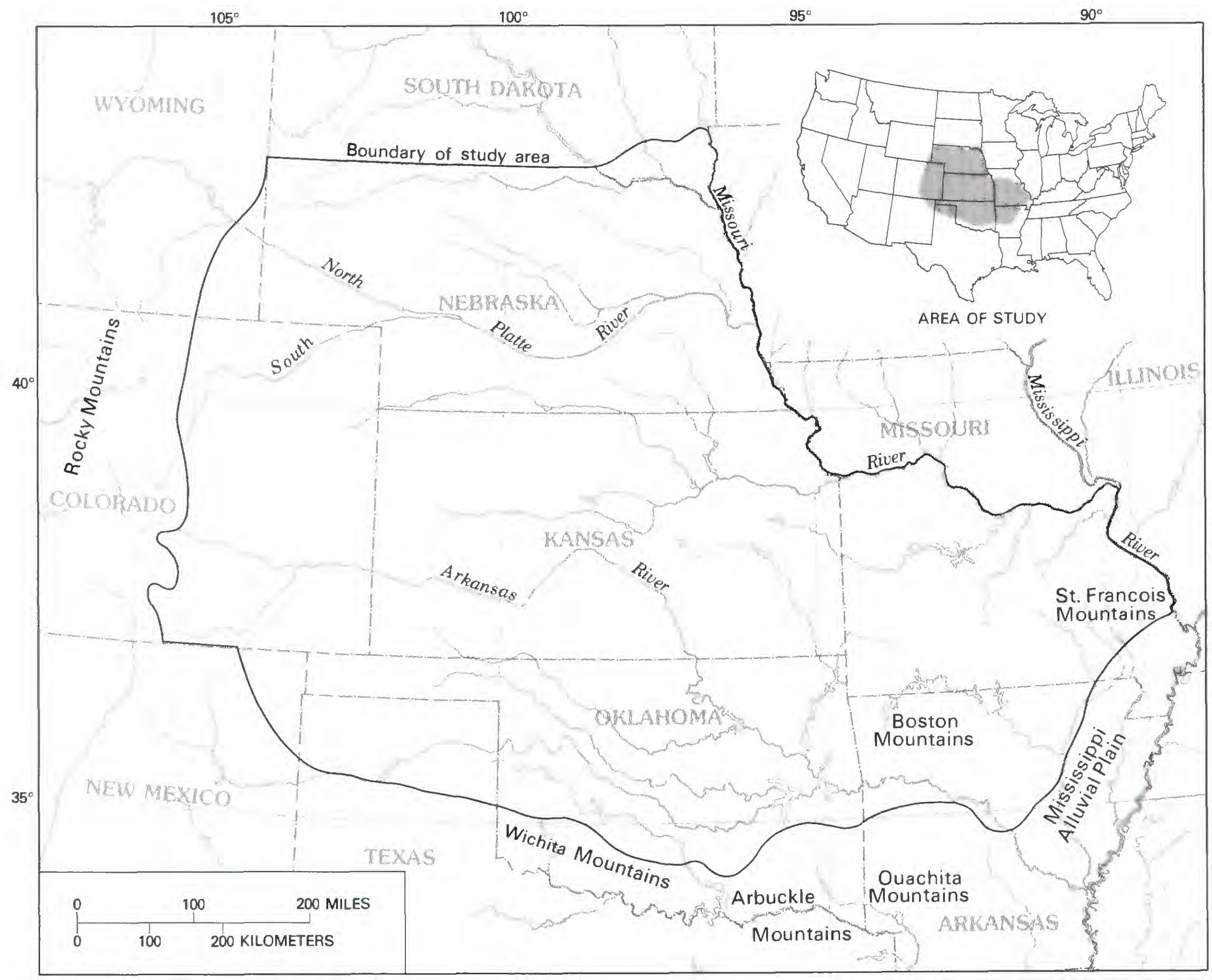
The purpose of this chapter is to describe the regional aquifers and confining units in the Central Midwest and the hydrogeologic framework in which they exist. The aquifers and confining units described are within the stratigraphic section from Cambrian rocks through the Cretaceous Dakota Sandstone and its equivalents within the study area. The scope of the study does not specifically include the rocks that contain the High Plains aquifer. The information on the High Plains aquifer can be obtained from U.S. Geological Survey Professional Paper 1400–A through 1400–E. Although at a few locations the High Plains aquifer is in direct connection with aquifer units of the Central Midwest RASA, it is a separate regional aquifer that overlies the units studied herein.

APPROACH

A description of a ground-water hydrologic unit (geohydrologic unit) in this report includes the extent, thickness, altitude, and geologic framework of the rocks of the geohydrologic unit, as well as its hydraulic properties and hydrologic relations with other units. The correlation of geologic formations (strata) to geohydrologic units is termed its "geologic" framework. The delineation of geohydrologic units in reference to the framework of geologic formations is especially useful because formations are relatively well defined and generally are well known. Because of the large size of the study area, correlation of stratigraphic units across structural basins and State lines also was required. The usual concept of geologic framework in most investigations is expanded in this report to include discussion of geologic and hydrologic history because these topics help to explain the hydraulic properties and water chemistry of the present hydrologic systems.

PROCEDURE AND TECHNIQUES

A geohydrologic unit, such as an aquifer, aquifer system, confining unit, or confining system, is defined largely on the basis of hydraulic conductivity and its resultant effect on ground-water flow. Water-bearing units (aquifers) that contain relatively freshwater have a characteristic potentiometric surface that is continuous and relatively smooth. The surface is a useful tool in defining a geohydrologic unit. The potentiometric-surface map is based on altitude of the water level measured in wells finished in the aquifer unit. The configuration of the potentiometric surface



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

FIGURE 1.—Location and extent of study area.

is also helpful in identifying directions of ground-water flow and areas of recharge and discharge. In areas where fresh ground water is readily available and is developed, considerable hydrologic and hydraulic information are available. The information is used to delineate the geohydrologic systems. However, in most of the study area hydrologic information is not available, especially where aquifers contain water of variable density. In these areas the geohydrologic systems are delineated on the basis of hydrologic relations inferred from geologic and geochemical information.

DATA COMPILATION

Data that were needed for the definition of geohydrologic units and their evaluation were compiled and entered into data bases. These data included lithologic and geophysical logs, water-level measurements, chemical analyses, records of fluid (water, oil, and gas) withdrawal or injection, hydraulic properties, and oil- and gas-reservoir properties. A data base of estimates of intrinsic permeability and dissolved-solids concentrations based on geophysical-log data was also created. The existing U.S. Geological Survey Ground Water Site Inventory (GWSI) computer-based data-storage and retrieval system was used to the degree possible.

Information from geophysical-log interpretations was essential in compiling maps of a geohydrologic unit. In most of the area, the lithologic and geophysical logs that were used were of test holes for petroleum. However, in the areas where the rocks contain freshwater, lithologic and geophysical logs were of water wells or test holes. Logs that were representative of an area, such as a county, were selected to be included in the project data base. Ideally, the chosen log was of a drill hole that penetrated the Cretaceous-to-Precambrian rock section. In areas for which numerous logs were available, such as near oil and gas reservoirs, only a few of the numerous logs avail-

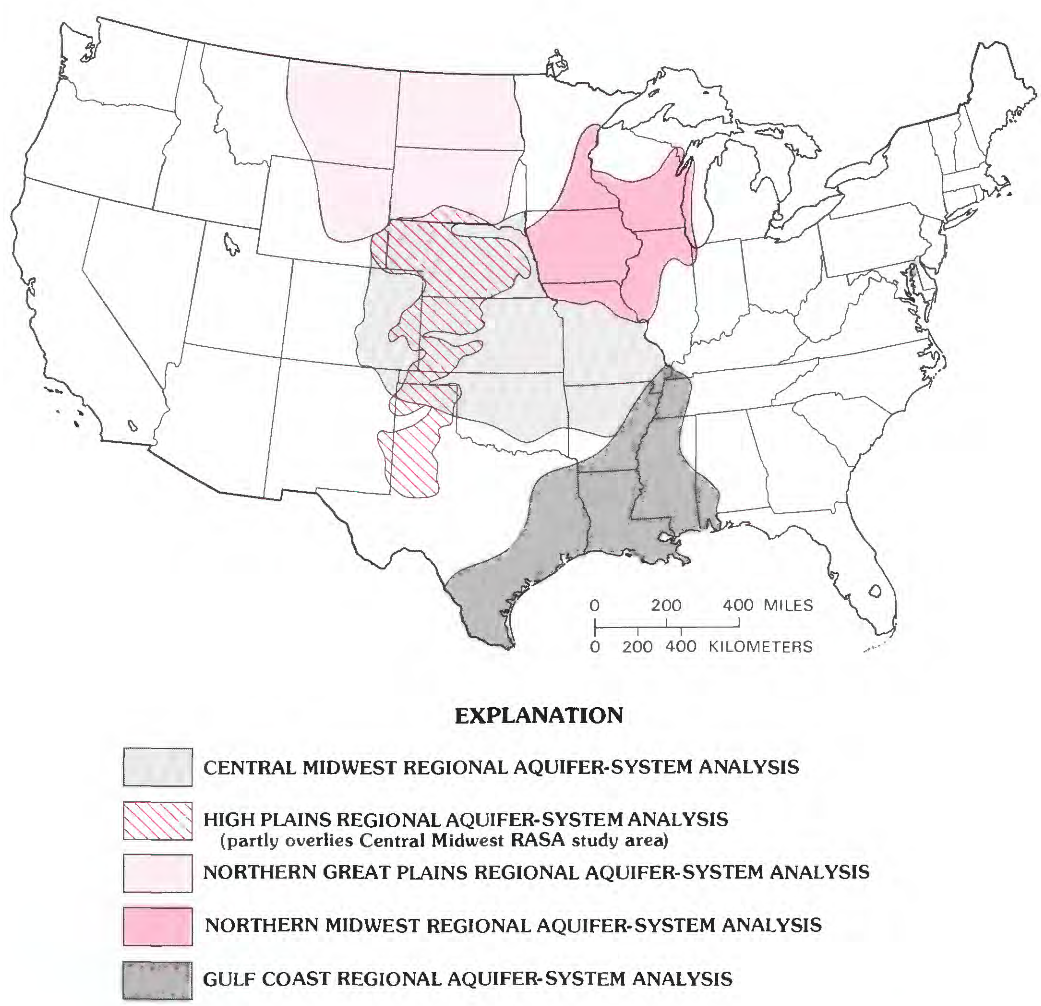


FIGURE 2.—Aquifer-system analysis contiguous to Central Midwest regional aquifer-system analysis.

able were selected. In other areas with few data, most available logs were selected.

Data of selected water-level measurements in wells were stored in the GWSI data base of the U.S. Geological Survey. Results of drill-stem tests were stored in a project file termed "Reservoir Parameter File." Hydrochemical data from many sources were entered in a "Hydrochemical File." Sources of data for this hydrochemical file included the U.S. Geological Survey WATSTORE Water-Quality file (Baker and Foulk, 1975), the National Uranium Resource Evaluation file (Arendt and others, 1979, p. 11), and the Petroleum Data Systems file (University of Oklahoma, 1980) as well as information from existing publications and other sources. Selected data from this hydrochemical file were used to create a project file termed "Hydrochemical Data Base" for water-chemistry maps.

Most of the chemical analyses of saline water were obtained from the petroleum industry. Large differences between the reported concentrations of dissolved solids from adjacent well sites typically characterized samples of saline water. The cause of these differences are difficult to determine. It is not known whether the differences are related to areal, vertical, and temporal variability, to errors resulting from the sampling procedure, or to methods of chemical analysis. For example, the exact source of many of the water samples is unknown. Some samples were obtained from drill-stem tests; others are "production" water. Some may be mixtures of in situ water and drilling fluids or of water from zones above or below the zone of interest. However, chemical analyses of water from adjacent wells located in the freshwater areas did not have large variability.

MAP PREPARATION

Maps showing the extent and altitude of the top of geohydrologic units were constructed using information from lithologic and geophysical logs and from topographic maps in outcrop areas. Typically maps of the altitude of geohydrologic units are more detailed in the Ozark area because they are based mostly on topographic control at outcrops, whereas in other areas, such as where the unit is deeply buried, less data are available. Thickness maps were made from measured data; however, if thickness information was not available, then the supplemental thickness was determined by calculating the difference between the altitudes of the top and bottom of the zone of interest. Fault locations were obtained from published geologic maps. Only major faults and those faults causing a major thickness discontinuity are shown on the thickness maps.

Many aquifers have a characteristic hydrochemistry that is the result of chemical processes occurring within the aquifers as well as the chemistry of water recharging the units. Maps showing preliminary interpretations of the dissolved-solids concentrations were prepared because more dissolved-solids data are available than any other type of chemical data. Selection of analyses used to prepare the dissolved-solids maps generally was governed by ionic balance and continuity with adjacent analyses. In the absence of analytical data, the concentration of dissolved solids was estimated from measurements of spontaneous potential from wireline-geophysical logs of boreholes or from cross plots of resistivity and porosity data also from wireline-geophysical logs. The procedure for estimating water resistivity and dissolved-solids concentration is described by Jorgensen (1989).

Maps of the configuration of the potentiometric surface in parts of aquifers containing freshwater were prepared to evaluate the continuity of an aquifer and to determine areas of recharge and discharge. A surface defined by equivalent-freshwater head is used in evaluating the lateral hydraulic continuity of permeable rocks. In parts of aquifers containing fresh ground water, maps showing the potentiometric surface were constructed to evaluate the flow system and areas of recharge and discharge. In parts of the aquifers containing variable-density fluid, a surface defined by equivalent-freshwater head is used. This surface of equivalent-freshwater head should be used with caution. Under certain conditions, flow direction may not be down the equivalent-freshwater head gradient. For rocks containing variable-density fluids, no potential field exists if density is not solely a function of pressure (Jorgensen and others, 1982; Hubbert, 1940). Nevertheless, the surface of equivalent-freshwater head is still useful if caution is exercised.

Altitudes of equivalent-freshwater head were determined from shut-in pressures of drill-stem tests in wells containing salinewater or by measurement of the water level in wells containing freshwater. The following equation, in consistent units, was used to calculate equivalent-freshwater head (h_e):

$$h_e = z + \frac{p}{d\,g} \qquad (1)$$

where

z is the altitude at the centerline of the rock section,

p is the pressure at the centerline of the rock section,

d is the density of freshwater, and

g is the acceleration due to gravity.

Pressure values from the drill-stem tests were adjusted to the centerline of the rock section tested. The adjustment to the pressure (p_a) was calculated using the following equation in consistent units:

$$p_a = d_f \, g \, (z_g - z) \quad (2)$$

where
d_f is the density of the in situ (formation) water and
z_g is the altitude of the pressure gage used for the drill-stem test.

Density of formation water increases with increasing concentration of dissolved solids and decreases with increasing temperature. In shallow wells containing freshwater, the correction for density is trivial, and the equivalent-freshwater head is considered equal to the altitude of the water level within the well.

Accuracy of the calculated equivalent-freshwater head values derived from results of drill-stem tests is difficult to evaluate because it is dependent on the accuracy of the recording gage, the conditions of the test, and the hydraulic character of the rock. Comparison of data from adjoining drill-stem tests in the same test hole or adjacent test holes indicates considerable differences. The differences may be due either to unknown inaccuracies, as reported in the drill-stem test results, or to areal, vertical, or temporal variations, such as the effects of petroleum development.

DETERMINATION OF HYDRAULIC PROPERTIES

POROSITY

Porosity of a water-saturated rock is the ratio of its interstices to its total volume (Lohman, 1972, p. 10). Porosity is an important element in determining both the storage coefficient and the hydraulic-conductivity properties of the materials in a geohydrologic unit. The relation among porosity, hydraulic conductivity, and other properties are described by Jorgensen (1980, p. 12–14). Additionally, the relation between effective porosity and permeability (or hydraulic conductivity) is extremely useful, especially in areas where porosity data are available but hydraulic-conductivity data are not. Porosity values were available throughout most of the study areas. Values were obtained from analysis of results from drill-stem tests, from laboratory analyses of rock cores of test holes, or from analyses of production data from oil or gas reservoirs. Measurement of porosity (or permeability) of fractured rock in the laboratory is nearly impossible because of the difficulty of obtaining a large enough rock sample to provide representative values of those properties and of arranging the fractured pieces in the same manner as they were in situ. Porosity (and permeability) of "repacked" samples of unconsolidated material may be erroneous. Reported porosity values for many oil and gas reservoirs are of unknown accuracy and were determined by generally unreported techniques. In situ porosity values can be determined from measurements made by wireline-geophysical equipment, specifically density (gamma-gamma), neutron, and sonic logs (MacCary, 1978, p. 9). Borehole-compensated dual-porosity logs (density and neutron), in combination with lithologic information, can also be used to calculate porosity.

Porosity values for this investigation were determined from borehole-compensated dual-porosity logs. These data were used to prepare maps of porosity. Log-determined porosity values were considered to be more representative of a regional geohydrologic unit than values reported from analyses of well data or from laboratory measurements of cores because these reported values represent local rock characteristics or portions of tested sections, not the entire thickness of the geohydrologic unit.

A comparison of reported porosity values for specific oil and gas reservoirs with the regionalized (log-determined) porosity values read from the porosity maps was made for different lithologies and for different stratigraphic units. Reported reservoir values compared well with the regional values for rock sections that consisted of Jurassic and Lower Cretaceous sandstone (fig. 3). The correlation probably reflects a

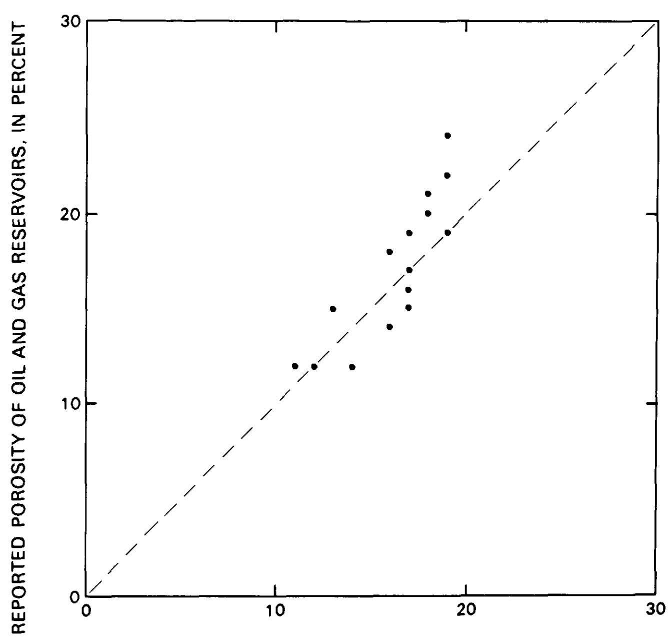


FIGURE 3.—Comparison of regional and reservoir porosity of Jurassic and Lower Cretaceous sandstone.

dominance of primary porosity over secondary porosity, because primary porosity is more isotropic than the highly anisotropic fracture porosity.

Reported reservoir porosity values for Pennsylvanian and Permian rocks, Mississippian limestone, and Cambrian through Devonian rocks did not correlate well with regionalized porosity values (figs. 4, 5, and 6). The poor correlations are attributed partly to the effects of the heterogeneous secondary porosity, which is due mostly to fracturing and dissolution of rock material. Oil and gas reservoirs in a heterogeneous rock section typically have porosity values greater than average (Brown, 1985). This is especially true in fractured rocks with substantial secondary porosity. Secondary porosity in fractured reservoirs commonly is developed in a thin vertical section that usually is of limited lateral extent. Dissolution of rock material generally is local and occurs along permeable paths. Therefore, reported porosity values for oil and gas reservoirs tend to be site specific and may not be representative of the entire hydrostratigraphic section either vertically or areally. This is to be expected because most oil and gas reservoirs are anomalous subsurface zones. Another comparison, not shown, indicates a general trend of decreasing porosity with depth. This trend is most pronounced in sandstone rocks of the study area, which generally have predominantly primary porosity. The trend is less pronounced in carbonate rocks, which generally have predominantly secondary

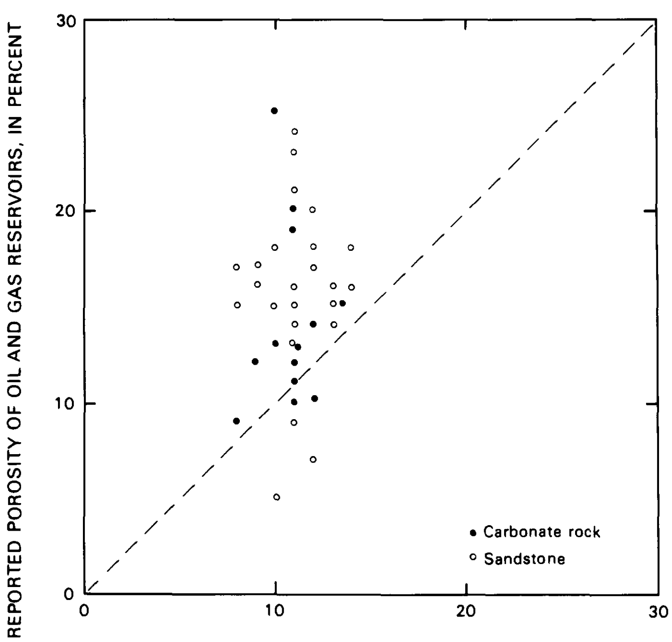


FIGURE 4.—Comparison of regional and reservoir porosity of Pennsylvanian and Permian rocks.

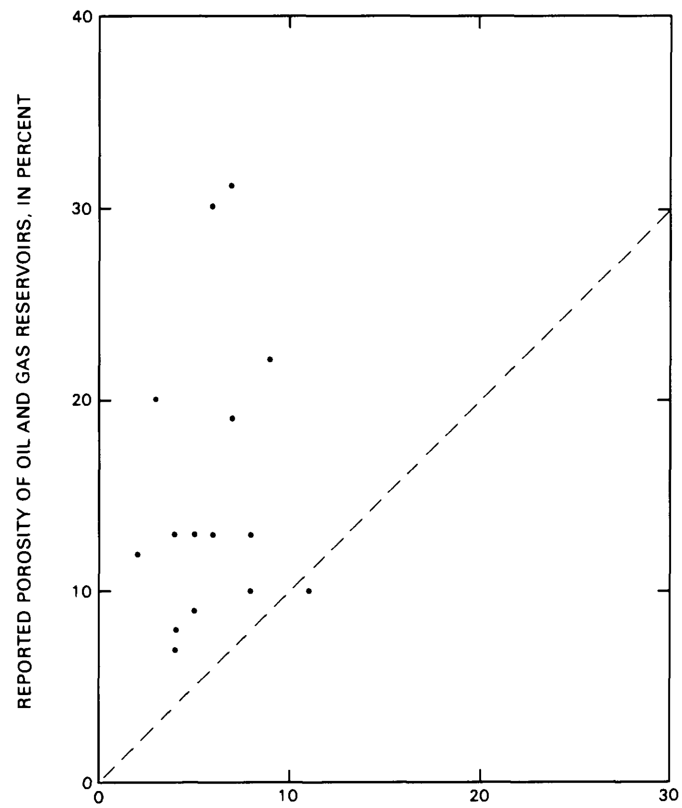


FIGURE 5.—Comparison of regional and reservoir porosity of Mississippian limestone.

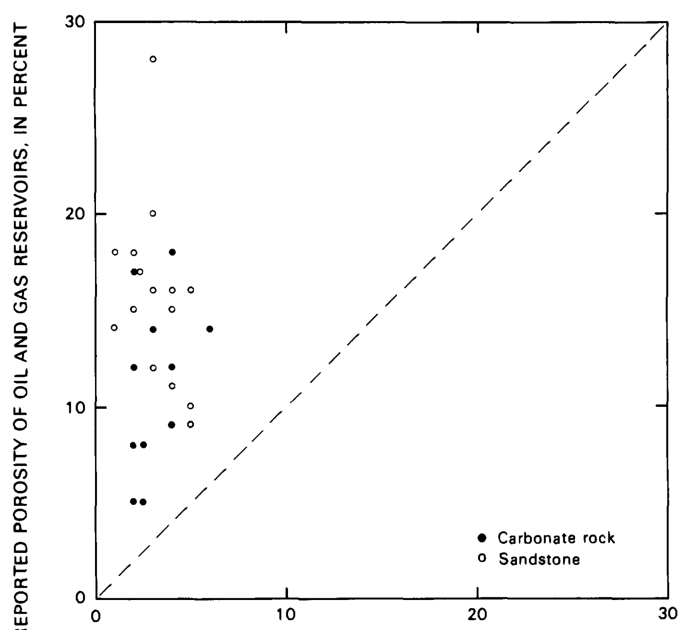


FIGURE 6.—Comparison of regional and reservoir porosity of Cambrian through Devonian rocks.

porosity. Porosity values of any type or source were not available for the deepest rocks in the study area. Estimates of porosity based on the relation of decreasing porosity with depth were made to supplement the geophysical-log or regionalized porosity values.

HYDRAULIC CONDUCTIVITY AND INTRINSIC PERMEABILITY

Hydraulic conductivity is the primary criterion in distinguishing between aquifers and confining units. Hydraulic-conductivity data for aquifers containing freshwater is obtained from aquifer tests using one well or more that completely penetrates a single aquifer. Unfortunately, few aquifer tests have been conducted in the study area. Hydraulic-conductivity data also can be estimated from specific capacity of a pumping well. Specific capacity is the ratio of discharge of water per foot of drawdown and is a function of hydraulic conductivity and well efficiency. The available specific-capacity data were from wells that generally were open to one aquifer or more and did not penetrate the complete thickness of the lower aquifer. Thus, the available specific-capacity data may not provide accurate estimates for an individual aquifer. Hydraulic-conductivity values determined from aquifer tests or specific-capacity data were stored in the GWSI file.

In rocks containing saline water, virtually no hydraulic-conductivity data are available. In these areas, permeability data were obtained from analysis of the results of drill-stem tests, laboratory analyses of cores, or oil-production tests. Intrinsic permeability (k) is the measure of the relative ease with which a rock or medium can transmit a fluid under a potential gradient, and it is a property of the rock alone. Hydraulic conductivity (K) is a measure of the ease of flow of water at a specified viscosity through a rock or medium. The equation, in consistent units, that relates the hydraulic conductivity and intrinsic permeability is:

$$K = \frac{k\,d\,g}{\upsilon_d} \qquad (3)$$

where

K is hydraulic conductivity,
k is intrinsic permeability,
d is density of the fluid,
g is acceleration due to gravity, and
υ_d is the dynamic viscosity of the fluid.

Because nearly all drill-stem tests are conducted in localized traps or reservoirs of permeable material, intrinsic-permeability values obtained by analysis of such tests may be representative of only the permeable sections of the reservoir or trap and may not be representative of the average regional permeability. Similarly, intrinsic-permeability values from cores of fractured rock also are difficult to evaluate as to their representativeness of effective regional permeability. For example, nonfracture intrinsic-permeability values from a 20-ft core of fractured and vuggy dolostone removed from a borehole within the study area ranged from less than 0.1 mD to more than 3,000 mD. The intrinsic permeability of the fractures in the rock core was not determined because it was not possible to represent the fractured rocks in the laboratory. Both laboratory tests and drill-stem tests generally are conducted on relatively thin rock sections of 20 ft or less, and the tests would not be representative of the thick regional-geohydrologic units.

To overcome these problems of estimating the average regional values, a method was developed to use data from wireline-geophysical borehole logs.

The intrinsic-permeability relation used is

$$k = \frac{\varepsilon}{S_s^2} \cdot \frac{N^{m+2}}{(1-N)^2} \qquad (4)$$

where

ε is a rock constant that is determined for each rock type,
N is porosity,
m is the cementation factor, and
S_s is the specific surface area.

The equation is obtained by combining the Archie equations developed for resistivity logs with the Kozeny equation of flow through rocks. The equation is based on the assumption that intrinsic permeability is a function of a medium or rock factor, the first set of terms, and a porosity factor (P), the second set of terms.

A plot of the porosity factor versus intrinsic permeability for 10 carefully selected data sets defined the following empirical equation for intrinsic permeability:

$$k = (1.828 \times 10^5)(P^{1.10}). \qquad (5)$$

Each data set included a porosity value, which was determined from a dual-porosity log, a cementation factor, which was determined from a cross plot of bulk resistivity versus porosity (MacCary, 1978, p. 18), and a permeability value from an in situ test. The equation has a coefficient of determination (r^2) of 0.90. The equation was useful in estimating intrinsic permeability of rocks in which electrical conduction along grain surfaces was not significant irrespective of whether the rock was dominantly a porous medium or a fractured medium.

Intrinsic-permeability values from aquifer and specific-capacity tests, along with the calculated estimates of permeability values using geophysical-log data and the above equation, were plotted on maps and contoured to show regionalized permeability.

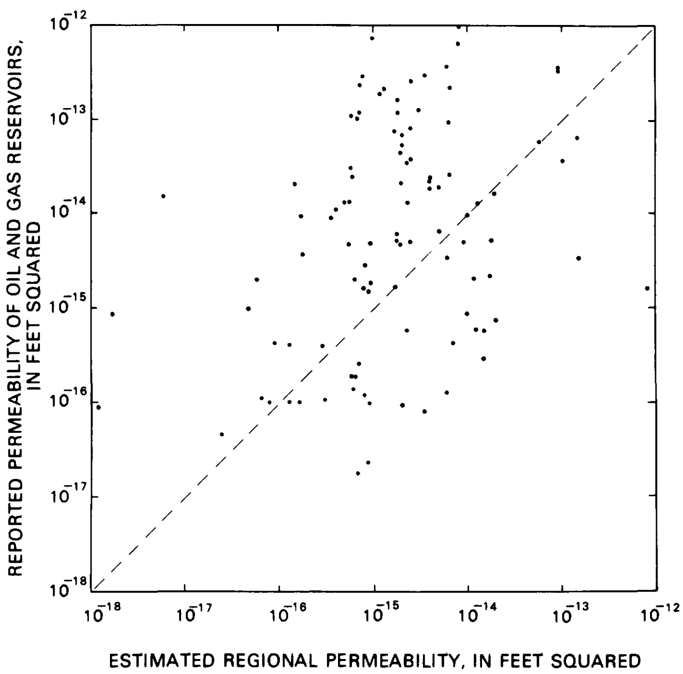


FIGURE 7.—Comparison of regional and reservoir permeability of Cambrian and Ordovician dolostone.

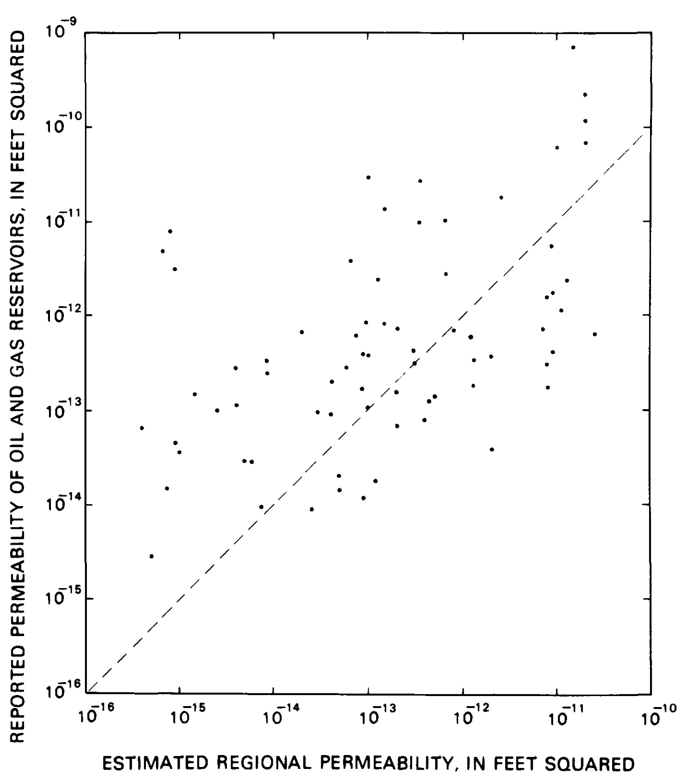


FIGURE 8.—Comparison of regional and reservoir permeability of Mississippian limestone.

Regional intrinsic-permeability values from maps were compared to site-specific intrinsic-permeability values from the "Reservoir Parameter" file, as shown in figures 7, 8, 9, and 10. The figures do not show a correlation between regionalized permeability and site permeability. Differences of two orders of

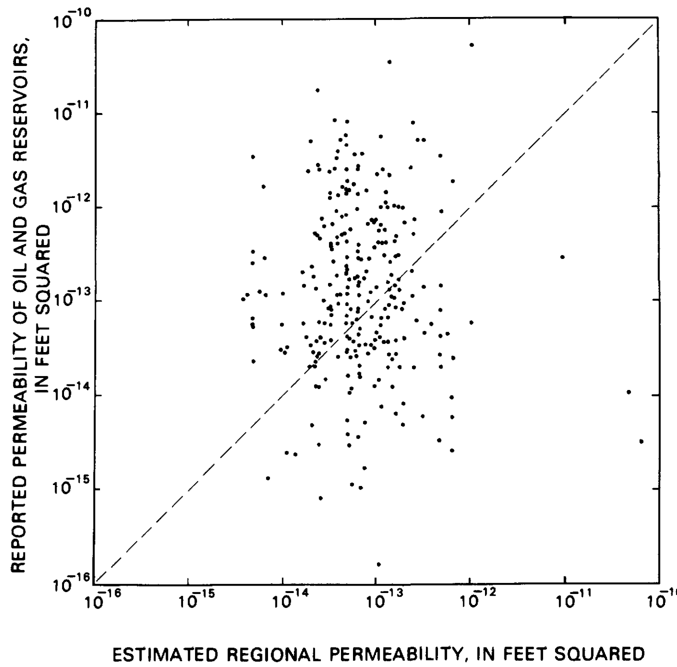


FIGURE 9.—Comparison of regional and reservoir permeability of Pennsylvanian and Permian rocks.

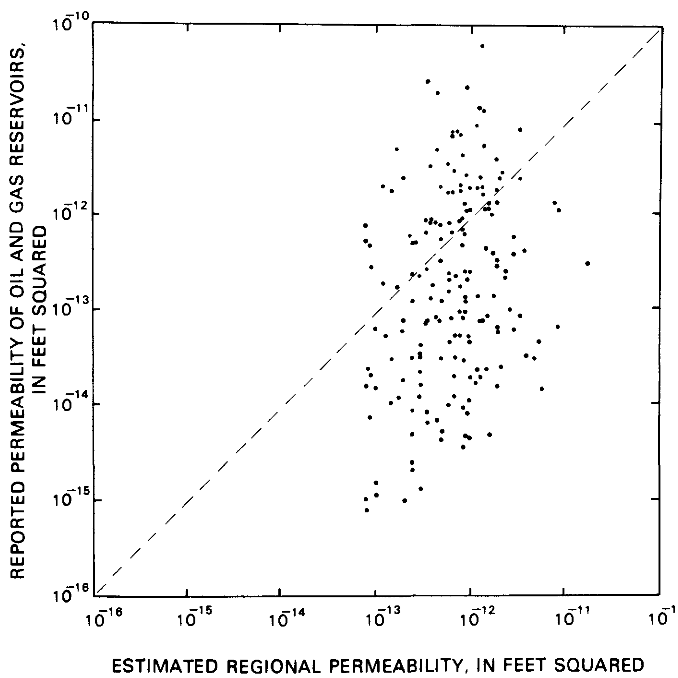


FIGURE 10.—Comparison of regional and reservoir permeability of Jurassic and Lower Cretaceous sandstone.

magnitude are not unusual. It should be remembered that site permeability values for oil and gas reservoirs were measured on thin intervals (20 ft or so), whereas the regional permeability values calculated from geophysical-log data were for thick intervals (generally 100 to 1,000 ft). It is concluded that permeability values determined from maps constructed on the basis of geophysical-log data represent estimates of regional permeability, whereas permeability values reported for oil and gas reservoirs represent localized site values.

Regional intrinsic-permeability values from the maps were the initial estimates of permeability used in a digital model of regional ground-water flow. The modeling procedure itself can be used to further refine estimates of intrinsic permeability.

PHYSICAL SETTING

Much of the study area is laterally bounded by the Rocky Mountains on the west and the Missouri and Mississippi Rivers to the east. The area is part of two major physiographic divisions, the Interior Plains and the Interior Highlands (Fenneman, 1946). The Interior Plains includes the Great Plains province and the Central Lowland. The Interior Highlands includes the Ozark Plateaus and the Ouachita province (fig. 11). 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 between the Mississippi Alluvial Plain and the Ozark Plateaus to about 6,000 ft in the extreme western part of the study area adjacent to the Rocky Mountains (fig. 12). The topography of the Ozark Plateaus and most of the Arkansas Valley is hilly to rugged, whereas most of the Interior Plains area is relatively flat. Much of the Ozark Plateaus area is covered by hardwood forest, whereas the Plains area is mainly a mixture of grassland and row crops.

Climatic characteristics for the central United States are shown in figure 13. Average-annual precipitation for 1931–60, which included two major droughts (1933–37 and 1952–57), ranged from 12 in. in eastern Colorado to more than 40 in. in the Ozark Plateaus (Eagleman, 1976, fig. 3). Potential evapotranspiration greatly exceeded precipitation except in southern Missouri and northwestern Arkansas for this same period (fig. 13). Annual surface-water runoff ranged from 1 in. or less in western Kansas and eastern Colorado to more than 25 in. in the Ozark Plateaus during 1931–60 (Busby, 1966). Annual surface-water runoff during 1951–80 exceeded 27 in. in part of the Ozarks (Hedman and others, 1987). Another regional study (Dugan and Peckenpaugh, 1985), which evaluated the quantity of water passing the root zone and reaching the water table during 1951–80, indicated that more than 15 in. per year of water was available for recharge in part of the Ozarks whereas less than 1 in. was available in western Kansas and eastern Colorado (fig. 14).

The eastern part of the study area has abundant water resources, especially surface water. Most of the western part of the study area is deficient in surface water but has substantial ground-water resources, especially the High Plains aquifer, which overlies the aquifers described in this report and has been studied previously (Gutentag and others, 1984).

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.

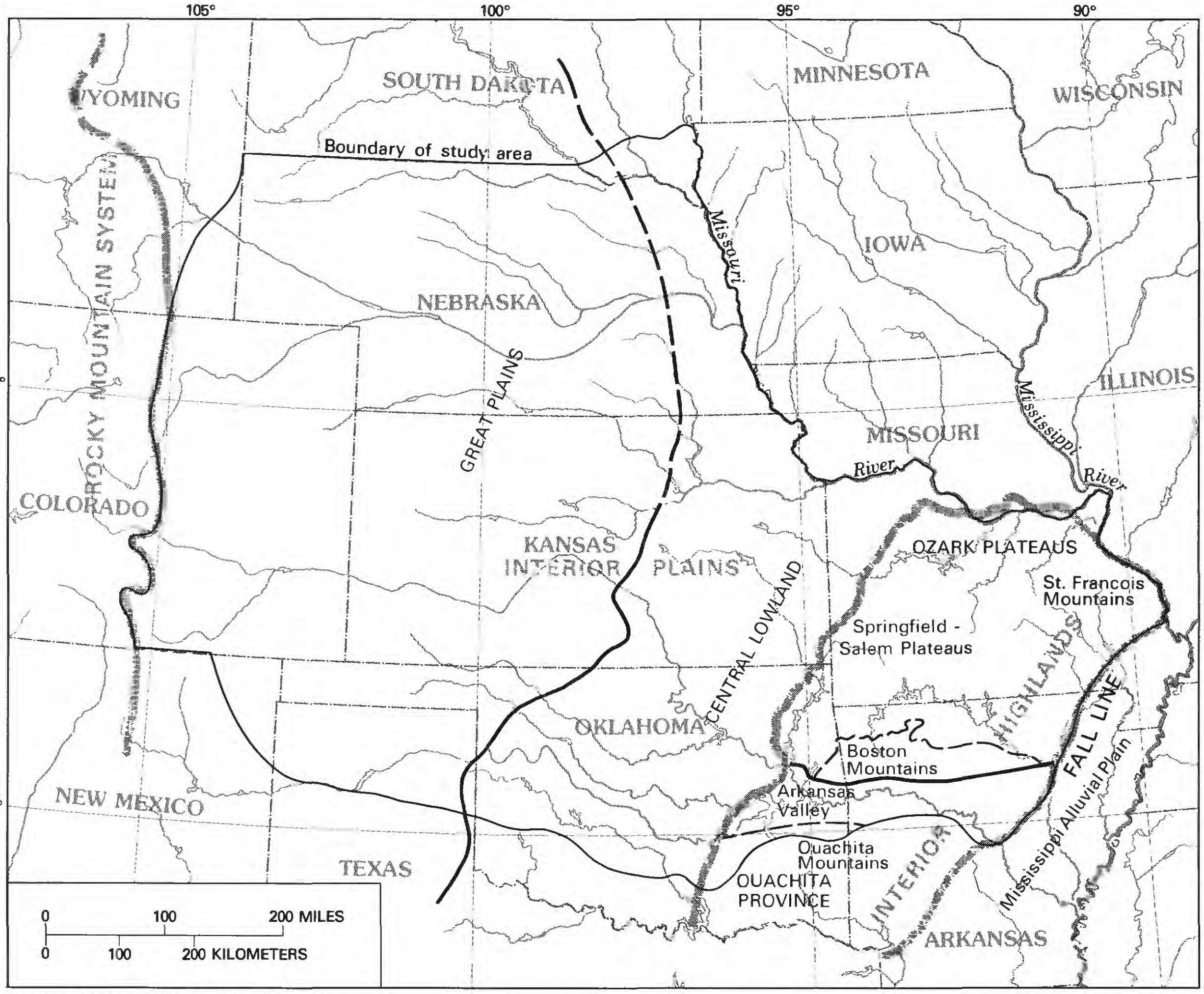
The study was greatly aided by a Liaison Committee between State agencies and the U.S. Geological Survey. The Liaison Committee not only disseminated information concerning the study to State agencies but also helped identify sources of data, defined areas of concern, and made valuable suggestions that aided the study. Committee members included: Orville Wise, Arkansas Geological 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.

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 Geologic Names Committee of the U.S. Geological Survey, contributed significantly to the resolution of problems related to stratigraphic correlation and nomenclature.

GEOLOGIC AND HYDROLOGIC HISTORY

Although structural deformation is not substantial throughout most of the study area, stratigraphic nomenclature differs markedly among States and the major structural areas (pl. 1 and fig. 15). Hundreds of names have been assigned to rock units within the thick stratigraphic interval studied. The stratigraphic names listed on plate 1 are believed to be representative of those most commonly used. The chart does not note every hiatus (a break in continuity of the rock record) but does show the major ones. Presence of a particular stratigraphic unit in a particular area, as indicated by the chart, does not imply the occurrence of that unit everywhere in that area. Furthermore, many other names and subdivisions have been applied by different investigators in different locations, depending on observed or interpreted differences in the strata. The geohydrologic units defined in this report (aquifers, aquifer systems, confining units, and confining systems) consist of all or part of one or more geologic formations.

The study area lies within the stable interior of the North American continent. Since Precambrian time, most of the study area has undergone relatively gentle deformation involving upwarp and downwarp



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

EXPLANATION

PHYSIOGRAPHIC-DIVISION BOUNDARY—Dashed where approximate

PHYSIOGRAPHIC-PROVINCE BOUNDARY—Dashed where approximate

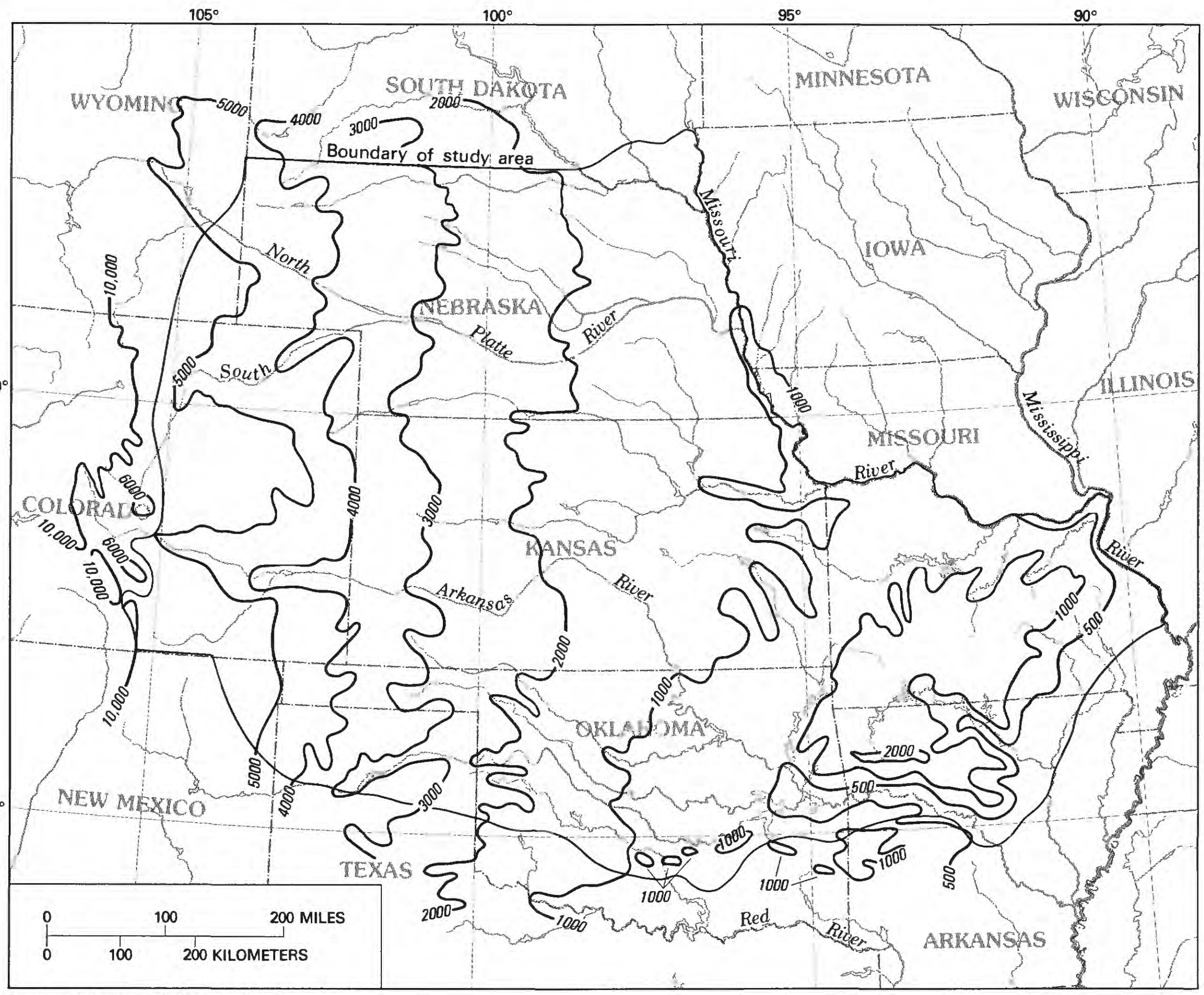
PHYSIOGRAPHIC-SECTION BOUNDARY

FIGURE 11.—Physiographic subdivisions (modified from Fenneman, 1946).

of the Earth's crust over large areas. Structurally, the study area has been dominated by broad basins and arches (fig. 15). Accordingly, most folding of sedimentary rocks has been subtle, and few major fault zones of regional significance occur. However, along the southern and western margins of the study area, strong crustal deformation by 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 places but transitional in others.

The present areal distribution of major time-stratigraphic units in the Central Midwest study area is shown in figure 16. Table 1 relates time-stratigraphic terminology to geologic time. The geologic cross sections in figure 17 illustrate the general regional continuity of the units; the greatest structural deformation is along the southern and western margins of the study area. Faulting (fig. 18) was substantial in these areas and caused large offset of rock units. Most faults in the interior of the study area have much less offset than the faults along the southern and western margins.

The present hydraulic characteristics, flow systems, and chemistry of the water within the geohydrologic units primarily are the result of past geologic and climatic events. However, present climate and human activities are now affecting water chemistry

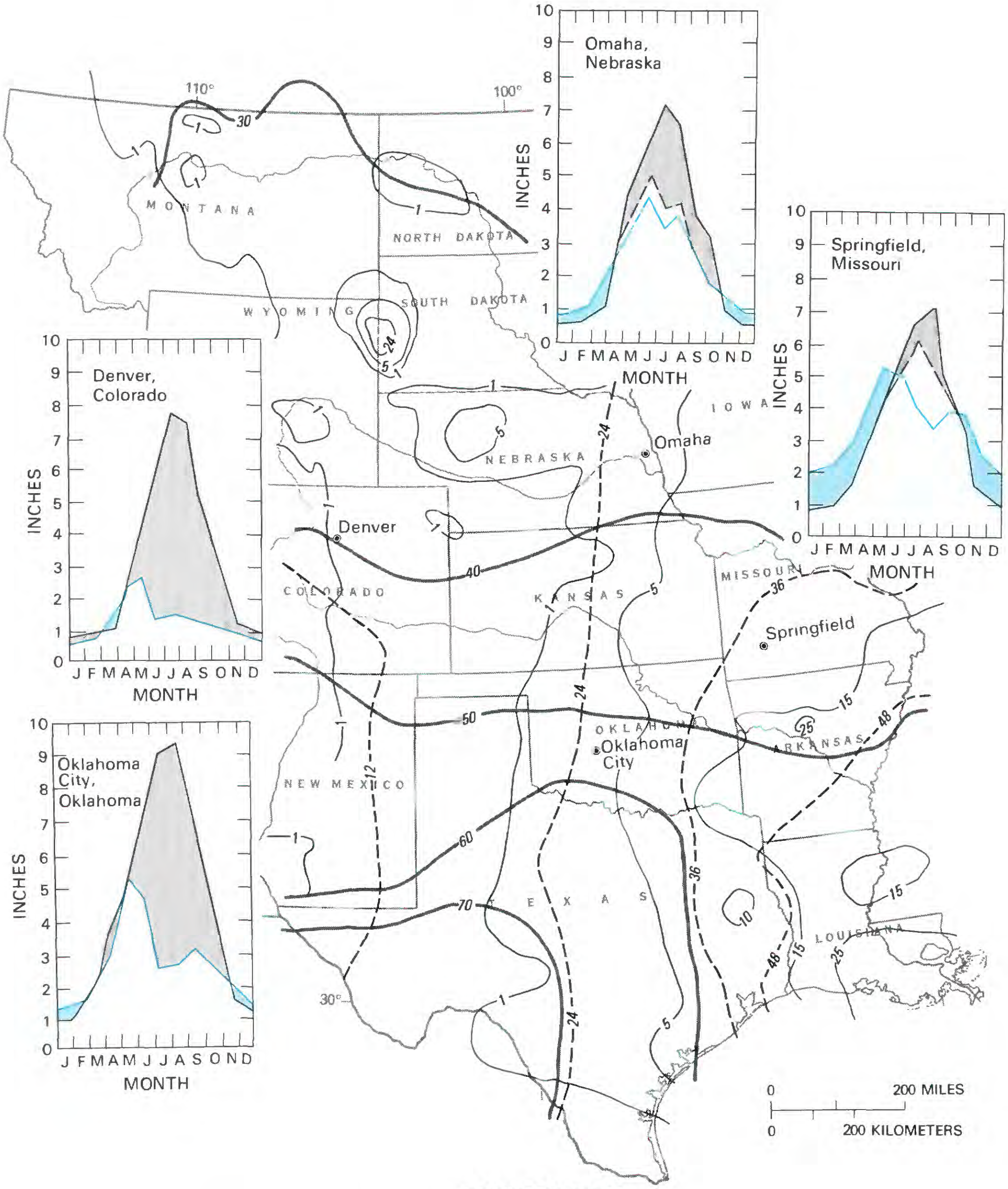


Base modified from U.S. Geological Survey 1:7,500,000, National Atlas, 1970

EXPLANATION

—4000— TOPOGRAPHIC CONTOUR—Shows altitude of land surface, in feet. Contour interval varies. Datum is sea level

FIGURE 12.—Generalized land-surface altitude.



EXPLANATION

CLIMATIC CHARACTERISTICS GRAPHS

Moisture deficit

Moisture surplus

Potential evapotranspiration

Precipitation

Actual evapotranspiration

—10— LINE OF EQUAL ANNUAL RUNOFF—Interval, in inches, varies

– –24– – LINE OF EQUAL ANNUAL PRECIPITATION—Interval 12 inches

—40— LINE OF EQUAL ANNUAL POTENTIAL EVAPOTRANSPIRATION—Interval 10 inches

FIGURE 13.—Climatic characteristics of central United States, 1931–60 (precipitation and evapotranspiration from Eagleman, 1976; runoff from Busby, 1966).

and the flow system. A summary of the paleohydrology follows and is presented in the context of geologic history with special emphasis on the changes and diagenetic processes that caused the present hydraulic characteristics, water chemistry, and flow systems.

The hydraulic characteristics of nearly all rocks are the result of diagenetic conditions of deposition and structural deformation. In large parts of the study area, no hydrologic or hydraulic data exist. However, inferred interpretations on the probable hydraulic character of the rock probably can be made by relating the rock to its paleohydrologic history. Geology, especially historical geology, is closely related to paleohydrology. Thus, a presentation of the paleohydrology is subject to the same uncertainties

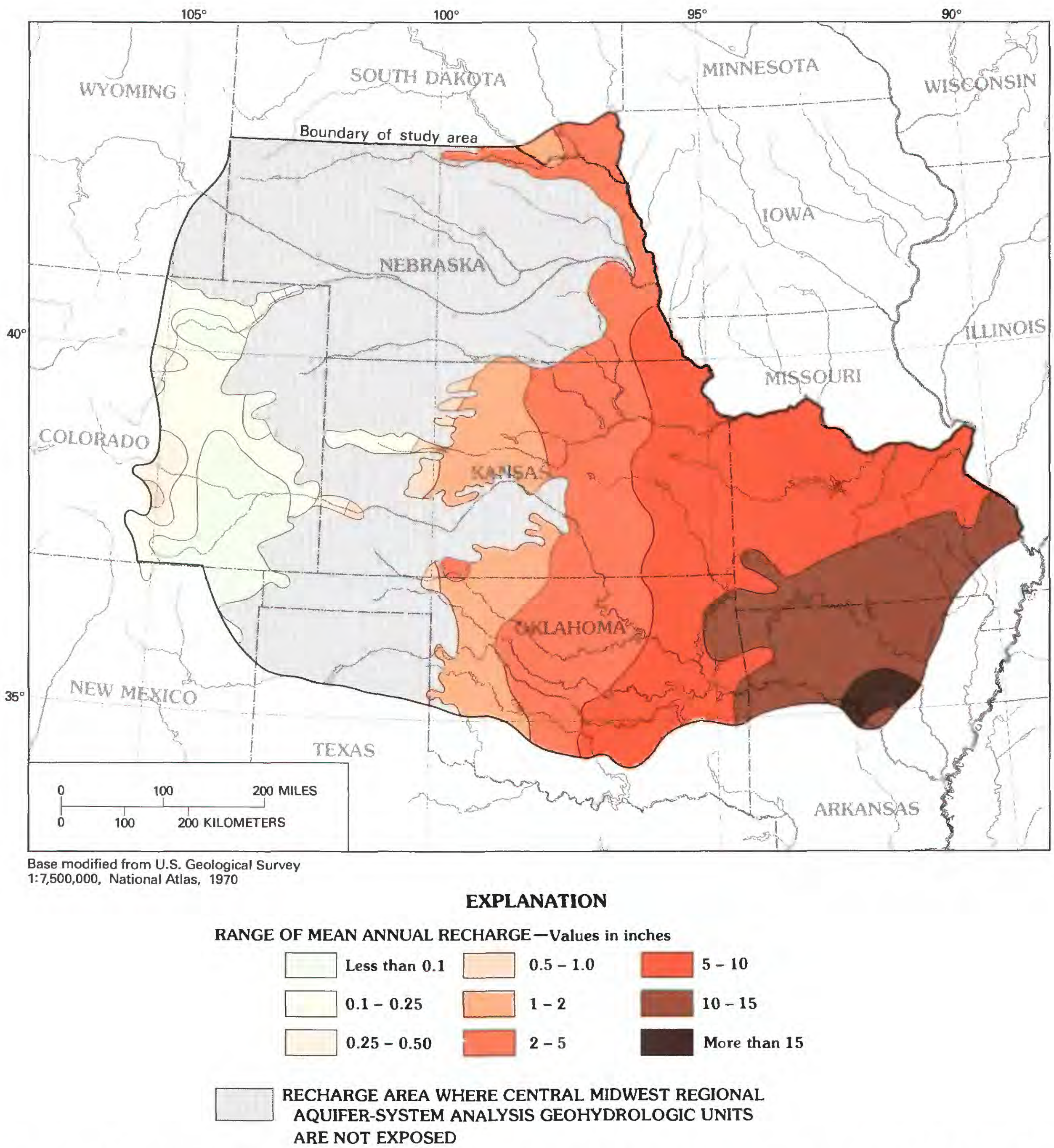
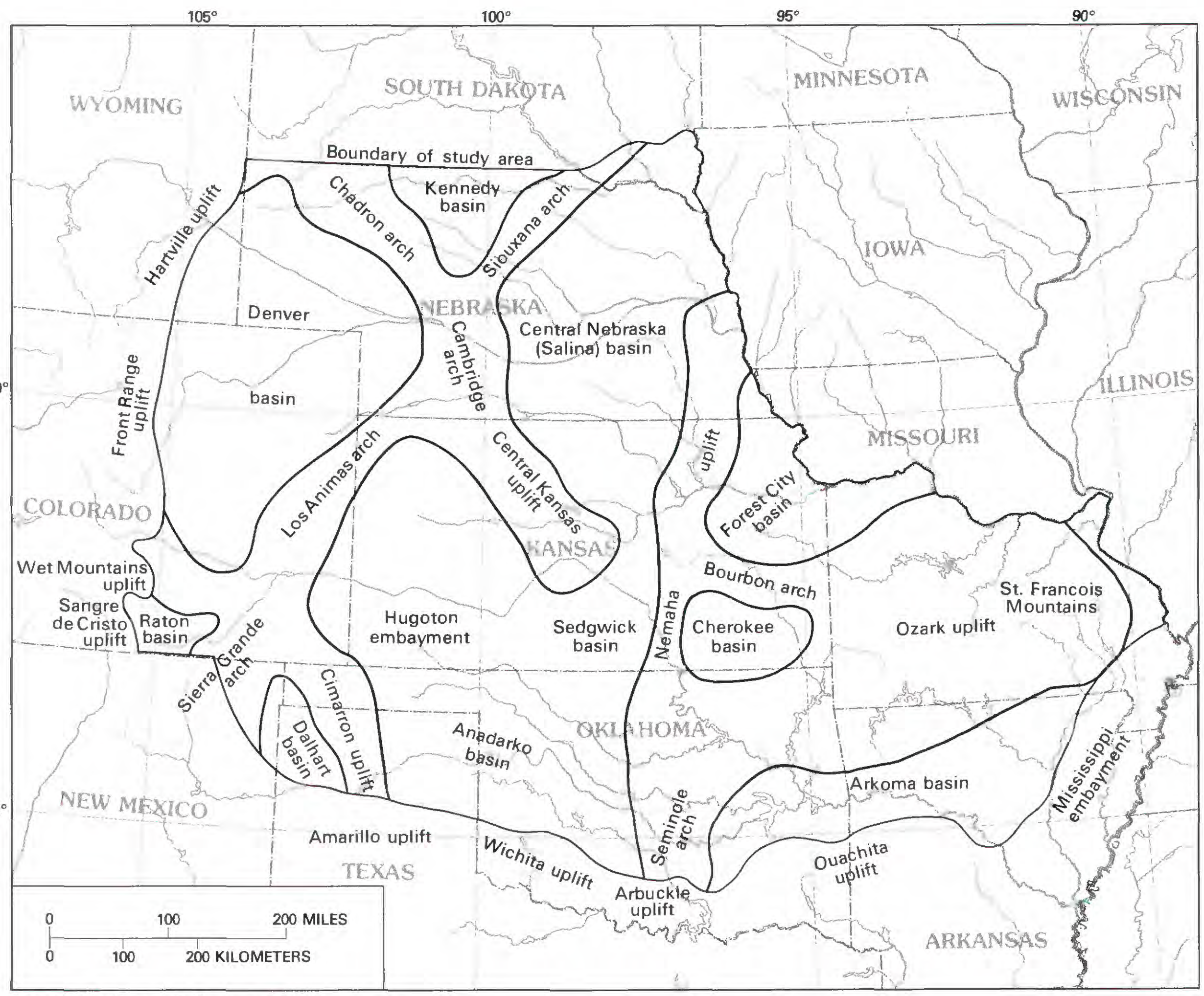


FIGURE 14.—Estimated annual recharge to exposed Central Midwest RASA geohydrologic units, 1951–80 (from Dugan and Peckenpaugh, 1985).

as the geologic history; that is, there is not always visible evidence because the evidence has been removed or obliterated. Nevertheless, inferred interpretation of what likely occurred may be made.

Many diagenetic deposition and deformation processes in reference to paleohydrology can be grouped into those associated with uplift or those associated with burial. The diagenetic processes associated with uplift or sea recession, such as nearshore lithification both above and below sea level, extensional fracturing resulting from erosional unloading, near-surface dissolution, and dolomitization in the mixing zone near coastlines, in general tend to increase porosity and permeability. Near-surface dissolution and weathering usually result in a marked increase in porosity and permeability. These diagenetic processes are termed “uplift” diagenesis herein.

Similarly, those diagenetic processes associated with subsidence of basins or rapid burial are termed “burial” diagenesis herein. These processes include compaction, pressure dissolution, thermal diagenesis of organic material, and thermal diagenesis of clay. Compaction decreases both porosity and permeability and releases pore water. Pressure dissolution dissolves rock material at points of great stress, such as grain contacts, and recrystallizes material in areas of decreased stress, such as pore space. Thermal diagenesis of organic material produces water, carbon dioxide (CO_2), and hydrocarbons. Thermal diagenesis of clay generally alters smectite to illite and releases



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

EXPLANATION

——— EXTENT OF STRUCTURAL FEATURE

FIGURE 15.—Major structural features (modified from Carlson, 1963; Merriam, 1963; Oetking and others, 1966, 1967; Bennison and Chenoweth, no date; Renfro, no date).

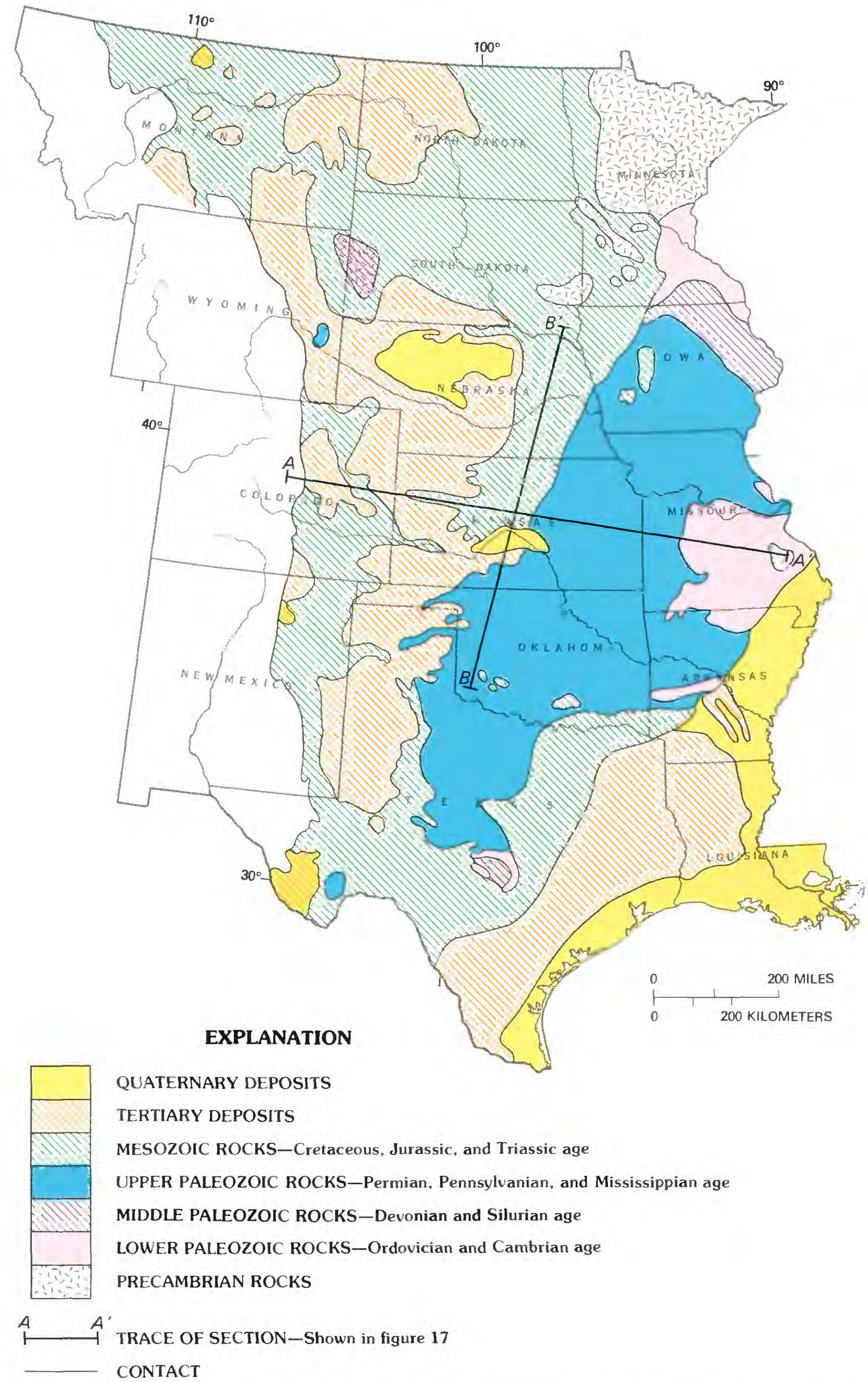


FIGURE 16.—Regional geology of central United States (modified from Kinney, 1966).

TABLE 1.—*Major geochronologic and chronostratigraphic units*

Eon or Eonothem	Era or Erathem	Period, System, Subperiod, Subsystem		Epoch	Series	Age estimates of boundaries (Ma)[1]	
Phanerozoic	Cenozoic (Cz)	Quaternary (Q)		Holocene		0.010	
				Pleistocene		1.65	(1.6–1.9)
		Tertiary (T)	Neogene Subperiod or Subsystem (N)	Pliocene		5	(4.9–5.3)
				Miocene		24	(23–26)
			Paleogene Subperiod or Subsystem (Pe)	Oligocene		38	(34–38)
				Eocene		55	(54–56)
				Paleocene		66	(63–66)
	Mesozoic (Mz)	Cretaceous (K)		Late	Upper	96	(95–97)
				Early	Lower	138	(135–141)
		Jurassic (J)		Late	Upper		
				Middle	Middle		
				Early	Lower	205	(200–215)
		Triassic (TR)		Late	Upper		
				Middle	Middle		
				Early	Lower	~240	
	Paleozoic (Pz)	Permian (P)		Late	Upper		
				Early	Lower	290	(290–305)
		Carboniferous Systems (C)	Pennsylvanian (IP)	Late	Upper		
				Middle	Middle		
				Early	Lower	~330	
			Mississippian (M)	Late	Upper		
				Early	Lower	360	(360–365)
		Devonian (D)		Late	Upper		
				Middle	Middle		
				Early	Lower	410	(405–415)
		Silurian (S)		Late	Upper		
				Middle	Middle		
				Early	Lower	435	(435–440)
		Ordovician (O)		Late	Upper		
				Middle	Middle		
				Early	Lower	500	(495–510)
		Cambrian (Є)		Late	Upper		
				Middle	Middle		
				Early	Lower	~570 [2]	
Proterozoic (Ᵽ)	Late Proterozoic (Z)	None defined				900	
	Middle Proterozoic (Y)	Late (Y3)				1200	
		Middle (Y2)				1400	
		Early (Y1)				1600	
	Early Proterozoic (X)	Late (X3)				1800	
		Middle (X2)				2100	
		Early (X1)				2500	
Archean (A)	Late Archean (W)	None defined				3000	
	Middle Archean (V)	None defined				3400	
	Early Archean (U)	None defined				3800?	
pre-Archean (pA)[3]							

Column heading spanning the first six columns: Subdivisions in use by the U.S. Geological Survey (map symbols)

[1]Ranges reflect uncertainties of isotopic and biostratigraphic age assignments. Age boundaries not closely bracketed by existing data shown by ~.

[2]Rocks older than 570 Ma also called Precambrian (pЄ), a time term without specific rank.

[3]Informal time term without specific rank.

water. Burial diagenesis generally reduces primary porosity and permeability but can selectively increase porosity and permeability through dissolution by CO_2-rich water.

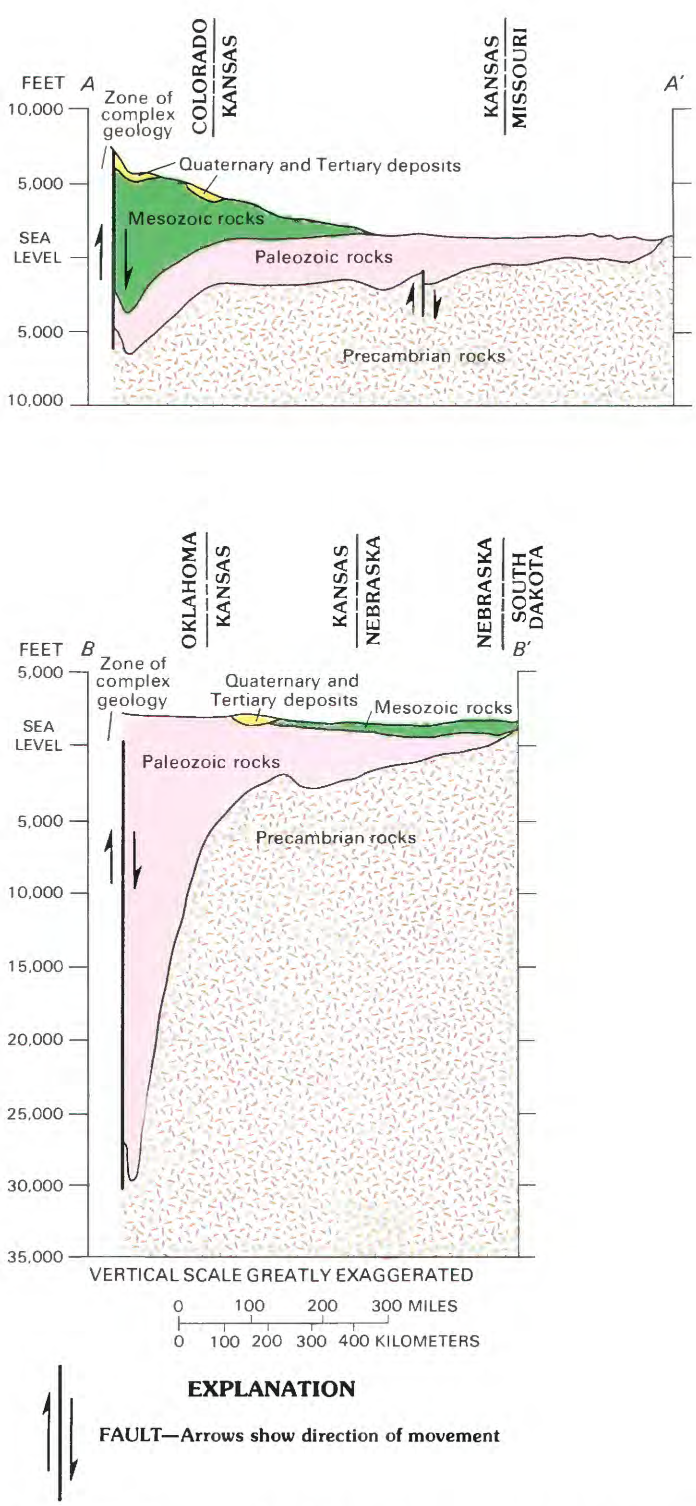


FIGURE 17.—Generalized geologic sections across study area; trace of sections shown in figure 16.

SYSTEMS OF THE PRECAMBRIAN

Little is known about the important hydrologic events during the Precambrian. Most of what is known is inferred from the Precambrian-rock record. Precambrian rocks, which underlie the stratigraphic section of interest to this study (pls. 1, 2), consist mainly of crystalline igneous and metamorphic rocks of various types that together form a basement complex. Deep burial of these rocks at most locations has precluded detailed knowledge of their nature.

Information concerning faults and fractures in the Precambrian rocks is of special importance because the faults mark weak zones that were sometimes reactivated during later geologic time. The orientation of fractures, faults, and anticlines also is an indication of the direction and magnitude of the tectonic stresses that acted on the rocks. Fractures are the major pathways for ground-water flow in well-indurated rocks.

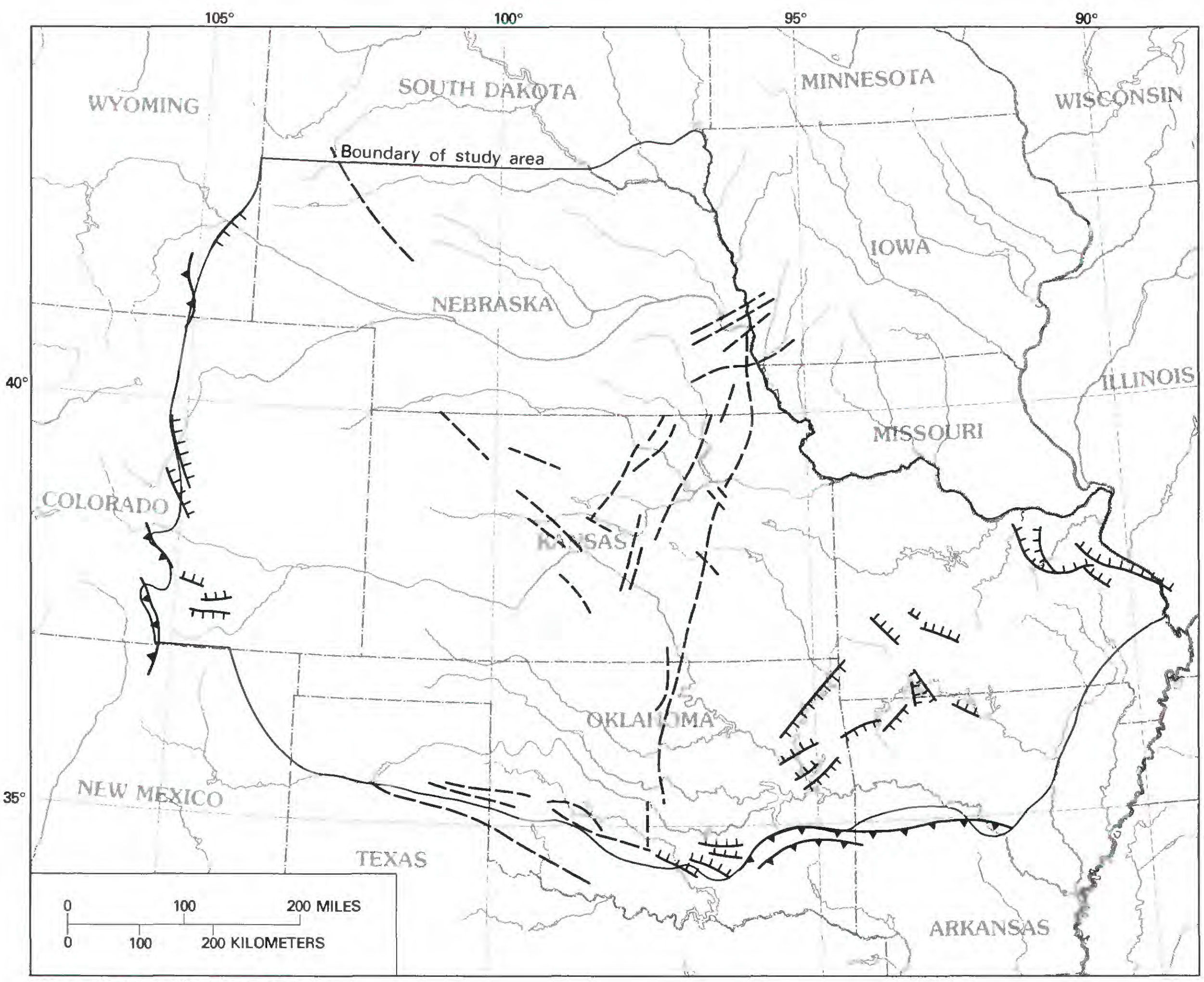
Many large faults in the study area are oriented to the northeast (fig. 18) and were formed during Precambrian time. This alignment parallels the alignment of the Colorado lineament (Warner, 1980), the Transcontinental arch (fig. 19), and the boundary between metamorphic and igneous Precambrian rocks in the region (Warner, 1980, p. 14; Sims, 1985). The dominant alignment of lineaments of the Precambrian basement in the northern midcontinent, as mapped by Sims (1985) and Hayes (1962), is N. 50° W. and approximately orthogonal.

Dake (1930, p. 194) stated that rhyolite, lava, and ash, along with granite, granite porphyry, and basic dikes formed a large land mass in the Ozark area during the Precambrian. He further stated that the land mass, which was almost 2,000 ft in altitude, was deeply eroded and faulted by Cambrian time. Precambrian faulting also is reported by Bridge (1930, p. 135). El-Etr (1967, p. 1) reported the greatest density of lineaments is associated with the St. Francois Mountains. The core of the St. Francois Mountains is reported to be an epizonal granite batholith emplaced 1,500 million years ago and is part of a broad belt of silicic igneous rocks of similar age that extends in the subsurface at least from Michigan through Oklahoma (Sides, 1978, p. 2).

Steeples (1982) and Yarger (1982) believe, on the basis of magnetic, seismic, and drilling investigations, that block faulting and possible dike intrusions, which normally are associated with continental rifting, exist along the central North American geophysical anomaly. The anomaly is about 50 mi west of and trends parallel to the Nemaha uplift, which extends from Nebraska through Kansas and into Oklahoma (fig. 15).

In northeastern Oklahoma, Dennison (1981, p. 26) outlines a series of parallel synclines and anticlines about 40 mi apart, trending N. 70° E. Also, the Labette fault in southeastern Kansas (not shown) and the ancestral Nemaha uplift are identified as Precambrian structures. A Precambrian basin may have existed in Oklahoma. Recent seismic investigations indicate that more than 20,000 ft of Precambrian sedimentary rocks may underlie the Wichita Mountains (Brewer, 1982, fig. 26). A Precambrian rift is believed to have existed below the present Ouachita Mountains (Krueger and Keller, 1986, p. 686). In addition, the Precambrian rift along the northern end of the Mississippi embayment (fig. 15) is believed to be late Precambrian in age (Houseknecht and Matthews, 1985; Schwalb, 1982). In the area of the Precambrian basin in southern Oklahoma (fig. 19), the oldest sedimentary sequence was modified by injection of igneous intrusive rocks or was buried beneath volcanic rocks (Chenoweth, 1968). Rascoe and Adler (1983, p. 982) state:

> The origin of the Amarillo-Wichita uplift and the adjacent Anadarko and Ardmore basins were strongly influenced by the structural, stratigraphic, and thermal evolution of the southern Oklahoma aulacogen. This graben was emplaced on the Precambrian



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

EXPLANATION

THRUST FAULT—Sawteeth on overthrust side

NORMAL FAULT—Hachures on downthrown side

CONCEALED FAULT—Relative movement not shown

FIGURE 18.—Major faults (modified from King, 1968; Sims, 1985; Krueger and Keller, 1986).

craton as described by Ham, Denison, and Merritt (1964). It measures approximately 100 mi (160 km) wide * * * across southern Oklahoma * * *. More than 20,000 ft (6,100 m) of graywacke, layered chert, spillitic basalt, and rhyolite were deposited in the graben during Early and Middle Cambrian time, following which the trough margin in southwestern Oklahoma was injected by gabbro and granite to establish a stable block that was the precursor of the Amarillo-Wichita uplift.

It is not known if the southern Oklahoma aulacogen was a so-called failed arm of the continental rift below the present Ouachita Mountains.

The top of the basement surface represents a major unconformity, resulting from a long period of erosion or nondeposition (pl. 3). The permeable broken or weathered rock zone on the basement surface, sometimes termed "granite wash," is included in the rocks studied because of its sediment-like character. The faulting and fracturing of the competent rocks of the basement complex created anisotropic permeability and established permeable paths for ground-water flow.

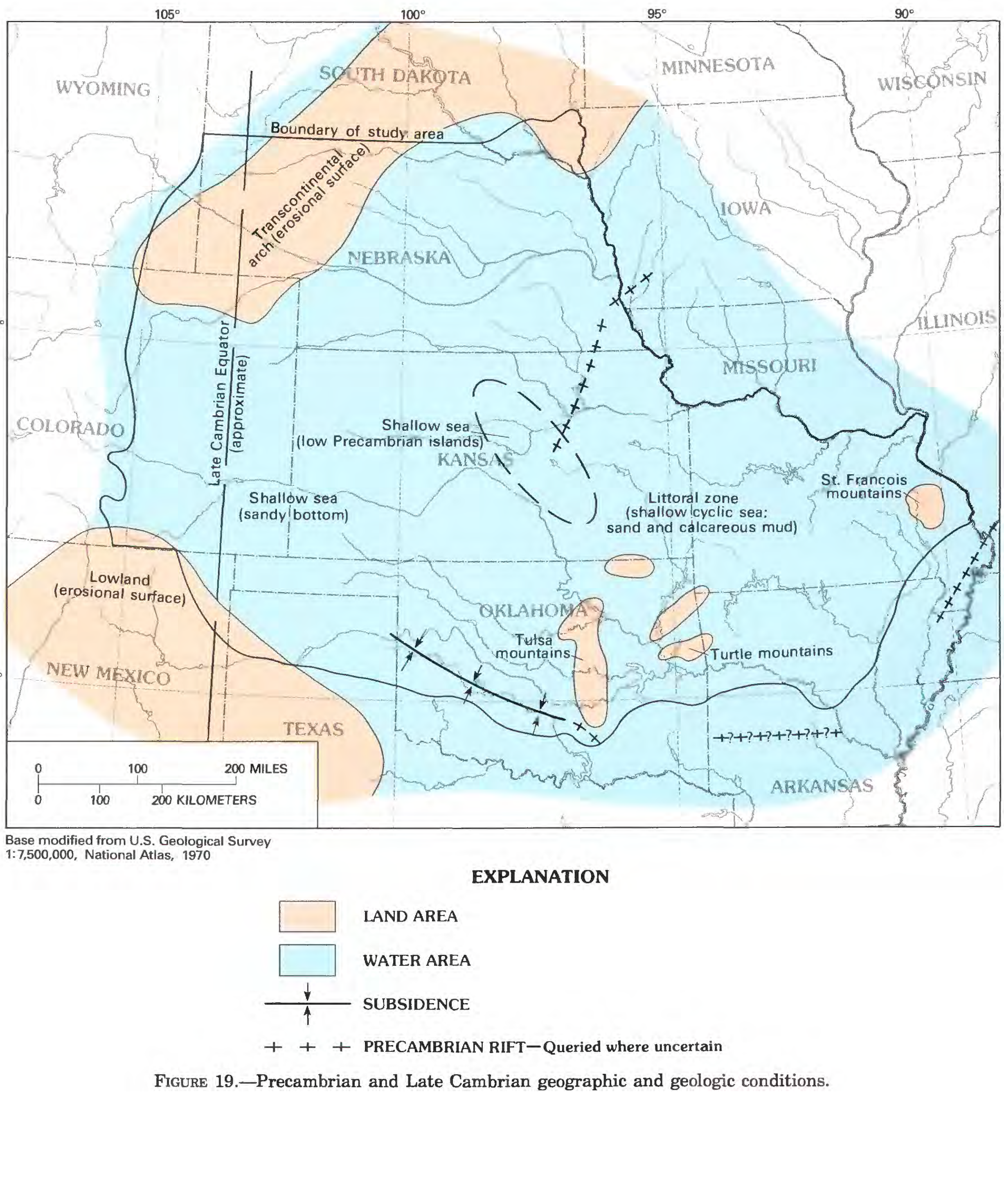


FIGURE 19.—Precambrian and Late Cambrian geographic and geologic conditions.

CAMBRIAN SYSTEM

Brown (1978), from an investigation in the northern Great Plains, reported that a wrench-fault tectonic system was active in Cambrian time and throughout Paleozoic time. Brown further reported that the tilting of blocks affected sedimentary deposition and that the faults themselves may be hydraulic barriers. The predominant direction of shear and faulting is northeast, with complementary fractures trending northwest.

The Precambrian surface, except possibly for one small subsiding basin, was exposed and was being eroded during Early and Middle Cambrian time. The unloading resulted from erosion-created extensional jointing. The joints (vertical fractures) were paths for water flow.

A cyclic but generally transgressive sea covered most, if not all, of the study area during Late Cambrian time. Paleogeographic maps (Scotese and others, 1979, fig. 3) indicate that nearly all the study area was near the equator and was covered by a shallow sea, except the low-lying Transcontinental arch, a lowland in parts of Colorado, New Mexico, and Texas and various islands (fig. 19).

Sand was the dominant sediment deposited in the shallow sea within the study area (Dott and Batten, 1976, p. 199). Formations, such as the Reagan Sandstone and equivalent Sawatch Quartzite in central Colorado, and the Lamotte Sandstone and the equivalent Mount Simon Sandstone east of the study area, are predominantly sandstone originating from deposition of permeable sand nearshore during the Late Cambrian. Detritus from the Ozark uplift is believed to be the source of material for the Lamotte Sandstone (Bridge, 1930, p. 136). The Lamotte is a basal sand deposited on a surface of moderate relief (Merriam, 1963). Small areas, former islands of pre-Paleozoic basement rock, are found in northwestern Arkansas, central Kansas, southeastern Missouri, and north-central and northeastern Oklahoma. Each successive transgression further eroded and covered these areas (Chenoweth, 1968, p. 1675; Walters, 1946, p. 660).

In the area of the Ozark uplift, cyclic deposits of clay, silt, fine sand, and carbonate mud occurred. The calcareous sediments now are represented by the Bonneterre Dolomite and by the Derby and Doe Run Dolomites of the Elvins Group.

Marine sand and calcareous mud were deposited in a sea with a salinity and chemical composition similar to that of the present ocean (Habicht, 1979, p. 2). During Late Cambrian time, the sand and calcareous mud had ample opportunity to lithify to sandstone and limestone. Lithification of littoral sediments occurred when they were nearshore or when they were periodically above water level. The entire study area, except for a basin in southern Oklahoma (the present Anadarko basin), was above sea level at various times during the Late Cambrian. Saline water, which had been deposited with the sediments, probably was flushed from the thin mantle of Cambrian rocks and the subjacent rocks at all locations above sea level. Extensional jointing of the consolidated rocks, which resulted from erosional unloading, would have created secondary permeability. The increased permeability accelerated the flushing of saline-depositional water from the rocks. At some locations, sediments containing saline water were in contact with fresh ground water from the land masses, and dolomitization would have resulted. Ham (1950) reports that Cambrian dolomitic rocks in southern Oklahoma are diagenetic in origin.

The present thickness of Cambrian rocks is the result of initial sedimentation and subsequent erosion. The maximum thickness of Cambrian rocks is 350 ft in Kansas (Merriam, 1963, p. 175), more than 750 ft in southeastern Missouri, and more than 1,500 ft in southern Oklahoma (Ham, 1950) in the arcuate basin that extended from southern Oklahoma to the bootheel of Missouri.

ORDOVICIAN SYSTEM

Lower Ordovician rocks, which are predominantly dolostone at nearly all locations in the study area, lie unconformably on the Upper Cambrian rocks. However, Ross and Tweto (1980) state that in central Colorado, the Manitou Dolomite (equivalent to the Arbuckle Group) was deposited in a vast supratidal and subtidal carbonate mudflat. In northeastern Kansas, southeastern Nebraska, and northern Missouri, calcareous sediments also were deposited. Bunker (1981, p. 18) implies that some minor tectonic activity occurred along the Nemaha uplift prior to Middle Ordovician time. All or nearly all of the area of the Ozark uplift, including the St. Francois Mountains, was submerged. Sediments in the uplift area were predominantly calcareous mud, with the exception of some permeable sand, such as those that form the Gunter Sandstone Member of the Gasconade Dolomite. The bottom deposits in the sea in the area of the Ozark uplift were largely algal lime. Algal reefs are typical throughout the Gasconade Dolomite. Also, calcareous mud in lagoons with restricted circulation was dolomitized (Burgess, 1964, p. 47).

The sea advanced and retreated several times during Ordovician time. During periods of retreat, uplift diagenesis occurred. Exposed calcareous mud was lithified. Dolomitization and additional weathering occurred during the numerous changes in sea level. Major periods of retreat are marked by several unconformities in the area of the Ozark uplift and in the Forest City basin. For example, the Gasconade Dolomite and Roubidoux Formation are separated by a major unconformity. Permeability developed rapidly on exposed limestone and dolostone during the long periods of erosion.

In the Ozarks, most Lower Ordovician limestone has been replaced by dolomite, such as the Gasconade Dolomite (Borahay, 1973, p. 56). Erosion of some of the earliest Ordovician sediments and rocks had occurred on the ancestral Nemaha uplift and the Cambridge arch by the end of Early Ordovician time (Smith and Burchett, 1967).

In southern Oklahoma, an extensive basin rapidly formed as evidenced by the approximately 6,000 ft of Lower Ordovician sedimentary rocks that are present in southern Oklahoma (Adler, 1970, p. 1002). In southern Arkansas and eastern Missouri, another deep basin also was forming. The limestone layers in the basin were losing primary porosity as the result of compaction and pressure dissolution, and gaining secondary porosity as a result of thermal diagenesis of organic material. The subsiding basin with its normal faulting is reported to have been initiated by a crustal extension (Brewer, 1982, p. 38).

At the end of the Early Ordovician and the beginning of the Middle Ordovician, the retreat of the sea and the Ozark uplift exposed rocks and sediments throughout the entire study area except for a subsiding basin in Arkansas and Oklahoma. The duration of the erosion, which followed the retreat, varied within the study area. Ross and Tweto (1980, p. 51) suggest that the hiatus in Colorado may represent 10 to 35 million years.

Erosion of Paleozoic sediments occurred along the flanks of the Transcontinental arch and the Ozark uplift. In Kansas, only a veneer of pre-hiatus Paleozoic sedimentary rocks remains along the eastern border. However, pre-hiatus rocks remain in Oklahoma and in the present Forest City basin in Nebraska.

During the period in which the Ozark uplift was formed, extensive uplift diagenesis, including jointing and near-surface weathering, occurred. For example, exposed Lower Ordovician rocks along the Arbuckle uplift in southern Oklahoma have joint sets that are parallel and perpendicular to the major Arbuckle fold. The joints, which are believed to be a product of tectonic activity that created the basin, have provided permeable flow paths and have aided aqueous diagenesis since their creation. "The 'Arbuckle limestones' are not as well jointed as the overlying Woodford, Chimneyhill, and Viola Formations, which are more competent ***" (Decker and Merritt, 1928, p. 12). (The Chimneyhill Limestone is part of the Hunton Group.) Joints in the Ordovician and Cambrian rocks along the Ozark uplift align about N. 25° W. and N. 70° E.

Ground-water flow systems developed in the uplifted areas and flushed the water from Early Ordovician and older rocks. In general, ground water is rich in CO_2 in recharge areas. The slightly acid water typically dissolves the rock matrix, especially calcareous material; porosity and permeability are thus increased. Cementing occurs in discharge areas where the water is under reducing conditions; porosity and permeability may be decreased in inland discharge areas. Regional dolomitization of limestone occurred near the coastline in the zone of mixing between the inland fresh ground-water flow system and the saline depositional water in the rocks below sea level. In general, the processes of dolomitization and jointing increased secondary porosity and permeability. The widespread unconformity, usually a karst at the top of the older dolostone and limestone, formed an excellent aquifer and a path for easy ground-water movement. Sediment deposition during subsequent periods of transgression during the Middle Ordovician (fig. 20) covered and preserved the unconformity surfaces. Very permeable onlapping sands were preserved. These sands are the parent material for the sandstones of the Harding Sandstone west of the study area in Colorado and New Mexico (not listed on plate 1) and the St. Peter Sandstone in the remainder of the area. After the period of general transgression, a period of relatively stable sea levels ensued during which calcareous sediments, represented by the Viola Limestone, were deposited on approximately the same area as the sand.

In northern Arkansas, the Everton Formation, a Middle Ordovician sandstone and limestone, is unconformably overlain by the St. Peter Sandstone (Croneis, 1930, p. 24). This unconformity indicates that the widespread regional hiatus may have occurred within the Middle Ordovician Epoch and not at the end of the Early Ordovician Epoch. Possibly, the sand of the Everton is detritus from the elliptical Ozark uplift. Thickness maps by Caplan (1957) indicate that the Everton Formation in north-central Arkansas thickens to the south, as does the St. Peter Sandstone, but at a much greater rate. The thickness of the St. Peter and the Everton is about 600 ft at the southern boundary of the study area in Arkansas. Both formations consist of clean quartzose sand, which formed a permeable aquifer immediately after deposition. The generally transgressive seas of Middle Ordovician time were interrupted by recessions; for example, four unconformities are recognizable in northern Arkansas. The unconformities mark the tops of permeable zones created by uplift diagenesis.

Deposition of calcareous mud, clay, and sand was continuous during the entire Middle Ordovician in the subsiding Oklahoma–Arkansas basin. Burial diagenesis, especially compaction, decreased the porosity of both the clay and sand. Calcareous sediments were lithified to limestone by pressure dissolution and recrystallization. Assuming a normal geothermal gradient, organic material in pre-Middle Ordovician sediments would have been altered by thermal diagenesis at a slow-to-moderate rate that would have resulted in increased secondary porosity and permeability locally. Because the pre-Middle Ordovician rocks generally were buried at depths of a few hundred to a few thousand feet, ground-water circulation in these rocks was either not extensive or did not exist. Dolomitization of the limestone probably did not occur in the basin.

Middle and Upper Ordovician sediments in northwestern Arkansas were marine, shallow-water, biogenic calcite and aragonite mud. These sediments were the parent material of the Kimmswick

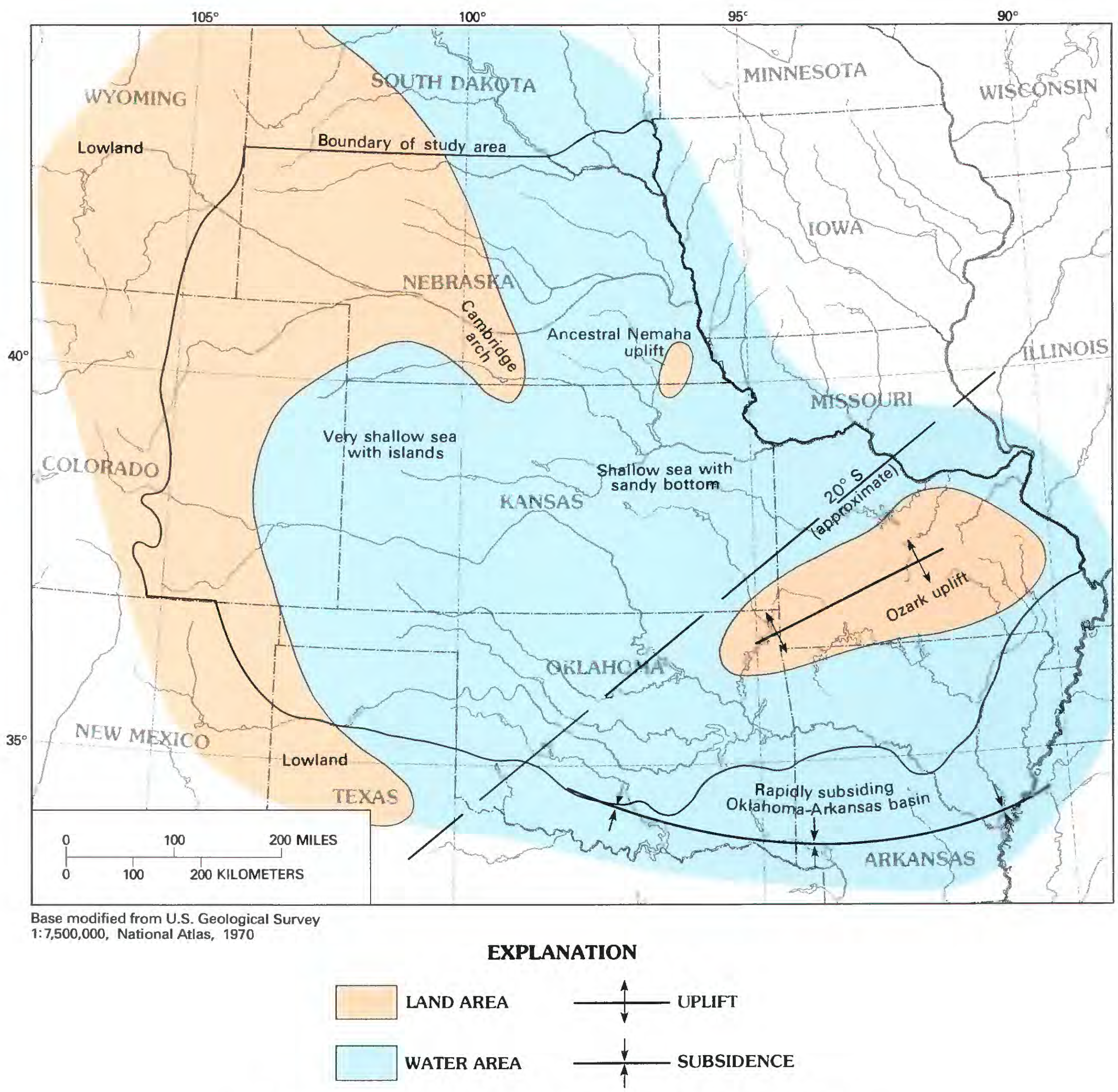


FIGURE 20.—Middle Ordovician geographic and geologic conditions.

Limestone, the Fernvale Limestone, the lower part of the Cason Shale, and other formations (Craig, 1975, p. 61).

The existing rock record of the Late Ordovician is confined largely to the present Forest City basin and the ancient Oklahoma–Arkansas basin (figs. 15, 20). Clay of the Maquoketa, Sylvan, and Cason Shales was deposited, as well as calcareous mud. In general, sedimentary deposits were thin even in the Oklahoma–Arkansas basin. Dott and Batten (1976, p. 229) imply that the study area was astride the equator. However, Habicht (1979) shows the area at about 25° south of the equator. The Appalachian orogeny, east of the study area, may have been the source of the clastics present in the eastern part of the study area. The submergence of most of the study area, which was accompanied by a general encroachment of saline water into the existing fresh ground water within the rocks along the transient coast, resulted in widespread dolomitization. Thermal diagenesis of organic material, which selectively created secondary porosity, continued at a moderate rate in southern Oklahoma and at a slow rate in Kansas and central Arkansas.

The end of the Ordovician Period was marked by regional uplifting, continued development of the Oklahoma–Arkansas basin, and intermittent but generally transgressive seas. Secondary permeability had developed in Cambrian and Ordovician rocks in nearly all areas except the basins where burial diagenesis had, in general, decreased primary porosity and permeability.

SILURIAN SYSTEM

Little is known about the paleohydrology and geologic history of the study area during Early Silurian time. The location of land masses is interpreted largely from the limited occurrence of Lower Silurian rocks. Early Silurian seas apparently were quite restricted in the study area (fig. 21). The Silurian was characterized by uplift that exposed extensive land areas. Accordingly, a considerable volume of pre-Silurian rocks was removed by erosion from the study area. Jointing, which further increased permeability, resulted from erosional unloading. Those rock units above sea level were flushed of saltwater by ground water of meteoric origin. Extensive mixing of freshwater and saline water occurred in aquifers near the coasts, resulting in dolomitization.

Calcareous mud was deposited unconformably on Ordovician rocks in the Forest City basin during the Early Silurian. In the Oklahoma–Arkansas basin, the upper part of the Cason Shale and the Brassfield Limestone are believed to be Silurian (Wise and Caplan, 1979, p. 1). The base of the Silurian in Kansas is characterized by extensively dolomitized oolitic limestone (Lee and Merriam, 1954). Thermal diagenesis of organic material, which locally resulted in increased secondary porosity and permeability, continued at a slow-to-moderate rate in southern Oklahoma and at a very slow rate in the remainder of the area during Early Silurian time.

The extent of the Middle Silurian sea is difficult to determine because most of the rock record, similar to the Lower Silurian, has been eroded. Scotese and others (1979, fig. 15) indicate that during the Middle Silurian the entire study area was submerged by a shallow sea with no large land masses. Permeable reef structures are characteristic of Silurian time, implying that the paleoequator may not have been too distant. Frezon and Glick (1959, p. 184) reported: "During Silurian time, the seas advanced over the eroded Ordovician rocks and may have covered the entire Ozark region." The submergence and marine sedimentation would have initiated region-wide burial diagenesis.

In the present Anadarko basin, Silurian rocks are mostly limestone and dolostone. The dolostone is reported by Amsden (1975, p. 1) to have been formed as a penecontemporaneous replacement that took place at the depositional interface. In the present Forest City and Salina basins, the rock record consists of limestone, which comprises the lower part of the Hunton Group. In the Oklahoma–Arkansas basin, the rock record is represented by dolomitic limestone and dolostone, which also are hydrocarbon reservoirs (Wise and Caplan, 1979, p. 13).

The study area including the present Anardarko basin was completely exposed during part of Late Silurian time. Uplift diagenesis, especially widespread surficial and subaerial dissolution along joints, resulted in increased porosity and permeability. The thin Lower and Middle Silurian rocks probably were flushed repeatedly by fresh meteoric water. Erosion exposed Precambrian quartzite and other competent basement rocks in central Kansas.

DEVONIAN SYSTEM

The paleogeography for the Early Devonian is shown in figure 22. Devonian rocks, which lie unconformably on older rocks, are preserved only in the deeper parts of the sedimentary basins. During the long Silurian–Devonian hiatus throughout the continental lowland area, saline pore water was displaced from rocks at shallow depth or flushed by fresh ground water of meteoric origin. Large-scale uplift and faulting at the end of the Early Devonian in the Ozarks resulted in extensive erosion and beveling of beds (Frezon and Glick, 1959, p. 184; Bush and others, 1980, fig. 4). No Middle Devonian rocks are present in the southern Oklahoma–Arkansas basin. It is possible, if the region was tilted downward to the north, that southern Oklahoma was above sea level, thus allowing uplift diagensis of Silurian and older rocks.

Initially, during the Late Devonian, the entire study area was above sea level, and extensive erosion occurred. However, during Late Devonian time, submergence occurred throughout most of the area as the sea again returned and probably covered the eastern part of the study area from southeastern South Dakota to the Oklahoma and Texas panhandles and most of the Ozark uplift. Colorado, western Kansas, and western Nebraska probably were not submerged. Most Devonian sediments were calcareous mud with locally intercalated permeable sand lenses. Algal mounds and coral reefs developed in the Forest City basin and along the flanks of the Ozark uplift. The coral and other reefs are very permeable. The transgressive sea replaced fresh ground

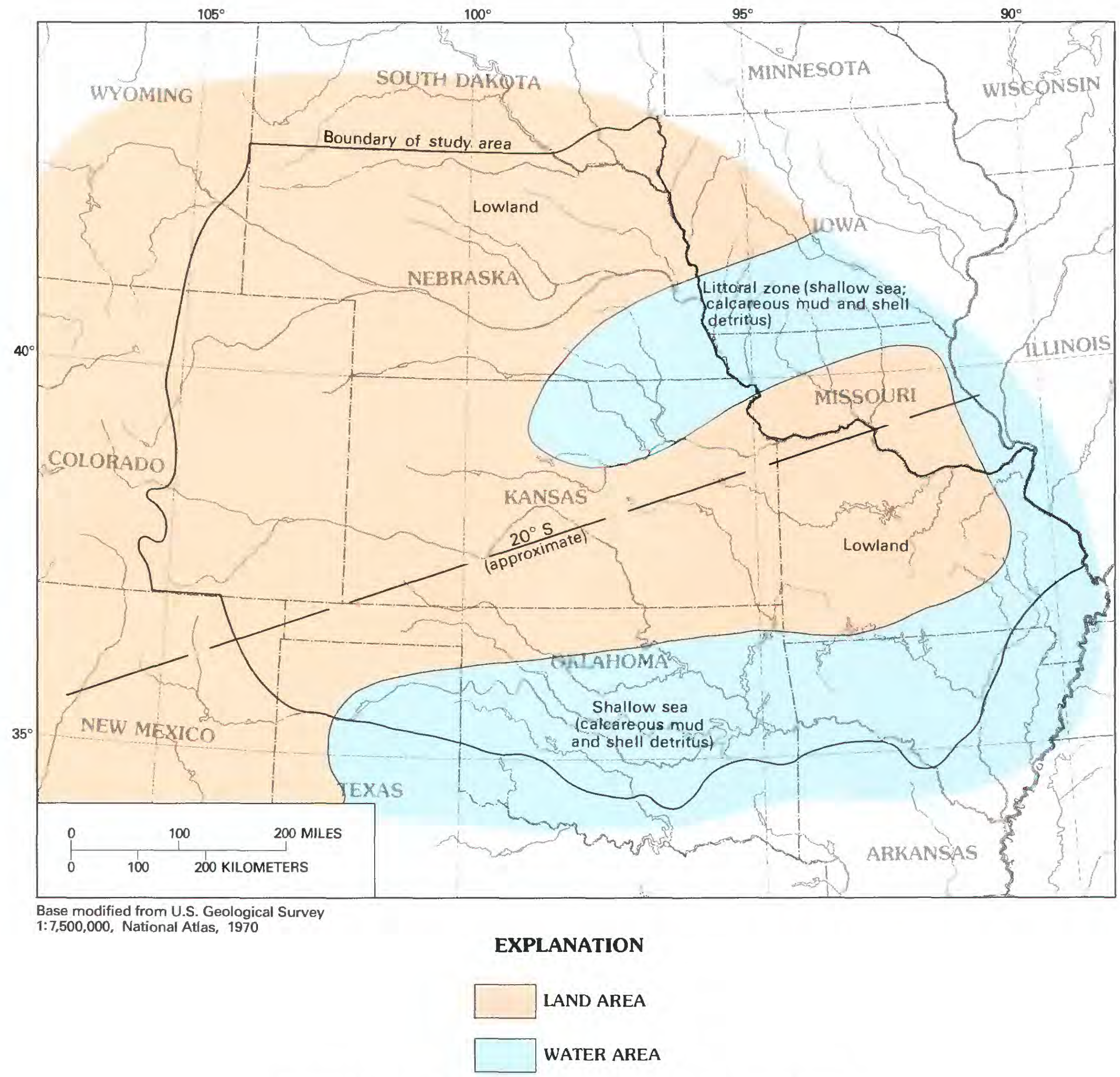


FIGURE 21.—Early Silurian geographic and geologic conditions.

water with seawater in the rocks not eroded during the Silurian–Devonian hiatus and probably induced subaerial dissolution of carbonate rocks near coastlines.

At the end of the Devonian Period, or possibly during very Early Mississippian time, transgressing seas are believed to have completely submerged the study area, exclusive of the Transcontinental arch. Sand and silt were deposited nearshore and clay farther offshore. For example, more than 500 ft of porous but slightly permeable clay were deposited in the rapidly subsiding basin in southern Oklahoma. Secondary porosity developed as a product of thermal diagenesis at a slow-to-moderate rate in the deeply buried sediments in the basin. Other clay, presently represented by the Chattanooga and Woodford Shales, probably was deposited offshore in a sea with restricted circulation. However, sand, such as the Sylamore Sandstone Member of the Chattanooga Shale, was deposited nearshore and preserved by the advancing sea.

MISSISSIPPIAN SYSTEM

During the earliest part of the Mississippian (Kinderhookian, pl. 1), dark clay continued to be deposited in the eastern part of the study area

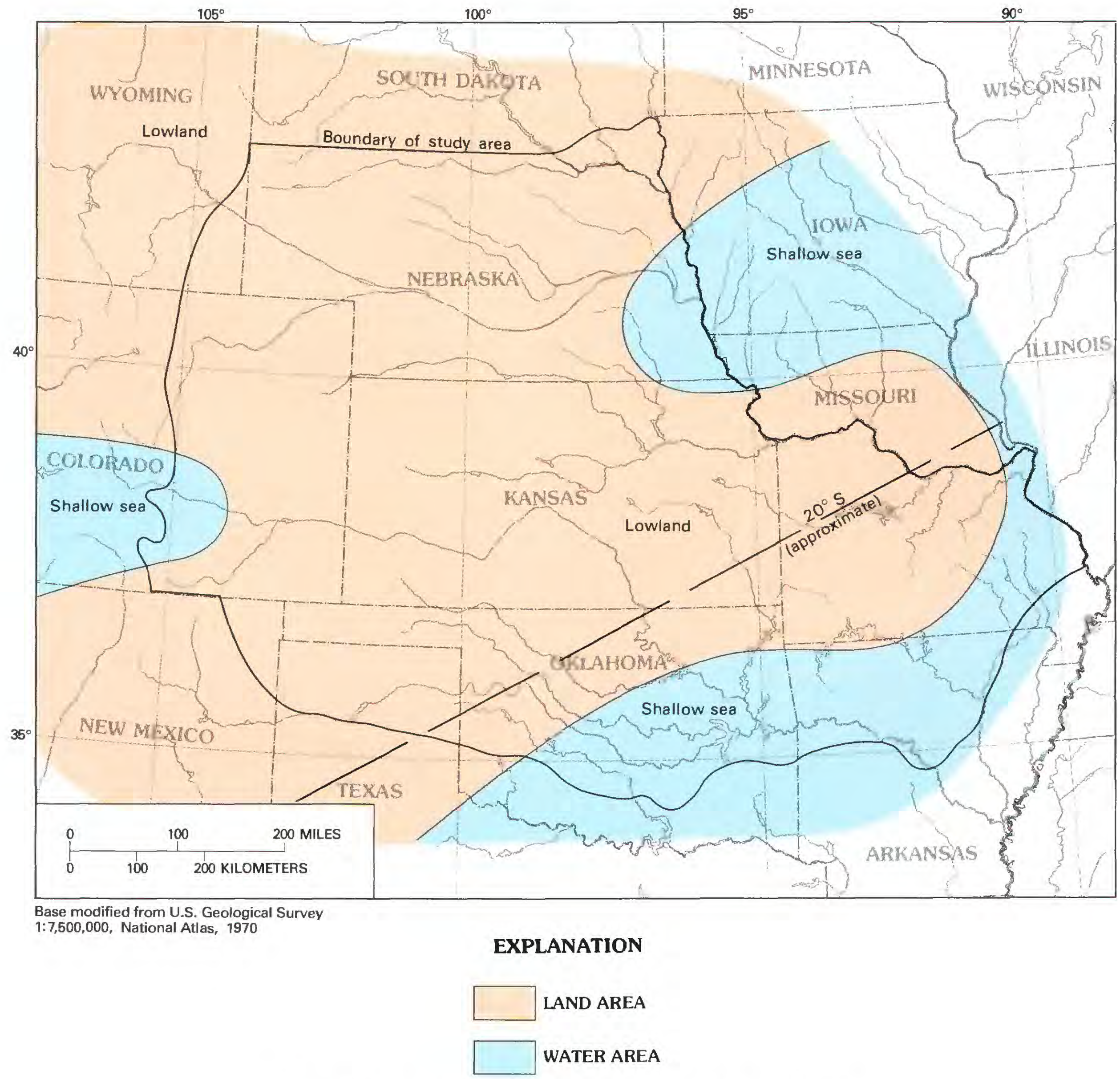


FIGURE 22.—Early Devonian geographic and geologic conditions.

(Carlson, 1963, p. 10). The clay, which is now represented by the Chattanooga Shale, is reported to have been deposited in a restricted circulation sea under euxinic conditions (Huffman, 1959; Craig and Varnes, 1979). The very slightly permeable clay restricted the movement of water and other fluids to and from the underlying dolostone and sandstone layers. The euxinic conditions were modified abruptly by a transgressive sea with normal circulation.

The dominant positive element during Early Mississippian time was the Colorado–Wyoming uplift, whereas the dominant negative element was the subsiding Anadarko basin (fig. 23), in which more than 2,000 ft of pre-Chesterian sediment was deposited. Initial tectonic movement resulted in the emergence of the Nemaha uplift (Steeples, 1982), the ridge that separates the Salina basin from the Forest City basin. The extent of the Early Mississippian sea at approximately the time of maximum transgression is shown in figure 23 (modified from Craig and Varnes, 1979). Initial sediments deposited in the transgressive sea are represented by detrital sand deposits in Oklahoma, Arkansas, and western Kansas. During the remainder of Early Mississippian time, calcareous sediments were deposited in the shallow equatorial sea.

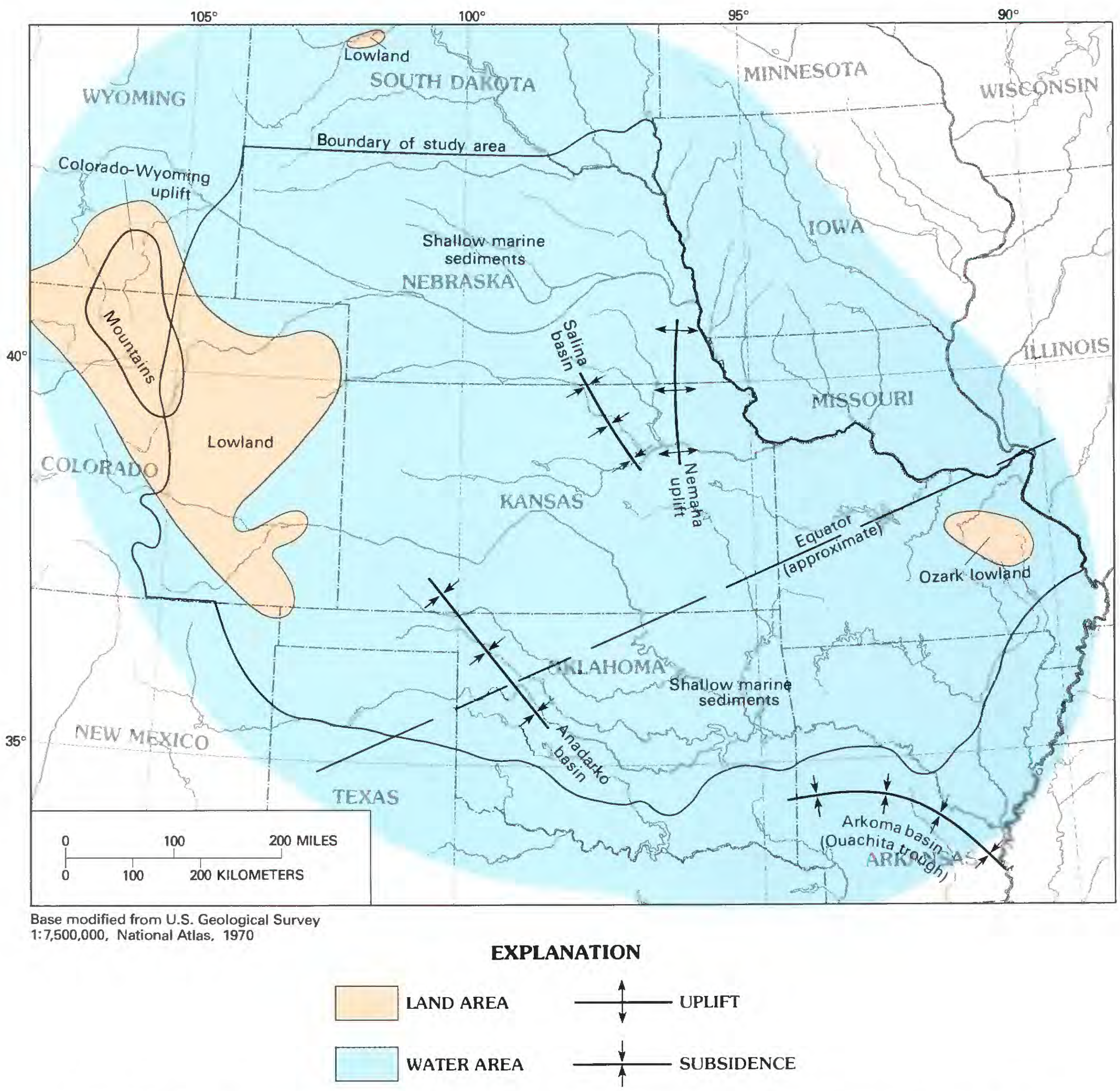


FIGURE 23.—Early Mississippian geographic and geologic conditions (modified from Craig and Varnes, 1979).

The rock record of the Early Mississippian, exclusive of the initial clastics, is represented mostly by a cherty limestone. Exceptions are some siliceous dolostone in eastern Colorado and a shale in northwestern Arkansas on the north slope of the subsiding Arkoma foreland basin (Houseknecht and Matthews, 1985, p. 337). The present carbonate rocks are mostly of biogenic origin and reflect alternating strong and weak energy zones in a widespread, clear-water, normal-marine depositional environment (Craig and Varnes, 1979, p. 395). In Kansas, Early Mississippian rocks are limestone, dolostone, and chert. Porosity and permeability of these rocks range from slight to moderate, being best developed in vuggy, weathered, tripolitic (diatomic) chert, or in crystalline dolostone (Brandt, 1967, p. 4). In the Anadarko basin of Oklahoma and Texas, more than 700 ft of Early Mississippian sediments were deposited.

Late Mississippian time (Meramecian and Chesterian) was characterized by cyclic but predominantly recessive seas. Uplift diagenesis acted on the extensive positive elements, which included the low-lying Transcontinental arch. Tectonic activity created uplifts transverse to the Transcontinental arch in Nebraska and Kansas. The dominant negative feature was the Arkoma foreland basin (Ouachita trough) where more than 5,000 ft of subsidence occurred. The Anadarko basin may be an ancillary foreland basin related to the subduction of the North American plate along a plane of weakness associated with the Precambrian rift that was located beneath the present Ouachita Mountains. Less subsidence occurred in the Anadarko basin; however, in an area from southwest Kansas to south-central Oklahoma more than 2,000 ft of sediments were deposited. Deposition rates in the rapidly subsiding basins were much greater than typical. Compaction resulting from the rapid burial would have expelled water to vertically adjacent layers.

Biogenic carbonate was the dominant sediment throughout most of the area. However, silica that was derived from the weathered lowland and from altered clay formed chert. In the Anadarko basin, rapid subsidence resulted in Cambrian through Devonian rocks being buried to depths of more than 10,000 ft and, assuming normal geothermal gradient, heated to temperatures of more than 167°F. The burial temperature (and pressure) resulted in compaction and the release of water. Water, carbon dioxide, and hydrocarbons were generated by the moderate thermal diagenesis of organic material. Burial diagenesis increased secondary porosity by selective dissolution of calcareous material in the deeply buried carbonate rock.

A regional uplift, especially along the Transcontinental arch, and a retreat of the sea occurred at the end of Mississippian time. A considerable amount of the Mississippian rock was removed on the shelf of the Transcontinental arch. Only the deeper parts of the Anadarko and Arkoma basins remained submerged. Many of the Mississippian deposits were eroded by the end of Mississippian time, especially over the Nemaha uplift in southeast Nebraska and northeast Kansas, on the Cambridge–Central Kansas uplift, and in south-central Oklahoma. Uplift diagenesis greatly increased the permeability of the exposed rocks, which were mostly Ordovician dolostone, by fracturing and dissolution.

In eastern Colorado, uplift of the regional Sierra Grande arch caused the sea to retreat in all directions from the center of the State (Maher, 1953, p. 913). Subaerial erosion and other uplift diagenesis at the end of Mississippian time developed an extensive karst with abundant sinkholes, caverns, and rubble breccia developed in the permeable limestone. A residual-clay regolith developed on top of the Mississippian rocks in Colorado (Devoto, 1980a, p. 57).

In the Ozark area of southern Missouri, erosion considerably decreased the loading, resulting in extensional jointing. McCracken (1971) reports a dominant joint set at N. 25° W. A regional flow system of fresh ground water of meteoric origin developed. Circulation probably extended downward to very slightly permeable strata, such as the Chattanooga Shale and equivalent, or to about a depth of 1,000 ft in the permeable carbonate rocks.

PENNSYLVANIAN SYSTEM

During the Early Pennsylvanian (Morrowan time), a cyclic but generally transgressive sea covered most of the permeable erosional surface that had developed by the end of the Mississippian. The east-central part of the study area either remained stable above sea level or was uplifted, whereas subsidence generally occurred in a wide arcuate belt along the western and southern parts of the study area. Strong compressive forces from the north and south developed. The principal directions of compression may be related to the collision of the African, the South American, and the North American plates. These stresses were relieved by thrust faulting, folding, and downwarping in the arcuate band. Block faulting occurred in Oklahoma along the preexisting Southern Oklahoma graben of Early Cambrian age (Edwards and Downey, 1967, p. 3).

Uplifts during Early Pennsylvanian time included the Amarillo–Wichita uplift (Frezon and Dixon, 1975, p. 182). Rapid uplift and erosion continued along the ancestral Front Range and the Apishapa–Sierra

Grande uplift (Devoto, 1980b, p. 17; see fig. 24). The uplift areas along the margins of the study area, in general, were easily eroded and provided coarse arkosic detrital material. More than 500 ft of so-called granite wash was deposited along the Amarillo uplift (Dutton, 1980, p. 16). The permeable granite wash was an aquifer and transmitted freshwater downdip to depths of thousands of feet. The lowlands interior to the study were, in general, sources of silt, clay, and carbonate mud. Gentle flexures developed in Nebraska, Kansas, and Missouri during the Early Pennsylvanian. Faulting occurred and resulted in partial or complete dislocation of formations along the east flank of the Nemaha uplift. Anticlinal folding along the Cambridge arch–Central Kansas uplift and the Nemaha uplift continued. Synclinal folding resulted in subsidence in the Forest City basin, in the Salina basin, and in the Hugoton embayment (Prichard, 1975; Stewart, 1975; Wanless, 1975).

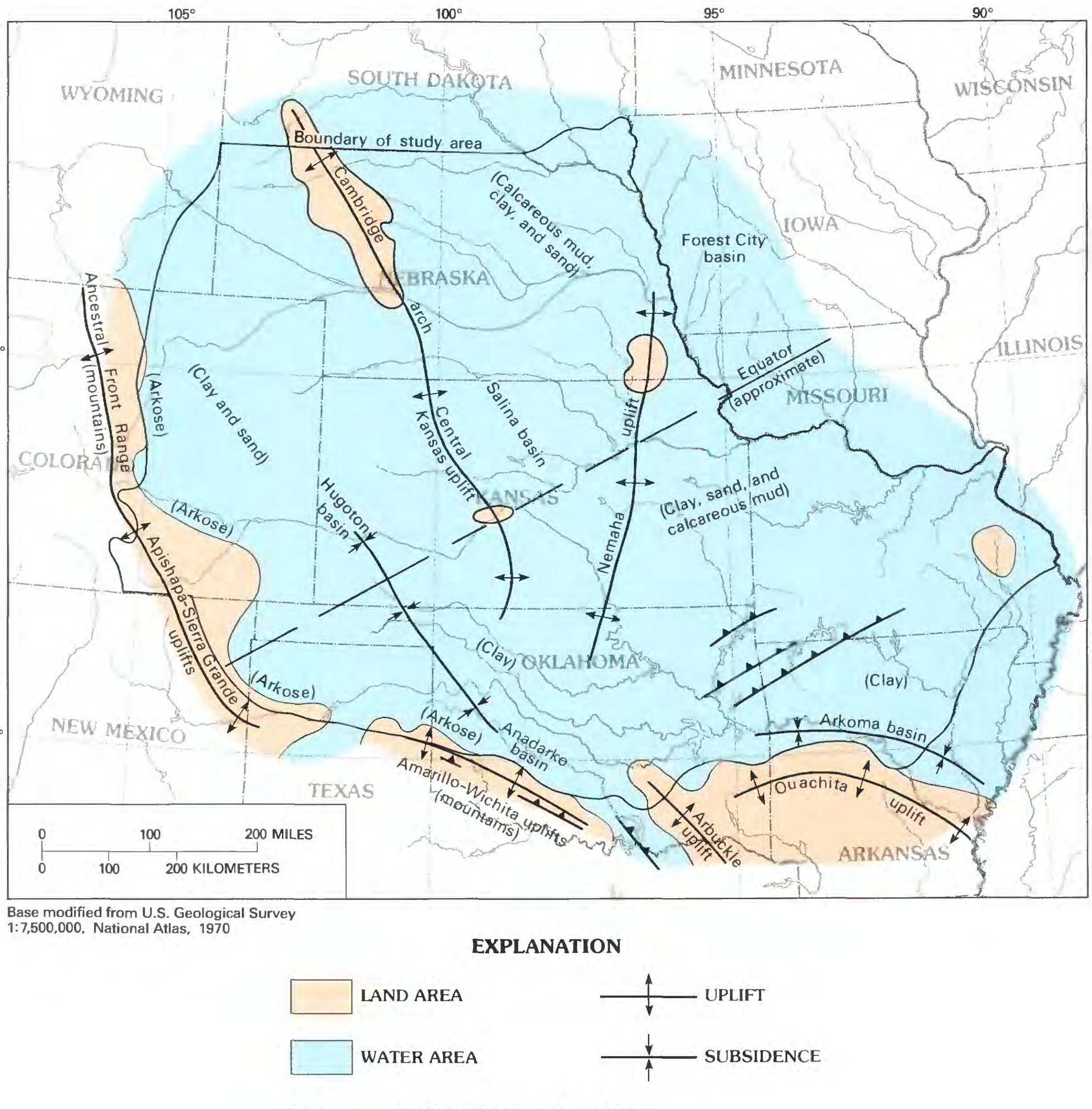


FIGURE 24.—Middle Pennsylvanian (maximum Desmoinesian sea) geographic and geologic conditions (modified from McKee and others, 1975, plate 15b).

Development of the Nemaha uplift and the Cambridge arch–Central Kansas uplift accelerated in response to the rapid tectonic movements during the Pennsylvanian (Carlson, 1970; Prichard, 1975; Stewart, 1975). Erosion on the Cambridge arch–Central Kansas uplift and the Nemaha uplift, which started during the Late Mississippian, removed a large quantity of rock in central Kansas and southeastern Nebraska and greatly enhanced permeability in the exposed Mississippian, Ordovician, and Cambrian rocks, as well as the exposed Precambrian basement rocks. Large-scale and permeable karst was developed on and near the erosional surface (Walters, 1946, p. 699). Detritus, especially chert from the Mississippian rocks, formed a very permeable aquifer on and along the ridges. Fresh ground water flushed the marine water from the exposed rocks in the positive areas above sea level.

The most rapid subsidence occurred in the downwarping Arkoma basin of central Arkansas and at a lesser rate in the Anadarko basin. Sedimentation was extremely rapid and kept pace with subsidence. Pre-Pennsylvanian rocks were buried to depths of nearly 20,000 ft. The deep burial was accompanied by an increase in temperatures to as much as 302°F in the Anadarko basin (Waples, 1982, p. 1152). Deep burial also occurred in the Arkoma basin. Thermal diagenesis of organic material in the deeply buried sediments was rapid, resulting in increased porosity and permeability in selected strata. During Morrowan time, deposition of very slightly permeable sediments occurred at a very rapid rate. If the water being squeezed from the compacted sediments was unable to dissipate and was trapped with the subsided sediments, the temperature of the confined water would have increased with burial, and hydrothermal pressuring would have resulted. The nearly impermeable overlying sediments would have confined the geopressure zone (pressure greater than hydrostatic). Within the zone, porosity increased greatly with the hydrothermal pressuring; consequentially the thermal conductivity of the zone was decreased and created an insulating blanket over the subjacent rocks. A large zone of geopressure in an area approximating the area of the Morrowan sediments may be of this origin.

In most of the subsiding basin, except the geopressure zone, compaction and other burial diagenesis resulted in nearly complete destruction of the already attenuated primary porosity. Joints in dolostone layers of the pre-Pennsylvanian rocks, except in the deeper parts of the Anadarko and Arkoma basins, probably remained open although narrower in width. However, primary porosity and permeability in limestone layers at depths greater than 10,000 ft were mostly eliminated as the limestone was ductile. At these depths, the limestone layers restricted vertical movement of fluids, and thus became confining units. Thermal diagenesis of organic material and smectite at that depth resulted in a pressure increase as CO_2, water, and hydrocarbons were generated and as clay water was liberated. The CO_2-rich water probably escaped vertically into adjacent permeable dolostone and sandstone layers and locally increased secondary porosity and permeability as it selectively dissolved carbonate cement, limestone, and dolostone.

At some locations adjacent to faults in the subsiding basins, granulation, especially in sandstone, decreased primary porosity and permeability. However, the actual fault planes may have been permeable avenues that transmitted fluids from strata to strata.

Cyclic but transgressive seas were present during most of Middle and Late Pennsylvanian time (Merriam, 1963, p. 103; Fagerstrom and Burchett, 1972, p. 385) and probably covered nearly all of the Ozark area (fig. 24). Thus, both marine and nonmarine sediments are present. Clay, silt, sand, plant material, and shell detritus with calcareous mud were deposited. Pennsylvanian sediments are important source beds for hydrocarbons in the study area (Volk, 1970, p. 673; Bucke, 1969, p. 3). Frezon and Dixon (1975, p. 188-189) report:

> In Middle and Late Pennsylvanian time uplift and intense folding and faulting designated as the Ouachita orogeny occurred in eastern Oklahoma and Arkansas. During the orogenic period the depositional area that had been the Ouachita geosyncline developed into two new structural elements, the Ouachita uplift to the south and the Arkoma basin to the north.
>
> Uplift in the Ouachita region apparently started as early as late Morrow *** time; uplift and, later compressive movements continued intermittently into Early Permian time. These movements caused folding and faulting in rocks as old as *** (Des Moines) and fracturing in rocks as young as Early Permian. These structures occur within a broad region that includes the east half of Oklahoma.
>
> *   *   *   *   *   *   *
>
> Overthrust faults * * * may not have developed until later Missouri or even Virgil time. Studies by Ham and Wilson (1967, p. 386–387) pointed out that some of the compressive forces responsible for the overthrust faulting produced strike-slip faulting in the Arbuckle Mountains during * * * (Virgil) time.
>
> The compressive forces of later phases of the Ouachita orogeny created joint systems and belts of en echelon faults in rocks as young as Early Permian in the eastern half of Oklahoma. The joint

systems radiate outward from the Ouachita region * * * and are attributed to compression (Friedman, 1964, p. 485–486). The en echelon faults *** are regarded by Friedman (1964, p. 486) as 'near surface features related to wrench faults at depth' ***.

In unfolded strata in eastern Oklahoma the joints that parallel folds of the Ouachita Mountains are regarded by Friedman (1964, p. 486) as 'relaxation fractures—formed upon release of stored elastic strain energy.'

Subsidence along existing Ordovician faults was rapid in the Anadarko and Arkoma basins. In general, the rate of subsidence decreased rapidly northward out of the basins (Frezon and Dixon, 1975; Glick, 1975; Wilson, 1975). Deltas and alluvial fans of very permeable coarse-grained detritus, as thick as 750 ft, were deposited along the Amarillo uplift in Texas (Dutton, 1980, p. 24). Permeable coarse sand also was deposited near the Apishapa-Sierra Grande uplift and the Amarillo–Wichita uplift (fig. 24). Clastic sediment grading from sand to silt, to red and green continental clay, and finally to black marine clay was deposited away from the uplifts toward the basins. The coarse material forms the basal material of the Fountain Formation (Atokan or Middle Pennsylvanian not listed on plate 1) in central Colorado and a Lower–Middle–Upper Pennsylvanian arkose facies near uplifts in Oklahoma. These permeable sediments allowed limited water movement from near surface to the deeper aquifers in underlying older rocks (see pl. 2). However, the width of the coarse sediments was only a few tens of miles. Away from the uplifts, relatively impermeable clay and calcareous mud interbedded with sand were deposited in a cyclic pattern. The numerous clay layers formed a very effective seal, restricting vertical flow of water to and from the underlying Lower Pennsylvanian and pre-Pennsylvanian rocks and the permeable layers within the Pennsylvanian rocks.

Further burial in the deep basins resulted in continued rapid thermal diagenesis of pre-Pennsylvanian rocks. Porosity in fractured dolostone was selectively enhanced by dissolution. However, in general, the intense burial diagenesis decreased the porosity and permeability of older sediments and rocks. Porosity and permeability decreased in pre-Pennsylvanian limestone beds as they became more ductile with the increase in depth of burial. Limestone layers that had previously been relatively permeable were altered to less permeable confining-unit material at depths greater than about 10,000 ft. At shallower depths, porosity and permeability were reduced by pressure dissolution and recrystallization as well as compression. Clay layers, such as those deposited during Late Devonian and Early Mississippian time, were compacted to shale. Cambrian sandstone layers probably were cemented with pore-filling diagenetic clay.

Burial diagenesis in Arkansas ended with the complete development of the Ouachita uplift. The exact height of the uplift is unknown. Seismic data presented by Lillie and others (1983) indicate an uplift of about 13,000 ft. A height based on a projected anticline closure of 17,000 ft is possible (Glick, 1975, p. 172); however, erosion was rapid, and the height of the Ouachita Mountains at any time probably was much less than 17,000 ft.

By the end of the Pennsylvanian Period, most of the outer structural boundaries that control the present ground-water flow system were in place. The very slightly permeable clay formed an extensive confining system from Pennsylvanian time to present.

PERMIAN SYSTEM

The Early Permian was a time of decreased tectonic activity as compared with the Middle and Late Pennsylvanian. However, the effects of major Pennsylvanian tectonics were still being felt, and readjustment to stresses from the Ouachita orogeny was continuing. Sediments derived from Pennsylvanian uplifts were being deposited rapidly in the still-subsiding Anadarko basin.

The Early Permian environment is believed to have been arid and hot (Holdoway, 1978, p. 37–39), and the equator extended across the area (Habicht, 1979; Scotese and others, 1979). The sea during the Early Permian, as during the Late Pennsylvanian, was cyclic with alternate recessions and transgressions. Parts or all of eastern South Dakota, eastern Nebraska, eastern Kansas, eastern Oklahoma, and probably northwestern Arkansas and western Missouri were low-lying coastal plains during most of the Early Permian. Thus, sediments and existing rocks were exposed many times during the Early Permian. Near the coasts, unconsolidated calcareous sediments were lithified after exposure.

The eastern boundary of the Early Permian sea, as shown in figure 25, is shown in eastern Kansas and eastern Oklahoma. This interpretation differs somewhat from that of McKee and Oriel (1967, figs. 4, 5), who show the shoreline about 25 to 75 mi east of the present extent of Permian rocks. In central Oklahoma, this would have meant that about 5,000 ft of Permian sediments shown by McKee and Oriel (1967, pl. 7) would have wedged out in about 50 mi, which seems unlikely. Some of the decrease in thickness could be natural onlapping onto the existing uplifted Ozark area. However, if the Ozark uplift had been such a dominant positive element, the adjacent or onlapping sediments present today should reflect that condition. The rocks today are typically nearshore but do not include coarse-grained clastics and arkose. The modified interpretation (fig. 25) moves the extent of the sea eastward and is more consistent with conditions at the end of the Pennsylvanian. The eastern extent of the sea shown in figure 25 may be typical for the Early Permian and represents one position of the sea in its general recessive trend westward. Similarly the extent of evaporites was considerably eastward of their present extent shown in figure 25.

During Early Permian (early Wolfcampian) time, the seaway to the east through the Ozark area was most likely closed by regional tilting upward to the east. The closing of the seaway restricted circulation and probably created conditions favorable for evaporite deposition in the bay in southern Missouri. Accordingly, dense sea brines displaced normal marine pore water in the subjacent strata near the flanks of the Ozark uplift. However, farther offshore to the west and south, greater than hydrostatic pore pressure in the underlying sediments undergoing compaction would have prevented the dense brines from sinking downward to great depths in the subsurface basin.

By the end of Wolfcampian time, as regional tilting continued, a positive element, which sloped away from the Ouachita uplift to the apex of the existing axis of the Ozark uplift, may have existed. If so, a topographically controlled regional ground-water system may have developed with flow northward to the Ozark uplift.

Erosional unloading in the eastern part of the study area caused additional jointing and increased permeability. Erosion decreased the depth and the temperature of the buried rocks, thus slowing the rate of thermal diagenesis of organic material over much of the eastern part of the study area. However, the rank of the Pennsylvanian coals along the eastern margin of the Ozark and Ouachita areas is indicative of a large degree of thermal diagenesis of organic material. The origin of the apparently anomalous heat that caused the diagenesis is unknown. The rank of coal decreases northward from anthracite near the Ouachita fold belt to bituminous in central Missouri (Hendricks, 1935; Damberger, 1974). The mineral zones of the Ozark area are Mississippi Valley-type deposits; mostly lead and zinc that were deposited by hydrothermal solution(s) in permeable zones, such as fractures, joints, and reefs. Fluid inclusions in the minerals indicate a saline source fluid and a depositional temperature of 194–320 °F (Leach and others, 1985, p. 8). Because the temperature of mineralization approximately matches the geothermal gradient implied by the rank of the coals, it has been speculated that the source of heat for thermal diagenesis of coals may have been a mineralized solution that was the source of the lead and zinc. Paleomagnetic studies of carbonate rocks by Beales and others (1980) and McCabe and others (1983) indicate that this occurred during Late Pennsylvanian and Early Permian time.

Tectonic activity in Colorado continued from the Pennsylvanian into the Permian (MacLachlan, 1967, p. 86). Arkosic sediments, mostly permeable, continued to be deposited along the ancestral Front Range uplift and the Apishapa uplift (fig. 25). Sediments were deposited in epicontinental marine, marginal, and continental environments. Neritic sediments of the eastern part of the study area intertongued with and overlapped deltaic and alluvial deposits to the west (Mudge, 1967, p. 97).

Lower Permian sediments in northeastern New Mexico and the Texas and Oklahoma panhandles include permeable detritus from the Sierra Grande, Pedernal, and Amarillo uplifts (not shown in fig. 25). However, most of the detritus probably originated from the positive elements (highlands) to the northwest in Colorado (Dixon, 1967, p. 65).

In Oklahoma, the Anadarko basin continued to subside, and the Wichita Mountains continued to be uplifted (Chase and others, 1956, p. 36). Detritus from the Wichita uplift was the prominent source of depositional material. The detritus, derived from Paleozoic limestone, dolostone, and Precambrian granite, was permeable near the uplifts, but permeability decreased rapidly basinward. In south-central Oklahoma, about 5,000 ft of sediments of Early Permian age accumulated. Burial diagenesis was dominant; compaction forced water from the clay into adjacent permeable strata. Thermal diagenesis of clay and organic material yielded water, CO_2, and hydrocarbons. The thickness of Early Permian sediments alone would have been great enough to sustain thermal diagenesis at rates from very slow to moderate of all pre-Permian rocks. Pre-Pennsylvanian rocks were buried beneath Permian sediments, and the thick section of Pennsylvanian rocks underwent compaction and rapid thermal diagenesis of clay and organic material. However, little unaltered organic material remained in pre-Pennsylvanian rocks and thus, very little additional CO_2 was produced and selective enhancement of porosity and permeability was minimal.

In Kansas and Nebraska, the shallow sea advanced and retreated in a cyclic manner. In general, after each sea recession, some of the exposed sediments were lithified, and exposed rocks and sediments were eroded in other places. During the Early Permian, silica gel was deposited along with calcareous sediments; the flint and chert beds of the Chase Group are of this origin. Later in the Early Permian, layers of evaporites, such as halite, were precipitated in the euxinic sea; clay was also deposited in layers. The extensive very slightly permeable clay layers and the nearly impermeable salt and gypsum layers virtually sealed off vertical ground-water flow to pre-Permian rocks throughout most of the study area with the possible exception of flow along faults or fractures in areas of major uplift. Permeable coarse

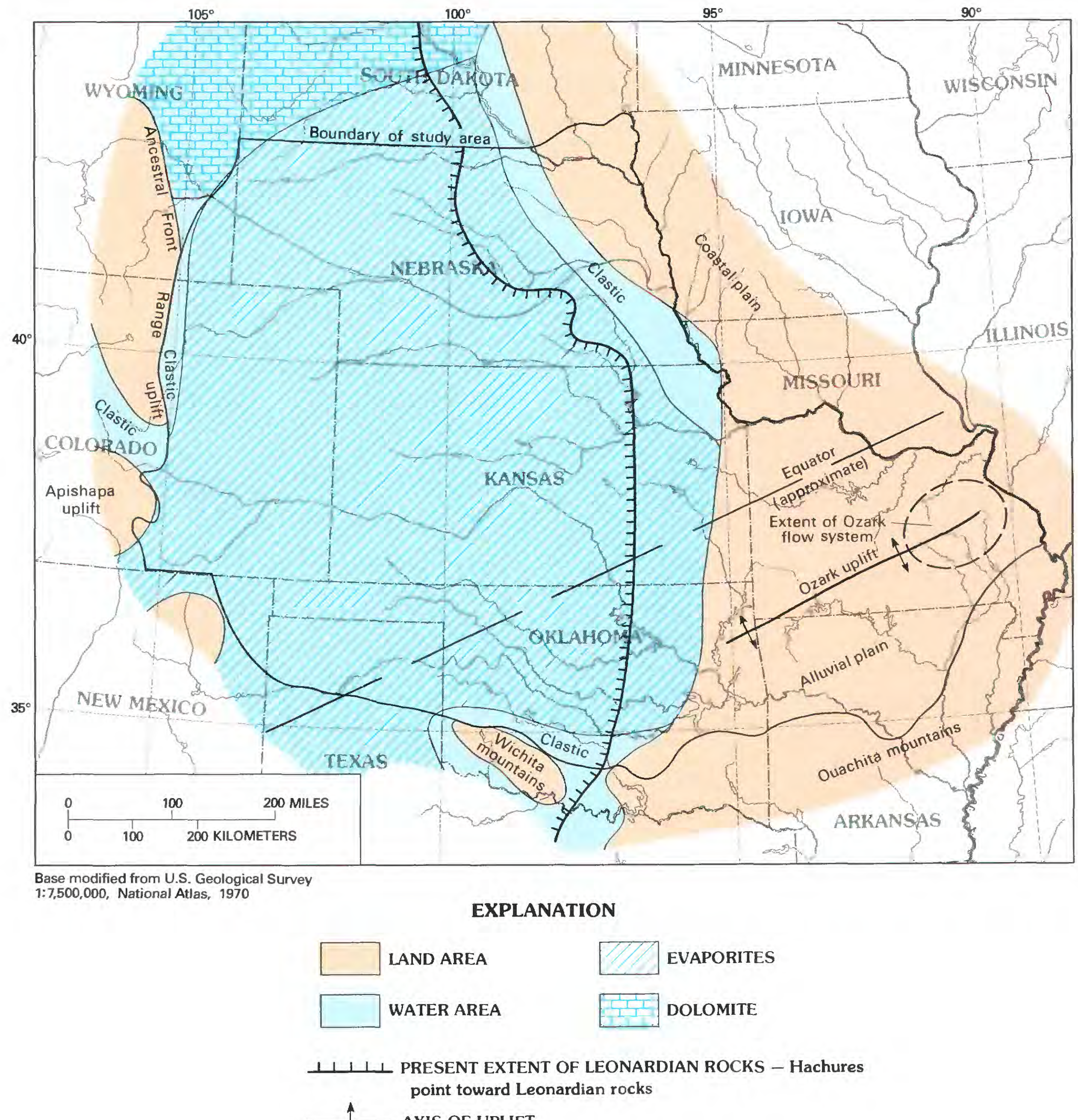


FIGURE 25.—Early Permian (Wolfcampian–Leonardian) geographic and geologic conditions (modified from McKee and Oriel, 1967).

clastic material was deposited adjacent to the Wichita and Front Range uplifts; however, basinward the less permeable fine-grained sediments were deposited.

Late Permian time was characterized by a cyclic but mostly recessive sea as the eastern part of the study area continued to be tilted upward. By the end of Permian time, marine deposition only occurred in a small part of the study area. Extensive uplift, possibly as much as 2,000 ft, occurred along the southern part of the Ozark uplift probably during late Guadalupian time. This uplift may have caused brines of Early Permian age that had infiltrated into the rocks on the flanks of the Ozark uplift to move westward in the subsurface. Other tectonic activity decreased substantially and no other area of rapid uplift is known. However, large-scale but gentle flexing did occur. Erosion of the positive elements, which produced large quantities of detritus during Early Permian time, had beveled most positive features, such as the Ouachita Mountains, to such a degree that, in general, the topography of the area was almost flat. Evaporitic and other marine sediments of a restricted-circulation environment continued to be deposited in the center of the study area. Along the southern and southwestern boundaries of the study area, both continental and shallow marine sediments were deposited. In the eastern part of the study area, Lower Permian sediments and older rocks were exposed to erosion, and large alluvial plains developed.

By the end of Permian time, more than 20,000 ft of Permian and Pennsylvanian sediments had been deposited in the centers of the Anadarko and Arkoma basins. Burial diagenesis was active, especially in the deeper parts of the basins. In the Anadarko basin hydrothermal pressuring of the Morrowan geopressure zone increased with burial. Thermal diagenesis of organic material occurred at a rapid rate in Permian and Pennsylvanian rocks; however, thermal diagenesis of organic material in the pre-Pennsylvanian rocks probably was nearly complete by the end of the Permian. The Upper Permian clay layers formed extensive confining units. The evaporite deposits, especially halite and gypsum, were nearly impermeable. The sand layers were transmissive and were aquifers. Collectively, the confining units of clay and evaporite deposits severely restricted water flow to the underlying permeable Cambrian through Mississippian rocks and formed a confining system. In areas where depth to the evaporite deposits was shallow, 1,000 ft or less, such as in the Ozark uplift area, subsurface dissolution of evaporite deposits by ground water of meteoric origin probably occurred. At the end of the Permian, there was little topographic relief, and the regional westward flow of ground water was probably sluggish. Erosion and removal of the very slightly permeable Pennsylvanian and possibly Permian rocks along the axis of the Ozark uplift would have expanded the ground-water flow system, which had started to form during the Early Permian, in the Ozark subregion.

TRIASSIC SYSTEM

In general, the Triassic Period was characterized by the relaxation of compressive forces that had existed during the Paleozoic. Crustal thinning, which resulted in rifting outside the study area, and subsidence of the Mississippi embayment started during the Triassic.

Deposition during Early Triassic time occurred only in northern Colorado and western Nebraska. Red clay, calcareous mud, and dolomite were deposited. The sediments are similar to those of Permian age, except they do not contain extensive halite and anhydrite beds. Conditions were somewhat similar to those of the Late Permian; however, the sea was less restrictive during Triassic time as compared to the Permian. Accordingly, sediments were more typical of normal marine-water circulation, and evaporite deposits were only deposited in some limited areas.

The land areas within the study area had little relief and, thus, were not major sources of sediment. Ground-water movement in the regional flow systems was sluggish. Because neither the magnitude of uplift nor the magnitude of subsidence was large, thermal diagenesis of organic material and its chain of diagenetic reactions probably continued at about the same rate as they had during the Permian.

At the end of Early Triassic time, the sea retreated, the entire study area emerged, and erosion ensued. Continental deposits of Middle Triassic age are not identifiable within the area. Dissolution of the soluble near-surface Permian and Triassic evaporite deposits to depths of several hundred feet resulted in increased secondary permeability. A limited proportion of the resulting dense brine probably infiltrated very slowly into or through the underlying confining units. There apparently was no substantial uplift in the Ozark area. Erosion along the axis of the Ozark uplift exposed older rocks in bands around the St. Francois Mountains. Karst with greatly enhanced porosity and permeability was developed in the exposed dolostone and limestone. The surficial Pennsylvanian shales marked, in general, the outward limit of the freshwater flow because the shale formed an extensive confining system restricting circulation of the meteoric ground water.

Tectonic activity began again during Late Triassic time when uplift of the highlands of central Colorado took place. The highlands eroded rapidly and were the principal source of sediment that was deposited in the Dockum basin (fig. 26). Some sediment was transmitted into the basin from the lowlands to the east. The increased erosion was in part the result of a general climatic change from the arid Permian to the more humid Triassic (McGowen and others, 1979, p. 3). However, during Triassic time, the climate varied from humid to arid. A large lake formed in the Dockum basin, whose water level fluctuated with climatic change. Accordingly, the deposits in the lake are fluvial, deltaic, prodeltaic, and lacustrine in origin, and in general, consist mostly of permeable fine-grained sand and gravel and less permeable red mud and overbank mud.

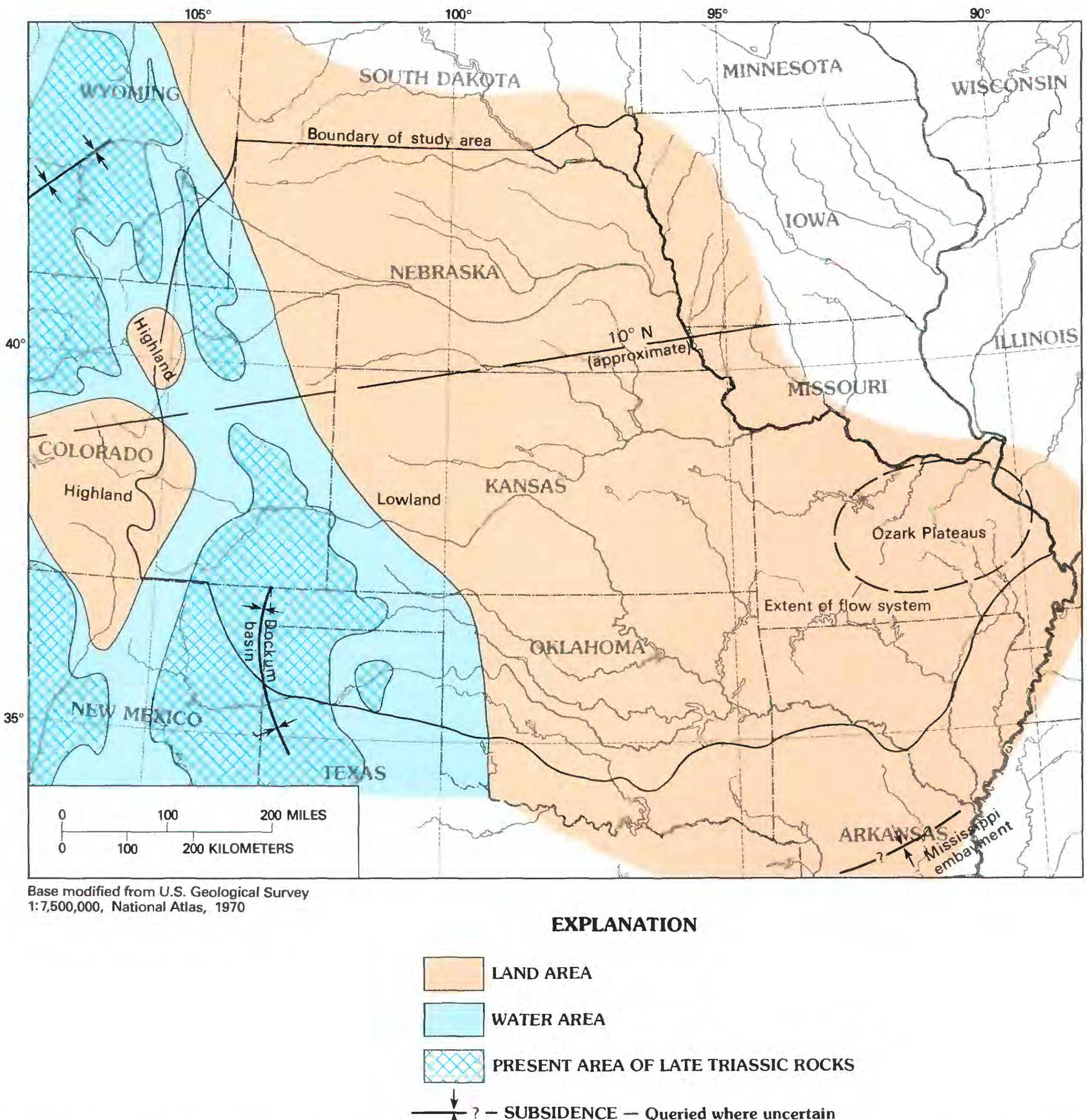


FIGURE 26.—Late Triassic (maximum sea) geographic and geologic conditions (modified from McKee and others, 1959).

JURASSIC SYSTEM

During the Early Jurassic, the entire study area was a low plain slightly above sea level. The climate was subtropical and ranged from humid to arid. The equator was believed to have extended through central Mexico near present-day Mexico City. The area south and southeast of the Ouachita uplift continued to subside slowly, forming the Mississippi embayment.

The sea advanced slightly into the study area during Middle Jurassic time, and continental deposits, mostly permeable arkosic sand, were deposited. The sand was the parent material for the Entrada Sandstone and similar sandstones. The sand of the Entrada is of eolian origin and grades northward into a muddy fluvial sand and finally into the marine sand of the Sundance Formation in eastern Wyoming, western Nebraska, and western South Dakota (Berman and others, 1980, p. 116–117).

The Late Jurassic sea submerged the western part of the study area. Variegated clay, silt, sand, and calcareous algal mud of the Morrison Formation were deposited in lakes on the flood plains and deltas along the coastal lowlands (Berman and others, 1980, p. 118). The geographic conditions of the Late Jurassic, including the probable maximum extent of the Late Jurassic sea and the approximate extent of the present-day Morrison Formation and equivalents, are shown in figure 27. The salinity of the sea varied from slightly brackish to normal marine.

The regional tilting (uplift of the eastern part of the study area) continued. The decrease of load by erosion of Permian and Pennsylvanian rocks resulted in extensional microfractures that enhanced permeability of the near-surface shale and other rocks. Ground water of meteoric origin probably moved downward through the fractures and dissolved evaporite beds at depths of as much as 1,000 ft. Thus, the subsurface extent of the salt beds slowly retreated in advance of the retreating extent of the outcropping Permian and Pennsylvanian rocks. The dissolution of the salt beds in the Permian rocks resulted in collapse of the overlying layers of shale, limestone, and sandstone, and further enhanced vertical permeability of the collapsed material. Ground water at the dissolution front would have been a dense brine, as it was probably saturated with sodium chloride. Some of the brine may have migrated downward through the underlying confining shale units into the underlying aquifer of Cambrian through Mississipian carbonate rocks along the eastern edge of the Ozark uplift. In general, the land surface sloped gently downward from east to west. Ground-water movement was sluggish except for the Ozark flow system; deep regional flow systems did not develop.

At the end of Jurassic time, the sea receded until the entire study area was above sea level, and the Morrison deposits were extensively eroded. During the long period that the eastern part of the study area was above sea level, the regional ground-water flow system of the Ozark Plateaus became well established. Surficial weathering and other processes of uplift diagenesis were active. Karst developed on the exposed carbonate aquifer material. The outcrop area of the aquifers over the Ozark uplift expanded with the continued erosion and removal of the Pennsylvanian shale layers.

CRETACEOUS SYSTEM

At the beginning of the Early Cretaceous, the entire study area was above sea level and was undergoing uplift diagenesis. This condition was ended by a rapid transgression of the Cretaceous sea from the north and from the south. Moderately permeable fine-grained sand and intercalated clay were deposited on alluvial plains and in nearshore estuaries by a generally advancing sea (Franks, 1975, p. 469). Continued advance of the sea moved the shoreline southward and eastward, and the very slightly permeable clay, the parent material of the Kiowa Shale and equivalents, was deposited offshore. The precise location of the eastern extent of the Kiowa sea is not known. However, it is likely that the sea covered the entire study area, with the exception of part of the Siouxana arch and the Ozark uplift (fig. 28). The sea filled the rapidly subsiding Mississippi embayment. Clay deposition was ended by a general recession of the sea, which in part was the result of the regional uplift of the eastern part of the study area. The uplift of the Pascola arch (not shown in fig. 28), which is in the bootheel of Missouri and in western Tennessee within the Mississippi embayment, may have taken place during Early Cretaceous time (Schwalb, 1982, p. 31). It is not known if this uplift was associated with the igneous intrusions of plutons that occurred along the southeastern study-area boundary in northeast Arkansas and the bootheel of Missouri.

Subsequent to the retreat of the sea, an extensive period of erosion ensued, which to a considerable degree leveled the eastern part of the study area and removed most of the Cretaceous sediments. The erosion exposed the permeable Cambrian and Ordovician rocks in southeastern South Dakota and northeastern Nebraska. Ground-water flow away from the Siouxana arch developed and resulted in flushing and mixing of freshwater with the ambient ground water adjacent to the uplift.

Erosion also exposed the very slightly permeable Pennsylvanian and Permian shale in an area from southeastern Nebraska to eastern Oklahoma. Again, unloading resulted in extensional microfracturing of shale layers and jointing of layers of more competent rocks. Because the Cretaceous sea is not believed to have covered the uplifted Ozark area, erosion there was uninterrupted and removal of the Pennsylvanian and Permian shale layers resulted in continued expansion of the flow system in the Ozark uplift area.

A second trend of sea advance followed the erosional period. The generally transgressive sea advanced to the south and east during the later stages of the Early Cretaceous and into the Late Cretaceous. The maximum extent of this sea is not known, but it is believed to have extended beyond

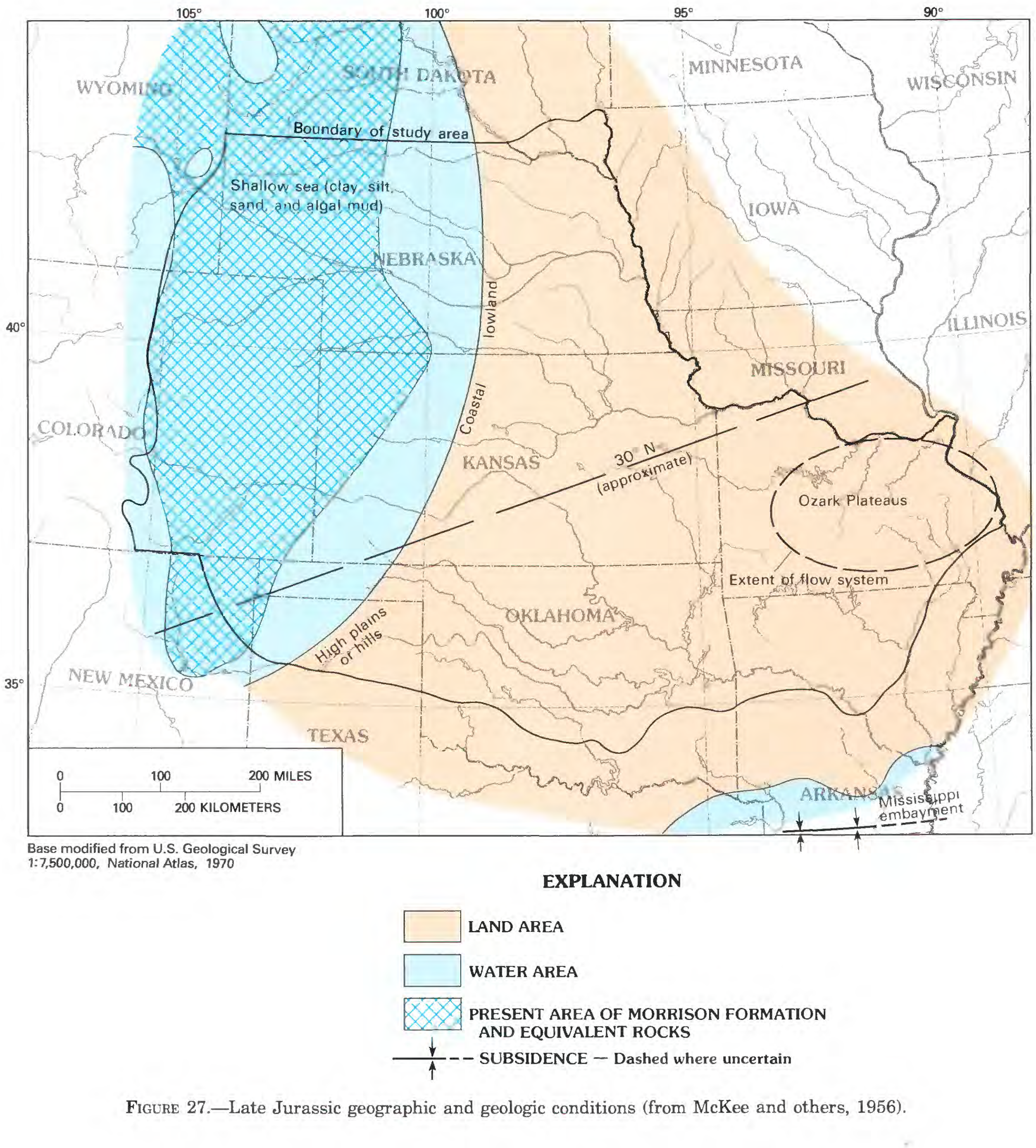


FIGURE 27.—Late Jurassic geographic and geologic conditions (from McKee and others, 1956).

the present limits of the Dakota Sandstone and may have exceeded the maximum extent of the sea during the Early Cretaceous, as shown in figure 28. Contemporaneously deposited sediments, such as those preserved in the Dakota Sandstone and equivalents, are likely to change from marine to continental in a traverse from west to east or from north to south. Most sediments were moderately permeable sand with some intercalated clay and organic material that were deposited on a low-lying coastal and deltaic plain. In general, sediments in Kansas, Nebraska, and South Dakota represent chemically resistant detritus, such as quartz and other silicates, from reworked rocks to the northeast of the study area; sand deposited in eastern Colorado and Wyoming was detritus from the highlands west of the study area. The nearshore sand deposits were porous and moderately permeable. Individual sand beds were discontinuous on a regional scale, but were generally contiguous with each other at some locations. Thus, hydraulic continuity existed throughout extensive areas. However, because the topography was moderate, strong flow systems did not develop.

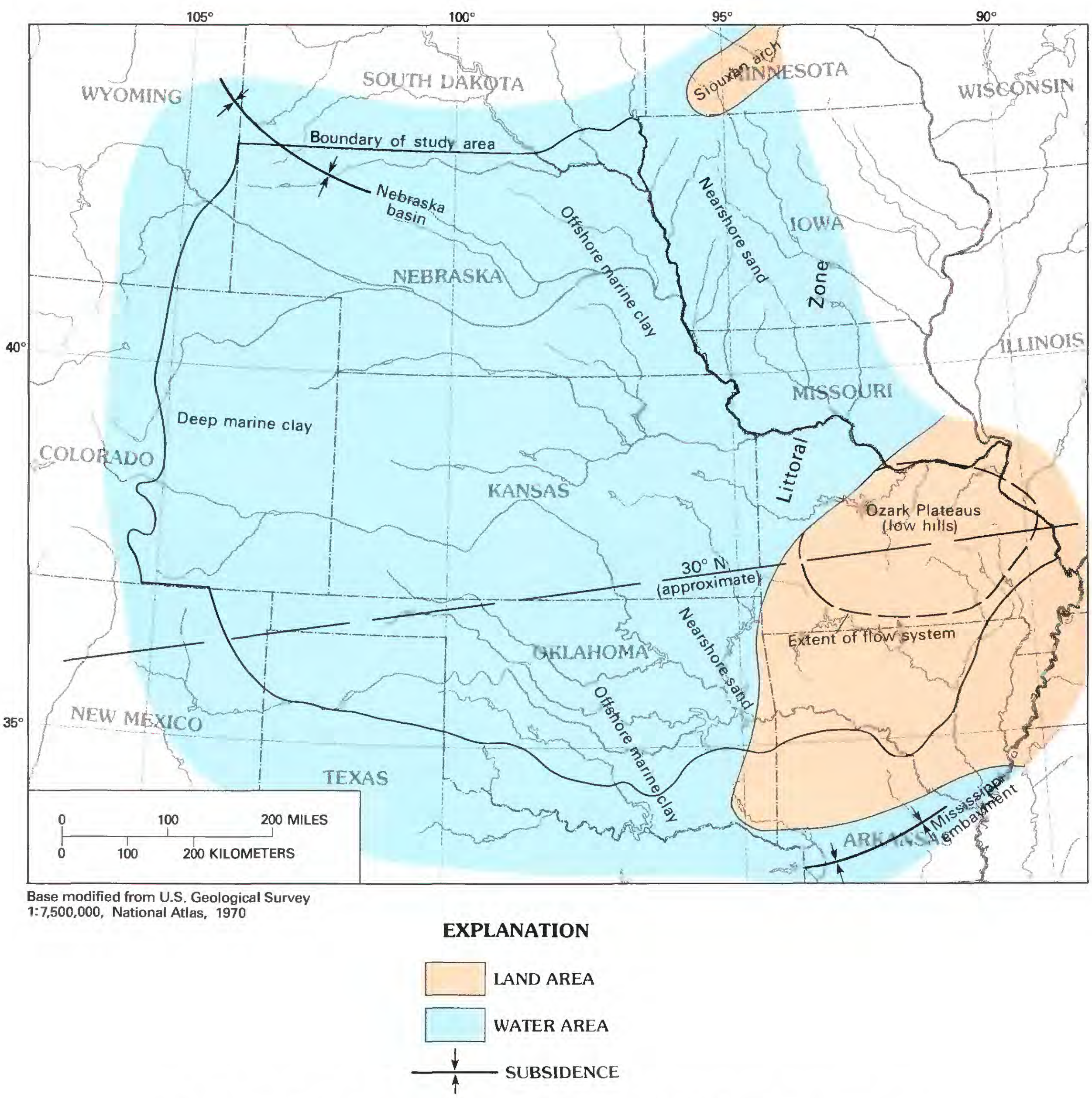


FIGURE 28.—Early Cretaceous (maximum sea) geographic and geologic conditions.

During Late Cretaceous time, burial diagenesis was again important. Relatively impermeable marine clay (rich in montmorillonite) was deposited offshore contemporaneously with nearshore sand and silt. These deposits are represented by the marine Graneros Shale and Dakota Sandstone (see table 2 for list of Upper Cretaceous formations). Biogenic carbonate sediment (Greenhorn Limestone) was deposited conformably in a shallow open marine sea on the clay (Graneros Shale) as the transgressing sea neared its maximum coverage. Thin layers of calcareous and noncalcareous clay, parent material of the Carlile Shale, were deposited on the calcareous sediment of the Greenhorn Limestone in an offshore marine environment as the sea receded (Merewether and Cobban, 1981, p. 53) into North Dakota, Wyoming, and Montana.

As the recession ended, the sea advanced far to the south and east, perhaps to the same extent as the sea in which the clay of the Graneros Shale was deposited. The first deposits in the advancing sea were nearshore calcareous mud and shell detritus, parent material of the Niobrara Chalk. These sediments were followed by offshore clay, parent material of the Pierre Shale (table 2). The very slightly permeable clay restricted water flow to and from the underlying permeable sandstone (the Dakota and Cheyenne Sandstones). Rapid subsidence began in the Denver basin in the western part of the study area, probably as a result of compressive forces.

Near the end of the Late Cretaceous, rapid uplifts of the Laramide orogeny started (fig. 29). The Laramide orogeny is related to the collision of the Farallon and North American plates, which resulted in east-northeast compression in the study area. Many of the uplifts were apparently along previous planes of weakness that were associated with uplifts during Pennsylvanian time. Tweto (1980) in reference to the Laramide orogeny in Colorado, stated, "* * * the Precambrian basement had been driven by major faults and shear zones since Precambrian time, and further fracturing had occurred in the late Paleozoic, if not also at other times. Laramide deformation was markedly influenced by these preexisting features."

Sedimentation rates increased substantially as 5,000 to 10,000 ft of clay were deposited in the rapidly subsiding Denver basin. The weight of the sediments compacted clay to shale (Pierre Shale) and released large quantities of water. The pore pressure in the Dakota and Cheyenne Sandstones and the pre-Cretaceous limestones probably increased to more than hydrostatic and probably caused increased solution of calcite. The temperature of the rocks also increased with burial. Thermal diagenesis of organic material increased to a slow to moderate rate. A study of the organic chemistry of the petroleum in the northern Denver basin by Clayton and Swetland (1980, p. 1613) indicated that the Carlile Shale, Greenhorn Limestone, and Graneros Shale along the axis of the basin are the source beds of the oil found in the "D and J sands" on the east flank of the basin. Thus, lateral migration of hydrocarbon of about 100 mi has occurred and may have been preceded or accompanied by CO_2-rich water, which in turn created secondary porosity and permeability by dissolution of carbonate material.

Faulting associated with the Laramide orogeny formed barriers to recharge in the foothills of the Rocky Mountains at some locations (Banta, 1986). High-angle faults, upthrown on the foothills side, eliminated or displaced outcrops of most pre-Cretaceous rocks along the foothills. In other places, outcrops along the foothills were not displaced, but basinward faulting created a barrier to water flow from the outcrops to the same rocks in the basin. Thus, the same formation may or may not have been part of the same aquifer across the fault. At a few locations, such as near Boulder and Canon City, Colorado, however, hydraulic connection between the foothill outcrops and the basin was not disrupted.

The hydraulic characteristics of rock material near the Laramide uplifts also were modified. For example, it is possible that the permeability of the coarse clastics of the Pennsylvanian- and Permian-age Fountain Formation in central Colorado was decreased by calcite cementation as the pore pressure was decreased with the uplifting.

The sea withdrew northward out of the study area before the end of Late Cretaceous time; accordingly, the final Cretaceous sediments are continental in origin and lacustrine and fluvial in nature. The withdrawal of the sea initially did not decrease the load in the Denver basin and surrounding area because detritus eroded from the uplifts was being deposited rapidly on the plain above the basin. This alluvial sedimentation represents a loading cycle during which fluids tend to be pushed outward from the center of the basin. Thus, the CO_2-rich fluids in the Denver basin may have moved outward accordingly (Ottman, 1984, p. 81). The acidic solution could have selectively dissolved carbonate cements and some feldspar in part of the Denver basin. However, along the southern flank of the basin freshwater mixed with the basinal water being moved updip. The mixed water probably was not saturated with silica, thus allowing dissolution of carbonate cements by CO_2-rich solutions without back-cementing of silica.

TERTIARY AND QUATERNARY SYSTEMS

The second major pulse of the Laramide orogeny occurred during Tertiary time, as evidenced by mountain building in central Colorado and Wyoming and in western South Dakota (fig. 29*A*). Extensive erosion of uplifts and widespread deposition of thick alluvium on the plains followed. The most extensive deposits were water-bearing sand and gravel, which were the parent materials of the Ogallala Formation (table 2). The maximum extent and the maximum thickness of the original deposits are not known. These deposits probably extended from the Front Range to eastern South Dakota, eastern Nebraska, central Kansas, and central Oklahoma.

With time, the mountain building slowed and erosion of the existing alluvial material exceeded deposition of new clastics from the uplifts. Estimates of the thickness of Cenozoic material removed are as much as 2,000 ft. The present water-bearing Ogallala Formation (fig. 29*A*) is an erosional remnant of a much more extensive deposit. (Presently, the thickness of

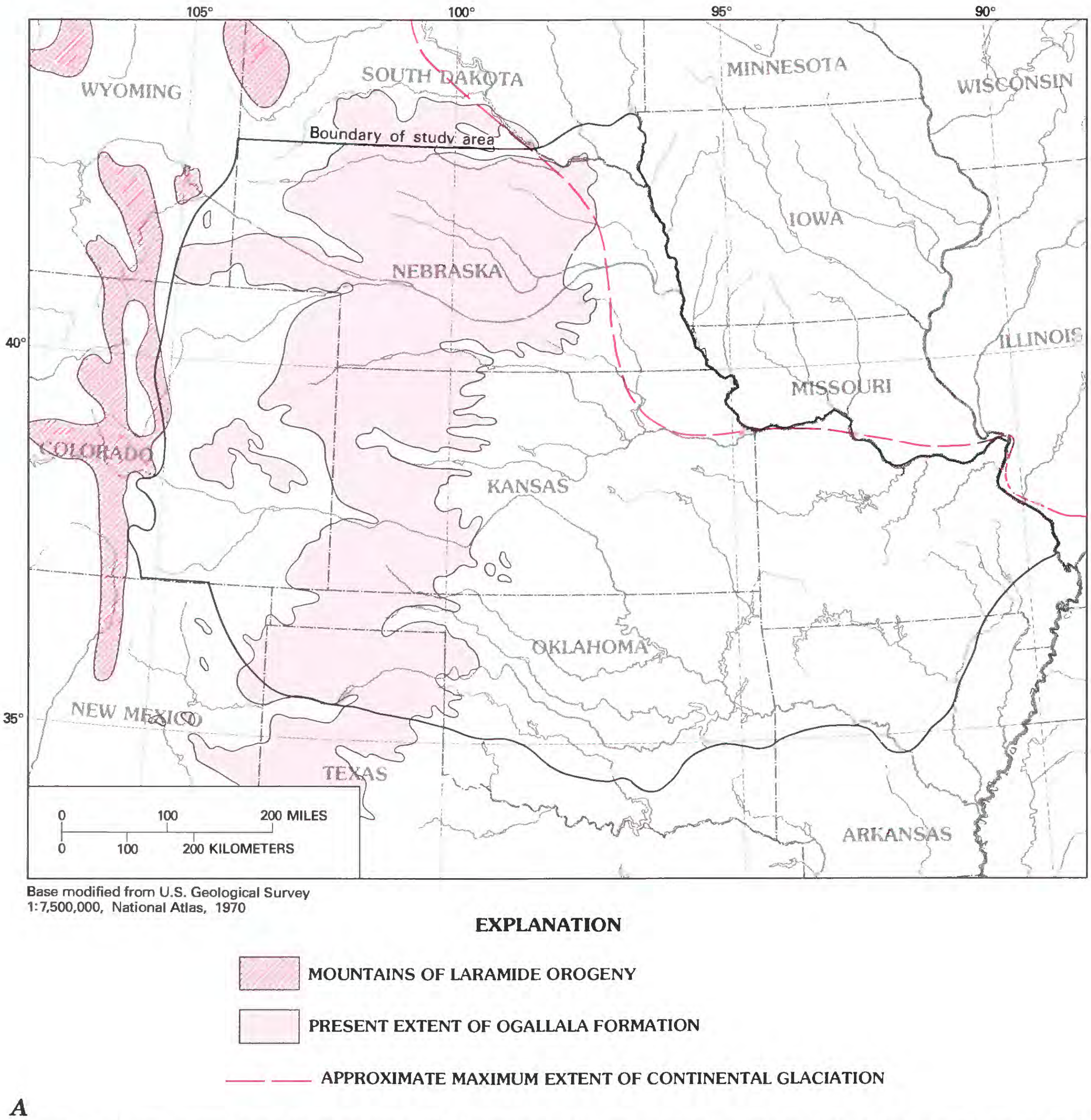


FIGURE 29.—Present conditions in study area. *A*, Mountains of Laramide orogeny, and extent of Ogallala Formation and glaciation. *B*, Estimated relative permeability distribution based on paleohydrology in Cambrian- and Ordovician-age rocks.

the Ogallala ranges from near zero to 1,000 ft, and 100 to 200 ft is typical.) The Ogallala is directly underlain by Cretaceous and older rocks, except in west-central Nebraska, where it overlies older undifferentiated Tertiary material (Weeks and Gutentag, 1981).

The unloading by the erosion of the Cenozoic sediments over the Denver and Anadarko basins has resulted in expansion of the rock mass and a decrease of pore pressure, thus ending the outward movement of water in the Denver basin and initiating an inward movement of water toward the center of the basin as the pore pressure in the formations became less than hydrostatic. The rate of generation of CO_2 from diagenesis of organic material would have decreased. With the spending of the CO_2-rich solution, increase of the pH, and the decrease in pressure, carbonate cement may have been precipitated.

Several regional ground-water flow systems were established by the end of the Laramide orogeny. Permeable zones, in the Cretaceous-age Dakota and Cheyenne Sandstones as well as in the Cambrian

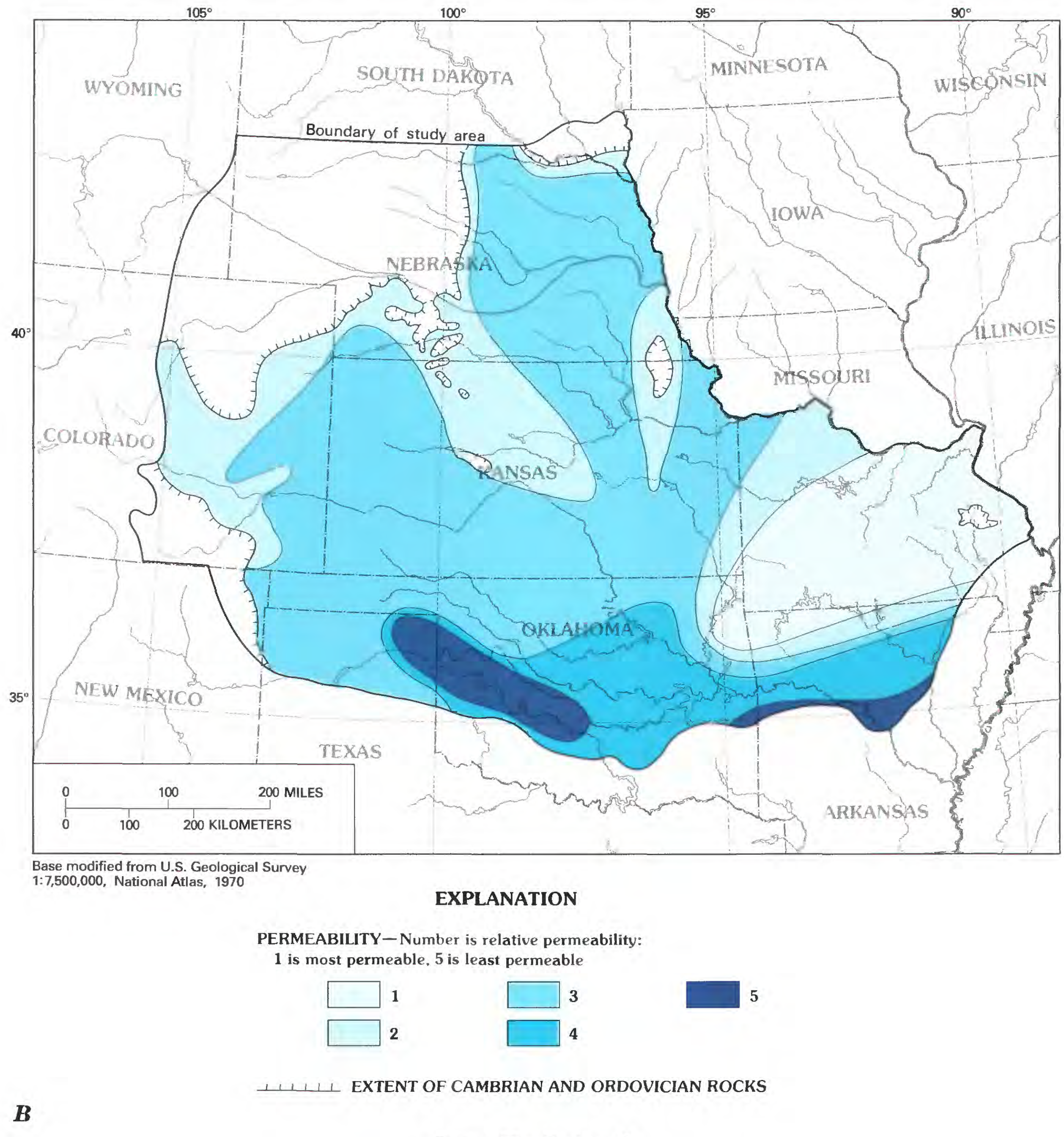


FIGURE 29.—Continued.

(fig. 29*B*) through Mississippian rocks, transmitted water very slowly in a general west-to-east direction, initiating the present flow systems in the Maha and Apishapa aquifers of the Great Plains aquifer system in the Cretaceous sandstones and the Western Interior Plains aquifer system in the Mississippian–Cambrian rocks.

At the end of Tertiary time, the sea retreated to the Williston basin in North Dakota and south of the Ouachita folded area in Arkansas and southeastern Oklahoma. Extensive forests grew in the subtropical climate. The equator may have been located along a line from southern Texas to southern Florida. Organic material was abundant, and drainage patterns similar to the present were established.

The Quaternary Period was marked by episodes of extensive glaciation that were interspersed with much warmer interglacial periods. Although continental glaciation directly affected only the northeastern part of the study area (fig. 29*A*), the climatic changes affected the entire study area. The advance and retreat of the glaciers were accompanied by a lowering and raising of sea level. A change in sea level directly affects the water table and also the base level of erosion. These changes altered pore pressure in the subsurface. The glaciers also altered the regional topography and the ground-water flow paths. The cyclic loading and unloading by the ice affected stress distribution and probably caused some additional fracturing of competent rock. The unglaciated area within the area of study underwent erosion and associated diagenetic changes.

GEOHYDROLOGY

CLASSIFICATION OF SUBSURFACE HYDROLOGIC UNITS

A regional aquifer system can have more than one aquifer or confining unit. An aquifer or aquifer system may consist of several formations, one formation, or part of a formation. The property that distinguishes a confining unit is its leakance, which is its effective hydraulic conductivity divided by its thickness. From a regional perspective, an aquifer may 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. In contrast, a confining unit may also contain discontinuous permeable zones. Again, the size of the permeable zones is much smaller than the size of the confining unit. For these reasons, the authors prefer to use geohydrologic units rather than hydrostratigraphic units to designate the subsurface hydrologic units.

In the hydrologic analysis of large regions, which contain many geohydrologic units, it is useful to group units into geohydrologic systems, such as an aquifer system or a confining system. An aquifer system consists of two or more aquifers in the same hydraulic system, which are separated at most locations by one or more confining units. A confining system contains two or more confining units separated at most locations by one or more aquifers that are not in the same hydraulic system.

GEOHYDROLOGIC UNITS

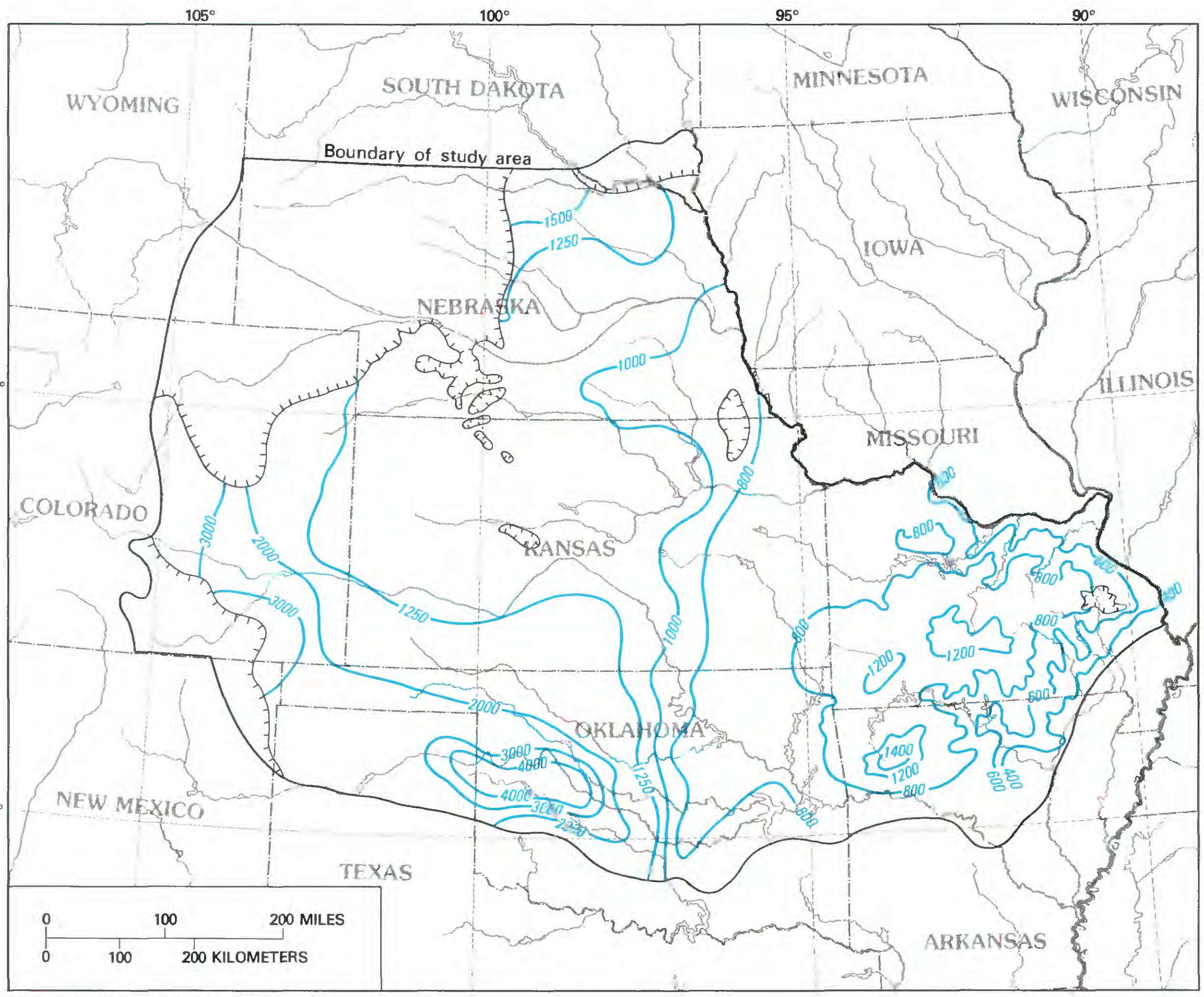
Geohydrologic units within the study area were defined by hydrologic relations and hydraulic properties of the rocks. The relation of the geohydrologic unit to ground-water flow is essential in conceptualization of regional aquifer systems. The flow within most regional aquifers, in general, is controlled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

The initial step in the delineation of the geohydrologic units was to identify water-bearing strata that contained freshwater. The term "water-bearing" indicates that the strata transmits and yields water and implies permeability. However, in most of the study area, little information was available as to either the hydraulic properties of the rock units or the hydrologic relations among them. In areas lacking hydraulic and hydrologic information, the permeability was inferred from lithology. For example, rock sections that included thick beds of shale or evaporite deposits separated by smaller sandstone or limestone layers were assumed to be confining units because the shale and evaporite deposits generally have very slight permeability.

The geohydrologic units within the study 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 the regional stratigraphic units. The major exception is along the physiographic boundary between the Interior Plains and the Interior Highlands (fig. 11). At this boundary, two regional ground-water flow systems are laterally adjacent. In general, the ground-water flow system that originates in the Ozark Plateaus extends outward until it meets the ground-water flow system that underlies most of the western part of the Interior Plains. The approximate location of the boundary between these two flow systems is marked by a low in the equivalent-freshwater head surface (fig. 30), which is nearly coincidental with a topographic low in eastern Kansas and northeastern Oklahoma (fig. 12). The topographic low is a discharge area to both flow systems (fig. 31). The boundary parallels the physiographic boundary of the Central Lowland province in the Interior Plains.

The extent of the flow systems in most areas also is apparent from the map of the dissolved-solids concentration (fig. 32). The Interior Highlands, except south of the Boston Mountains, has water with less than 1,000 mg/L (milligrams per liter) dissolved solids. For convenience, the two subregions of this regional analysis are referred to herein as simply the Plains subregion and the Ozark subregion. The geohydrologic units in the two subregions are described separately.

The lowermost confining unit in both the Plains and Ozark subregions is the basement confining unit. The basement confining unit is composed mostly of crystalline rocks. The rocks may be fractured and



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

EXPLANATION

EXTENT OF CAMBRIAN AND ORDOVICIAN ROCKS

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

FIGURE 30.—Predevelopment equivalent-freshwater head in Cambrian and Ordovician rocks.

yield water at some locations, such as in the Denver basin and in southeastern South Dakota, but on a regional basis the basement unit is assumed to form the base of the regional flow system. The top of the basement unit varies 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 to about 500 ft above sea level in southeastern South Dakota to more than 7,000 ft below sea level in the Denver basin along the Rocky Mountains in east-central Colorado (pls. 2, 3).

PLAINS SUBREGION

The Plains subregion contains six major regional geohydrologic units of which the Western Interior Plains aquifer system, the Western Interior Plains confining system, and the Great Plains aquifer system, were studied in detail (fig. 33, table 2, pl. 2). The Great Plains confining system was not studied in detail, and the High Plains aquifer was studied as a separate regional aquifer system (fig. 2).

WESTERN INTERIOR PLAINS AQUIFER SYSTEM

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 (pl. 2). The major stratigraphic units included in the system are listed in table 2. A geologic formation within the aquifer system may be an aquifer in one part of the area and a confining unit in other parts. The Western Interior Plains aquifer system includes the lower units, a confining unit, and an upper unit (table 2). Equivalent-freshwater heads and water-chemistry data (figs. 30, 32) indicate that the lower units and the upper unit are part of the same flow system.

The lower units of the Western Interior Plains aquifer system, at most locations, consist of aquifers of water-bearing dolostone, limestone, and sandstone of Cambrian and Ordovician age, which include confining units of very slightly permeable shale or limestone at depths greater than 10,000 ft. These lower units of the aquifer system are separated at many locations from the overlying upper unit by a relatively thin confining unit composed of very slightly permeable shale, such as the Chattanooga and Woodford Shales. The upper unit of the aquifer system is an aquifer composed of permeable limestone of upper Devonian and Mississippian rocks.

Flow in the aquifer system is regionally (but not necessarily locally) from north-central Nebraska southeastward and otherwise from west to east toward a broad physiographic low (fig. 31). Discharge in the broad low area generally is upward to streams or to the near-surface water table. Two conspicuous discharge areas exist. The first is in Saline County, Missouri, where several salinewater springs are

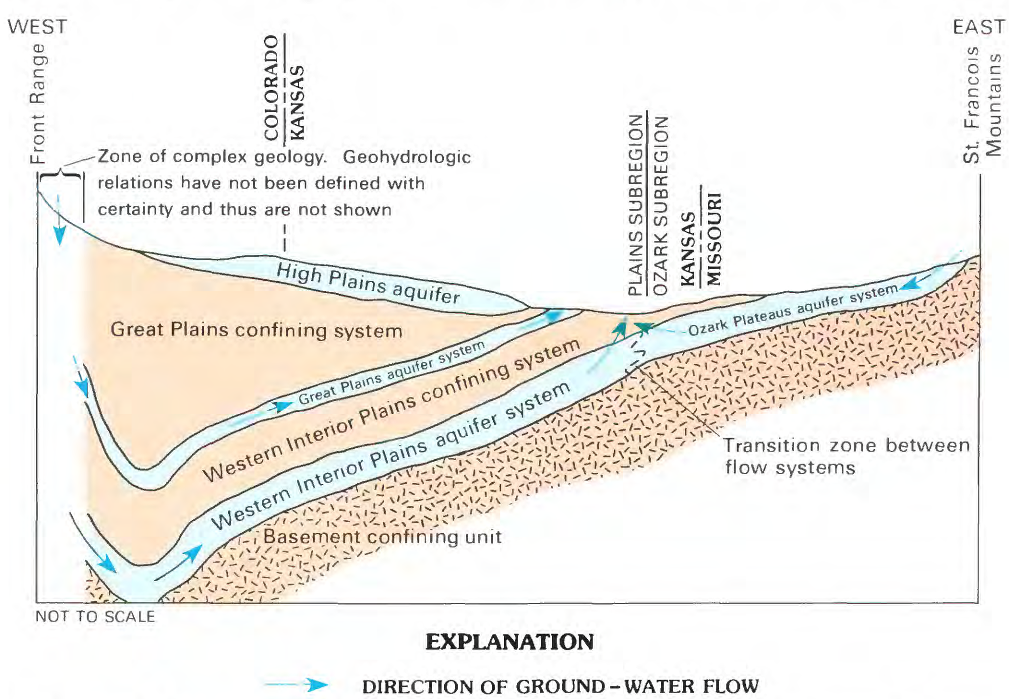
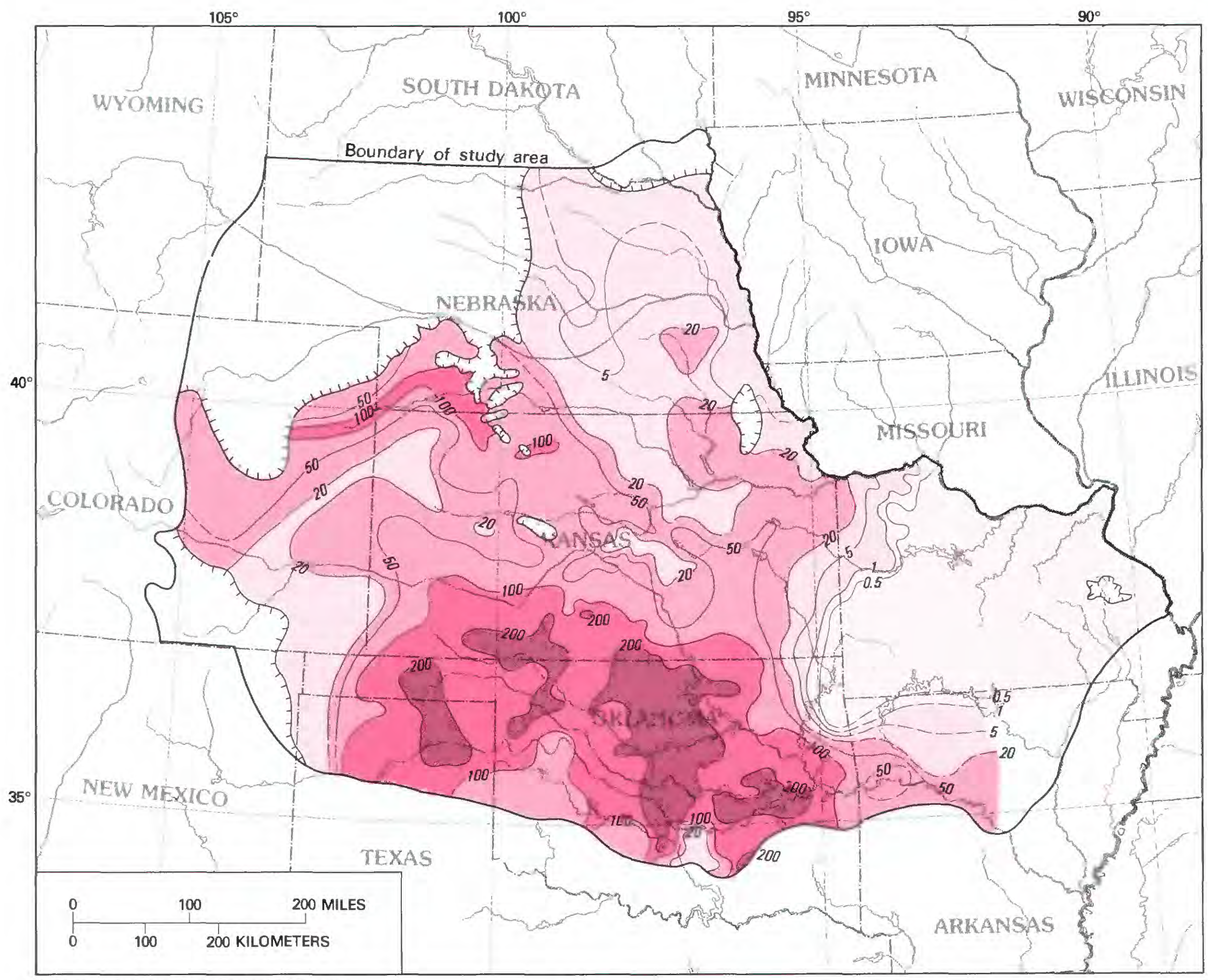


FIGURE 31.—Major regional geohydrologic units in the Plains and Ozark subregions. Section extends from central Colorado to St. Francois Mountains in southeastern Missouri.

present. The second is in Henry County, Missouri, where salinewater discharges upward in low areas near the Osage River.

In northwestern Nebraska, the lower units of the Western Interior Plains aquifer system are separated laterally from similar permeable carbonate rocks in South Dakota and Wyoming by the Siouxana arch and the Chadron arch. At many locations along the western and southern boundaries of the study area and near uplifts, such as the Front Range, Amarillo, Wichita, and Ouachita, complex faulting has disrupted the strata. At these locations, the hydraulic relations among specific strata are complex and generally unknown, and the aquifers cannot be described easily in terms of regional geologic formations. However, the hydrologic continuity of the geohydrologic system is implied by the continuous nature of the generalized map of equivalent-freshwater head (fig. 30).



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

EXPLANATION

DISSOLVED-SOLIDS CONCENTRATION—Values in milligrams per liter

0-1,000

1,000-20,000

20,000-100,000

100,000-200,000

More than 200,000

—50— LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION—Dashed where approximate. Interval, in thousands of milligrams per liter, varies

APPROXIMATE EXTENT OF CAMBRIAN AND ORDOVICIAN ROCKS

FIGURE 32.—Dissolved-solids concentrations in water from Cambrian and Ordovician rocks (preliminary).

The altitude of the top of lower aquifer units of the aquifer system is shown on plate 4. The altitude of the shale confining unit that separates the upper unit from the lower units is shown on plate 5. The altitude of the top of the upper aquifer unit of the Western Interior Plains aquifer system is shown on plate 6. All units of the system generally slope downward 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 are in the Anadarko and Arkoma basins (pl. 7). These areas are where maximum deposition occurred. Additionally, these rocks have been protected, for the most part, from erosion since their deposition. Thus, uplift diagenetic processes, which generally are associated with uplift and erosion and result in large increases in permeability, have not acted in these areas. Accordingly, stratigraphic units in these deep areas are considerably less permeable than the same stratigraphic

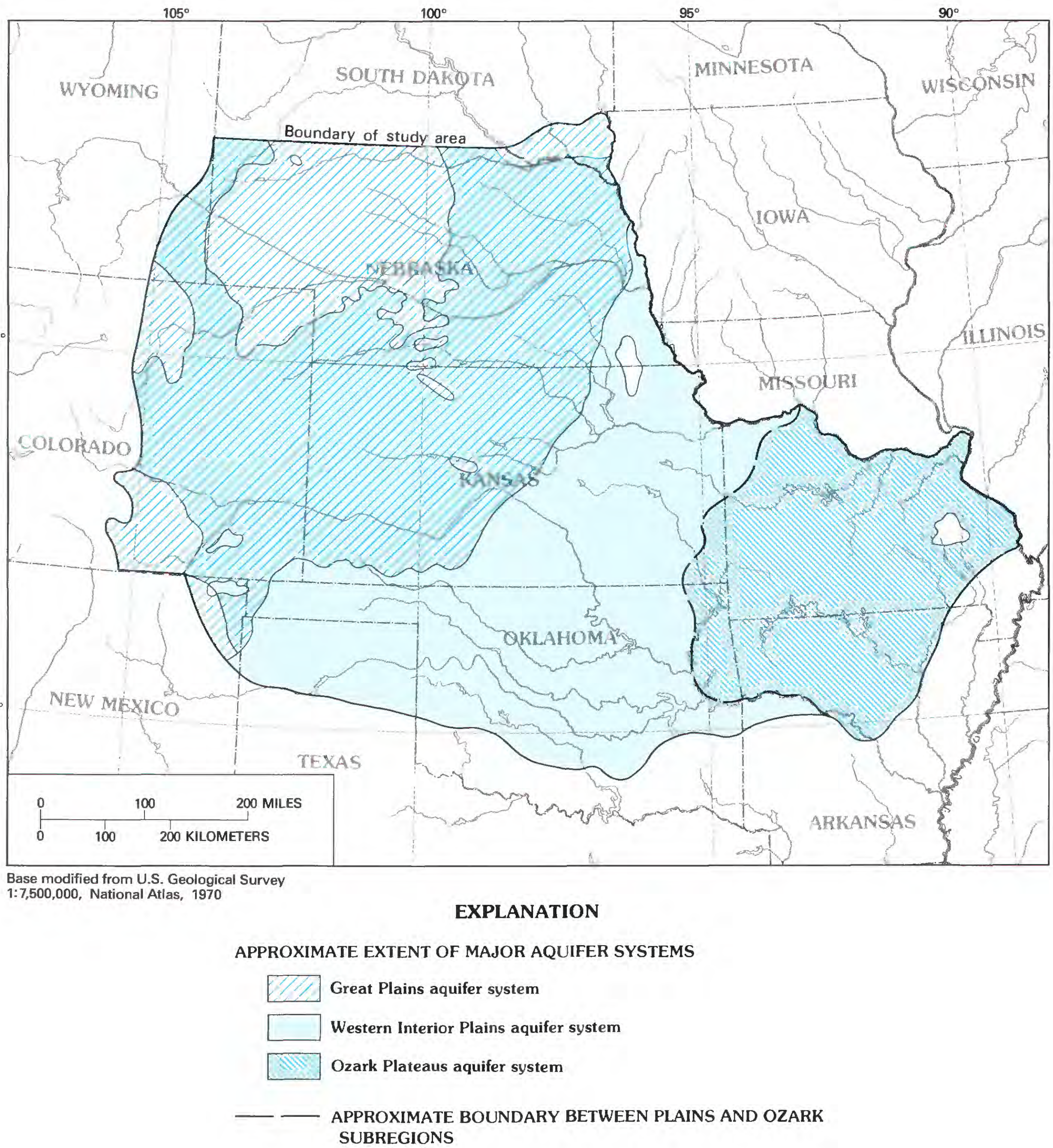


FIGURE 33.—Extent of major aquifer systems.

TABLE 2.—*Generalized correlation of stratigraphic units to geohydrologic units in most of the Plains subregion*

Geohydrologic unit		Principal 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 (includes Lower Cretaceous)	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 and Lakota Sandstones	
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 unit	Meramecian, Osagean, and Kinderhookian rocks	Upper Mississippian through Upper Cambrian
	Confining unit	Chattanooga and Woodford Shales	
	Lower units	Hunton Group, Sylvan Shale, equivalent of Galena Dolomite, Viola Limestone, Simpson Group, Arbuckle Group, and Reagan Group	
Basement confining unit		Mostly igneous and metamorphic rocks	Cambrian and Precambrian

formations in other areas that had undergone uplift diagenesis. For example, the dolostone and limestone in and adjacent to the Ozark uplift and the Cambridge arch–Central Kansas uplift and the Nemaha uplift in southeastern Nebraska and northeastern Kansas are fractured, have solution cavities, and are very permeable because they have undergone uplift diagenesis and surficial weathering for several extensive periods.

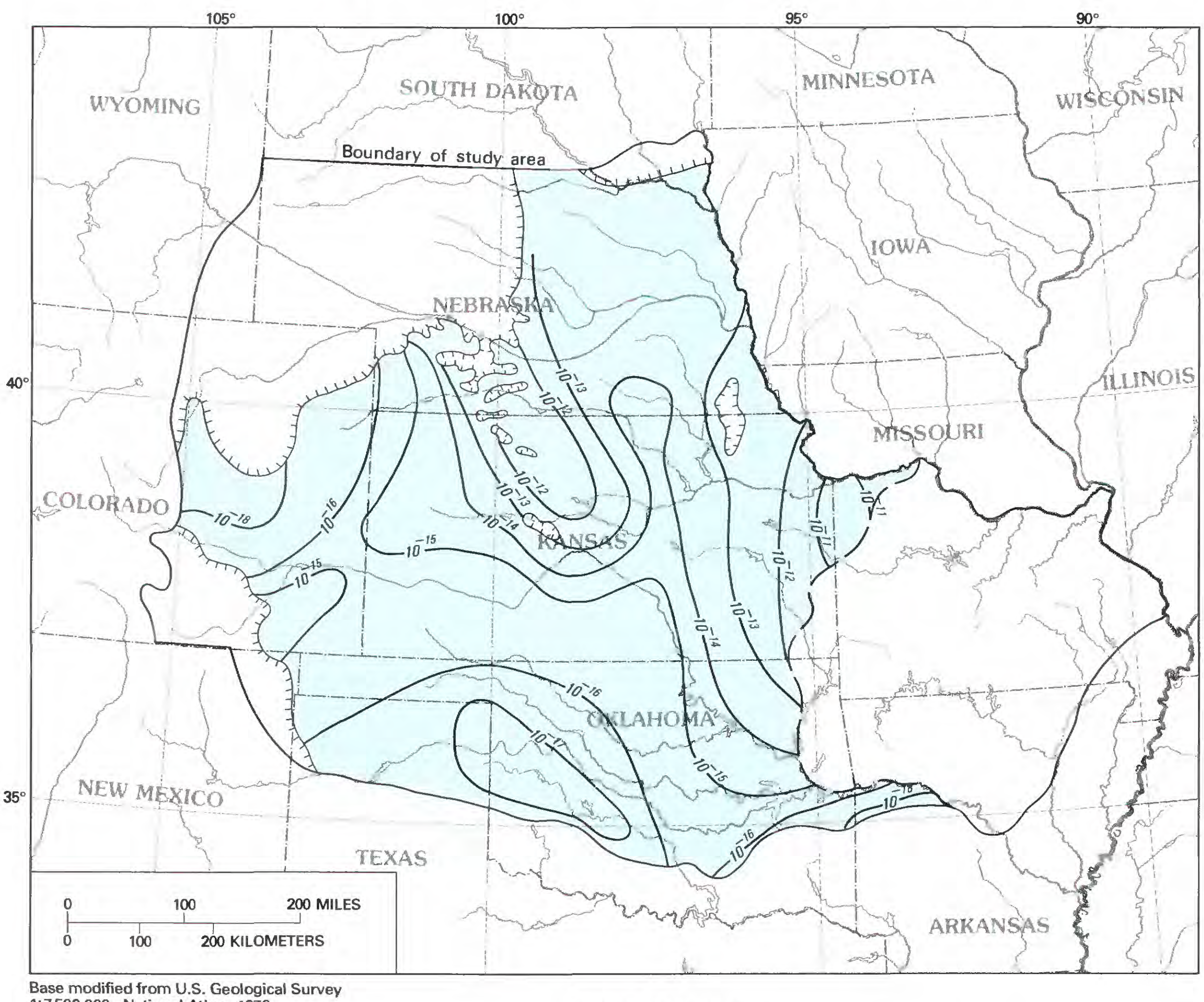
Regionalized intrinsic-permeability values for the lower aquifer units of the Western Interior Plains aquifer system are shown in figure 34, and values for the upper aquifer unit are shown in figure 35. The permeability estimates were made from borehole geophysical logs according to methods described previously.

The estimates of the intrinsic permeability for the lower units (fig. 34) vary from about 1×10^{-11} ft^2 in eastern Kansas and western Missouri to about 1×10^{-17} ft^2 in the Anadarko basin in Oklahoma and to about 1×10^{-18} ft^2 in the Denver basin. The intrinsic-permeability values shown in figures 34 and 35 are the thickness-weighted mean horizontal-permeability values of the entire section. These values should be considered preliminary because they are to be used as initial estimates for computer simulation of the geohydrologic system. (The computer simulation will be discussed in chapter C of USGS Professional Paper 1414.) Intrinsic-permeability values clearly are affected by depth, as is indicated by the permeability values in the Arkoma, Anadarko, and Denver basins. In general, values of intrinsic permeability less than 1×10^{-15} ft^2 are considered typical of confining units, not of aquifer material. The very slight permeability of the Western Interior Plains aquifer system is evidenced by the large equivalent-freshwater head in part of the Anadarko basin (fig. 30). Pressure from the overlying geopressure zone in the Morrowan sediments is attenuated downward into the aquifer system. However, because permeability in the aquifer system is so slight, the pressure is not dissipated rapidly by lateral flow. Ground water moves very slowly in the Western Interior Plains aquifer system because in most of the area the intrinsic permeability is very small and the hydraulic gradient is very slight. Small recharge through the overlying Western Interior Plains confining system probably also is a factor.

The dissolved-solids concentrations of water in the lower units of the Western Interior Plains aquifer system range from less than 1,000 mg/L to more than 200,000 mg/L (fig. 32), a dense brine. The large concentrations are in part due to slow flow rate and long residence time. The brines originated in the geologic past. The eastern edge of the dense brine in Oklahoma (fig. 32) approximately aligns with the zone of halite dissolution in the overlying confining system; however, because of very slight permeability and the large thickness of the confining system, the brine in the Western Interior Plains aquifer system is not believed to be dominantly of halite origin (S.C. Christenson, U.S. Geological Survey, oral commun., 1986).

WESTERN INTERIOR PLAINS CONFINING SYSTEM

The Western Interior Plains confining system restricts flow to and from the Western Interior Plains aquifer system. The extent and altitude of the top of



EXPLANATION

10^{-15} LINE OF EQUAL ESTIMATED REGIONAL PERMEABILITY—Value is the thickness-weighted mean horizontal intrinsic permeability. Interval, in feet squared, varies

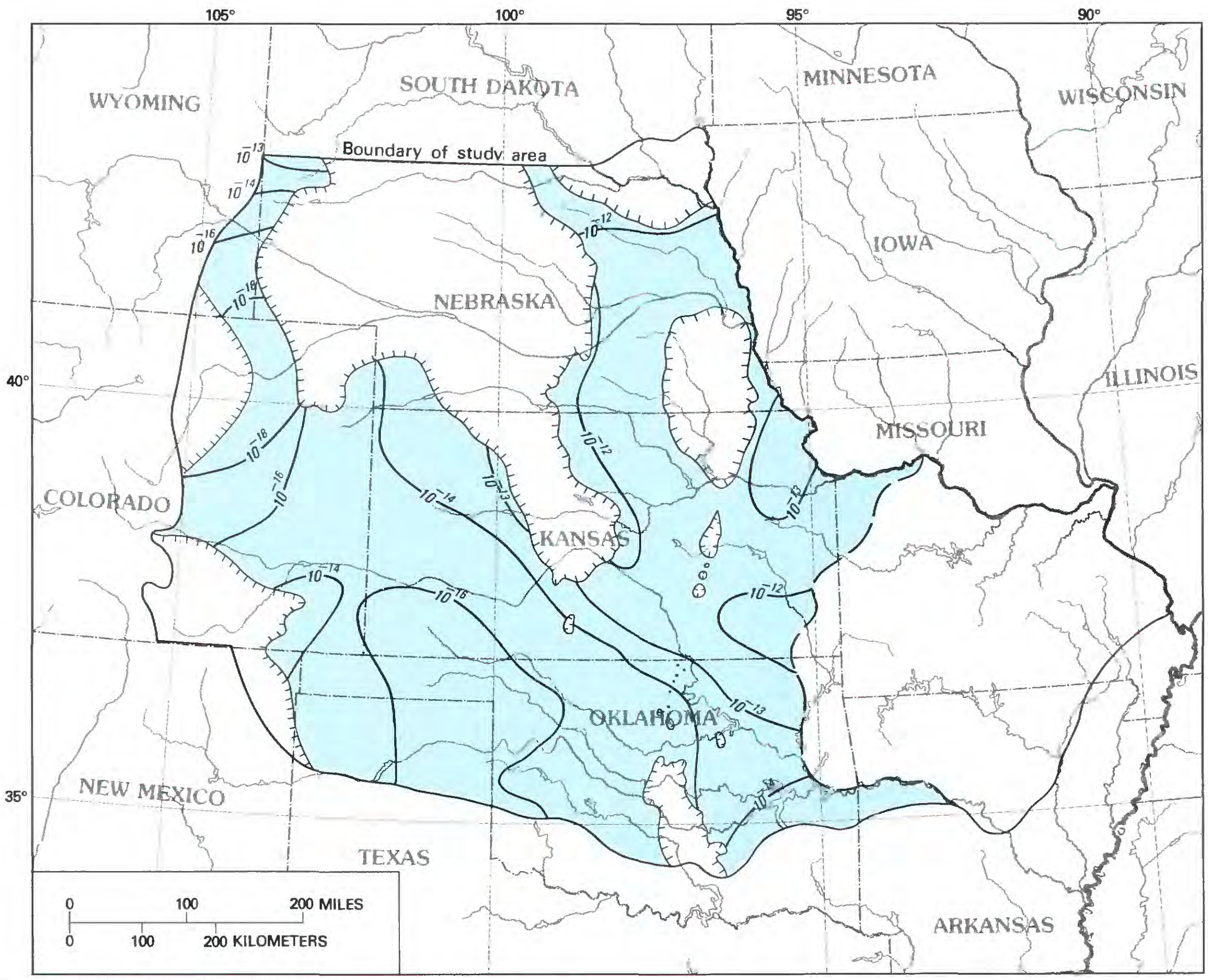
EXTENT OF LOWER UNITS OF WESTERN INTERIOR PLAINS AQUIFER SYSTEM

APPROXIMATE BOUNDARY BETWEEN PLAINS AND OZARK SUBREGIONS

FIGURE 34.—Estimated regional intrinsic permeability of lower units of the Western Interior Plains aquifer system.

the confining system are shown on plate 8. The altitude ranges from more than 3,000 ft below sea level in the Denver basin to more than 6,000 ft above sea level in northeastern New Mexico. In general, the top of the confining system slopes upward to the east toward a broad physiographic low near the outcrop area adjacent to the western perimeter of the Ozark subregion (pl. 2). The thickness of the confining system (pl. 9) ranges from zero in northeastern Nebraska and in the Ozark subregion to more than 20,000 ft in the Anadarko basin. The confining system is composed of rocks of Late Mississippian through Jurassic age (table 2).

The Pennsylvanian formations are a major part of the confining system (pl. 2) and consist mostly of shale and minor limestone and sandstone. 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 1. Adjacent to the Amarillo–Wichita and Apishapa–Sierra Grande uplifts (fig. 24), thick sections of permeable arkosic gravel of Pennsylvanian



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

EXPLANATION

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

EXTENT OF UPPER UNIT OF WESTERN INTERIOR PLAINS AQUIFER SYSTEM

APPROXIMATE BOUNDARY BETWEEN PLAINS AND OZARK SUBREGIONS

FIGURE 35.—Estimated regional intrinsic permeability of upper unit of the Western Interior Plains aquifer system.

and Permian age are present and are termed "granite wash," as they are believed to have been eroded from granitic uplift material. However, these permeable deposits extend only a few tens of miles from the uplift and are not important regionally.

The Permian formations in the Western Interior Plains confining system consist mostly of shale and minor evaporites, sandstone, and limestone. Triassic and Jurassic formations are mostly shale, sandstone, and limestone.

In general, the sandstone and limestone beds contained in the Western Interior Plains confining system are permeable; however, they do not extend areally across the extent of the confining system. Therefore, they are not a distinct hydraulic system regionally. The estimated thickness-weighted mean horizontal intrinsic permeability of the confining system ranges from about 1×10^{-16} to about 5×10^{-13} ft^2 (fig. 36). The aquifer units in the Western Interior Plains confining system are, in general, more permeable than the aquifer units in the underlying and deeper Western Interior Plains aquifer system, because permeability and porosity generally decrease with depth. However, the vertical leakance of the confining system at most locations is considerably less than the vertical leakance of the Western Interior Plains aquifer system, because the confining system is very thick and includes thick confining units of shale as well as extensive layers of nearly impermeable evaporites.

The pressure of the pore water in the permeable units in the confining system varies both vertically and horizontally, which is consistent because these permeable units are not in a reasonably distinct hydraulic system. Pore pressure as measured in drill-stem tests near the centerline of the permeable units is less than hydrostatic pressure throughout large areas. Large pressures exist in a geopressure zone near the base of the confining system in the Anadarko basin in Oklahoma. At this location, equivalent-freshwater head exceeds 6,000 ft in Morrowan sand and shale. This pressure affects the underlying dolostone.

GREAT PLAINS AQUIFER SYSTEM

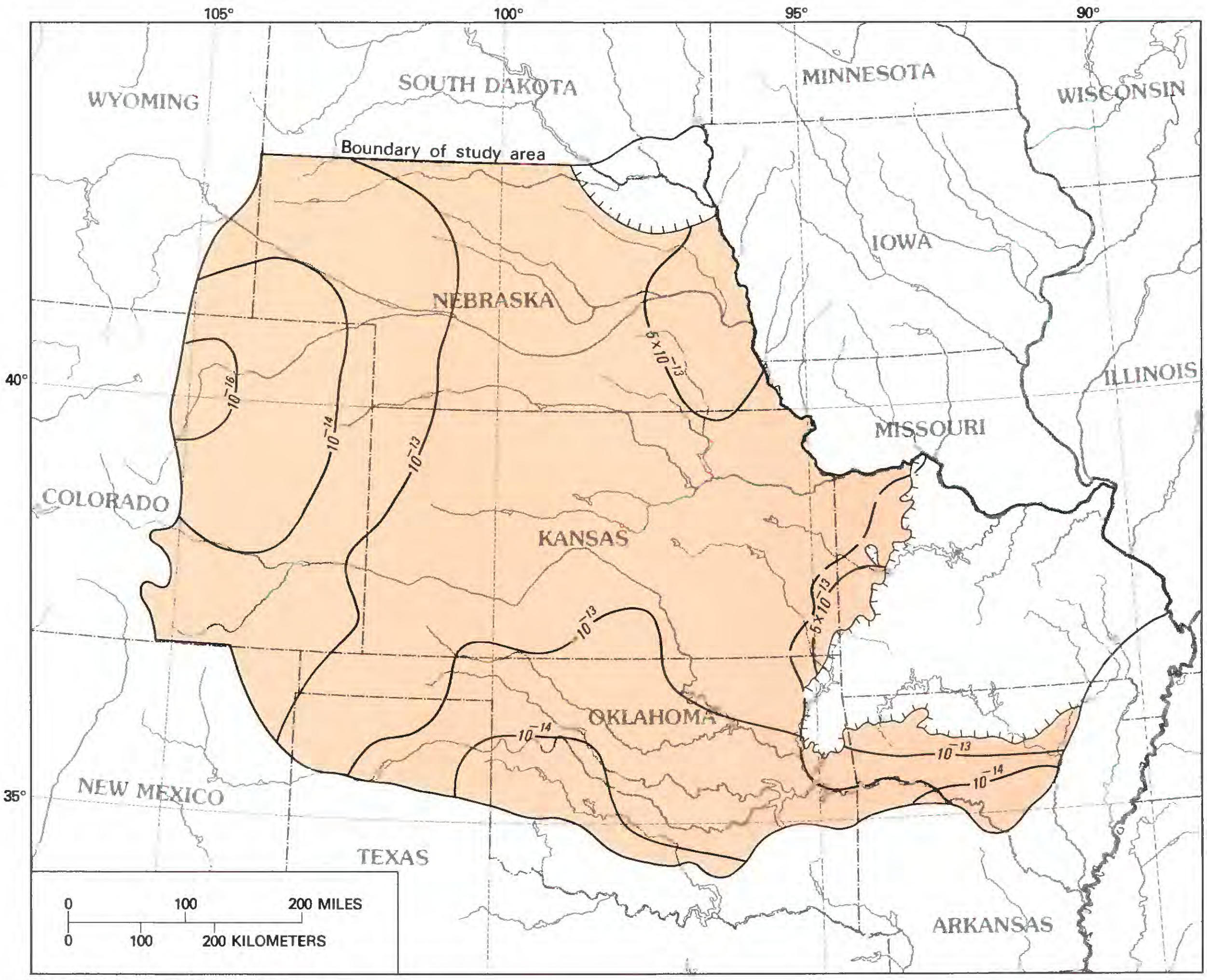
The Great Plains aquifer system consists of two regional aquifers separated by a confining unit. The aquifers are mostly composed of Lower Cretaceous water-bearing sandstone. The Great Plains aquifer system is one of the most extensive aquifers in North America (Helgesen and others, 1982), extending from near the Arctic Circle in Canada to New Mexico (fig. 37). In the United States, the two major regional aquifers in the Lower Cretaceous rock section of the Great Plains aquifer system are the Apishapa and the Maha (fig. 38). In general, water in each aquifer flows from west-southwest to east-northeast, as was recognized by Darton (1905). However, at that time, sufficient data were not available for clearly differentiating between these two aquifers at most locations. Therefore, these two aquifers were termed the "Dakota aquifer system" by some investigators. The aquifers have also been called the "Dakota aquifer." Others have termed the upper major regional aquifer the "Dakota aquifer" and still others termed the lower major regional aquifer the "Dakota aquifer." The name Dakota also has been used in lithologic terms as the Dakota Sandstone, the Dakota Formation, and the Dakota Group. The controversy as to correlation and terminology were termed aptly the "Dakota controversy." Nearly all the controversies relate to correlation of lithologic units, not to hydrology. Many investigators prefer to name aquifers using the stratigraphic nomenclature.

In this report, the aquifers that consist mostly of Lower Cretaceous sandstone and that are part of the regional-flow system are termed the Great Plains aquifer system. The term Great Plains was chosen because, generally, the aquifer system is present at most locations in the Great Plains of North America and because the term has not been used to name a geologic formation or group of formations. The extent and altitude of the top of the Great Plains aquifer system, which includes the Apishapa (lower) and the Maha (upper) aquifers and the intervening Apishapa confining unit, are shown on plate 10. The altitude of the Great Plains aquifer system decreases 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.

Nearly all hydrologic information relating to hydraulic head, permeability, and water chemistry for the Great Plains aquifer system within the study area is for the Maha aquifer (figs. 39–41). The potentiometric surface for the Apishapa aquifer is suspected to be similar to the potentiometric surface for the Maha (fig. 39). However, in some areas there may be considerable head differences. For example, in central South Dakota just north of the study area, a substantial head difference between the two aquifers exists. The major recharge to the aquifer system is in southeastern Colorado and northeastern New Mexico (fig. 39). Most ground water flows from the major recharge area east-northeast toward the outcrop area in central Kansas and eastern Nebraska. Near the southern and eastern extent of the Great Plains aquifer system, the aquifers are close to the land surface, and locally, recharge occurs (fig. 38).

Intrinsic permeability for both aquifers is mostly primary, except possibly in the Denver basin, because the aquifer material is mostly a slightly cemented sandstone. Permeability and porosity decrease with depth. The estimated thickness-weighted mean horizontal intrinsic permeability is shown in figure 40. Permeability is greatest along the eastern extent of the aquifer system and least in the Denver basin.

The dissolved-solids concentrations of water in the Maha aquifer (Leonard and others, 1983) are shown in figure 41. Limited water-quality information within the study area indicates that in many locations, the water in the Apishapa aquifer has a greater dissolved-solids concentration than the water in the Maha aquifer.



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

EXPLANATION

10^{-16} LINE OF EQUAL ESTIMATED PERMEABILITY—Value is the thickness-weighted mean horizontal intrinsic permeability. Interval, in feet squared, varies

EXTENT OF WESTERN INTERIOR PLAINS CONFINING SYSTEM

APPROXIMATE BOUNDARY BETWEEN PLAINS AND OZARK SUBREGIONS

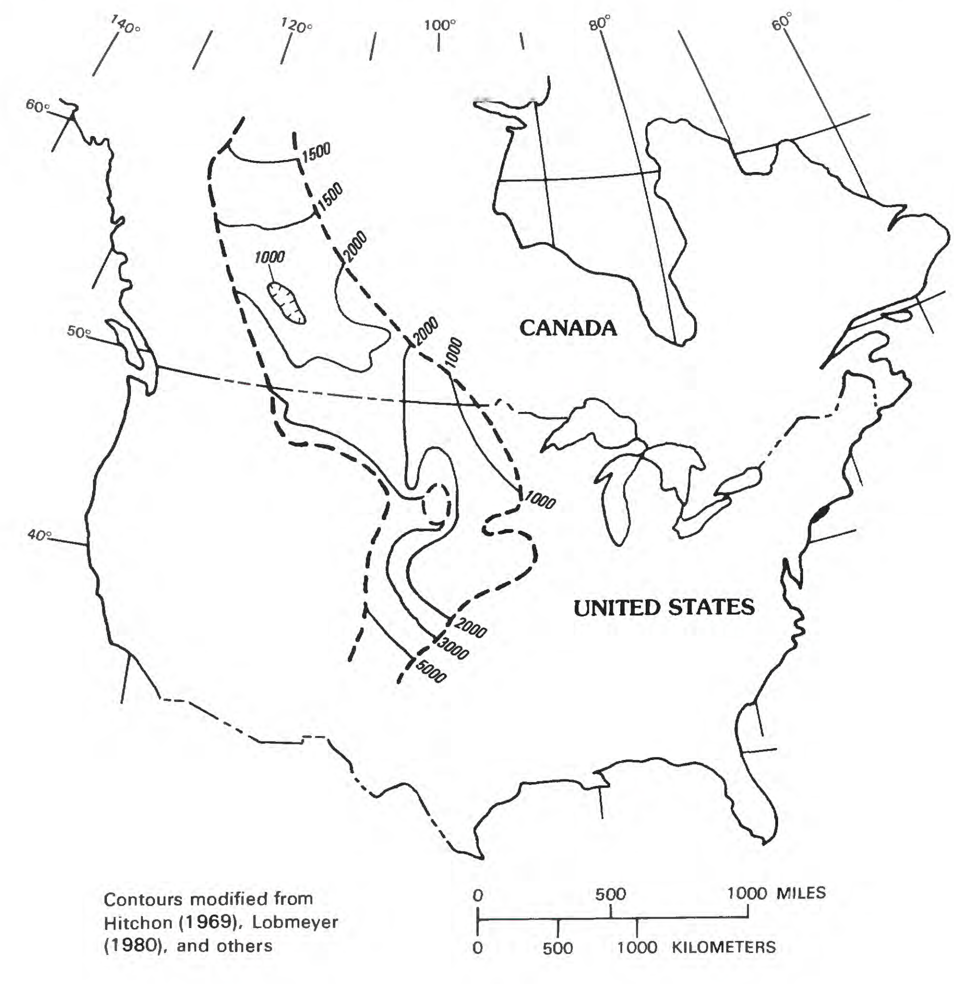
FIGURE 36.—Estimated regional intrinsic permeability of the Western Interior Plains confining system.

Apishapa Aquifer

The Apishapa is the lower of the two major regional aquifers in the Great Plains aquifer system and at most locations is composed of permeable, partially cemented, medium-grained to very fine grained sandstone of the Cheyenne Sandstone and equivalents, such as the Fall River and Lakota Sandstones north of the study area. The name Apishapa refers to the water-bearing sandstone layers that occur 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 name Apishapa was selected because the name is not used formally as a stratigraphic name for a Lower Cretaceous sandstone in the study area and, thus, is unique as an aquifer name.

Except for local outcrop areas in southeastern Colorado, the altitude of the top of the Apishapa aquifer is somewhat less than that of the Great Plains aquifer system shown on plate 10. The maximum thickness of the Apishapa aquifer exceeds 400 ft; however, the typical thickness is between 100 and 200 ft (pl. 11).

Adequate data to define the regional potentiometric surface for the Apishapa aquifer are not available. However, the potentiometric surface of the Apishapa within the study area is believed not to differ greatly from the potentiometric surface of the Maha aquifer as shown in figure 39.



EXPLANATION

—— 5000 —— **POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric surface of the Great Plains aquifer system. Hachures indicate depression. Contour interval is 500, 1000, and 2000 feet. Datum is sea level.**

— — — — — **LIMIT OF GREAT PLAINS AQUIFER SYSTEM**

FIGURE 37.—Great Plains aquifer system in North America (modified from Helgesen and others, 1982).

Apishapa Confining Unit

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 north of the study area. The altitude of the top of the unit is not shown because the unit is thin compared to the contour interval that would be required to show the available data. However, the altitude is, in general, about 200 ft less than the altitude of the top of the Great Plains aquifer system (pl. 10). The confining unit is thin, generally less than 100 ft (pl. 12), and is not as extensive as the Maha aquifer (fig. 38).

Maha Aquifer

The Maha aquifer, which is the upper regional aquifer unit of the Great Plains aquifer system (fig. 38), is more extensive than the underlying Apishapa aquifer. The Maha aquifer at most locations consists of water-bearing, partially cemented, medium- to fine-grained sandstone of the Dakota Sandstone and equivalents, such as the Newcastle Sandstone north of the study area and the "D" and "J" sandstones of informal oil field usage. The aquifer was named from exposures of the sandstone along the bluffs of the Missouri River valley between Blair and Ponca, Nebraska. This is the area the Maha (Omaha) Indians inhabited as reported by Lewis and Clark in 1803. The name Maha was chosen because the name had not been used to identify a geologic formation or group of formations. The altitude of the top of the Maha aquifer and the altitude of the Great Plains aquifer system (pl. 10) are the same except in a few small areas where the Maha is absent and the Apishapa aquifer is present. The aquifer thickens from less than 100 ft in eastern Colorado to about 600 ft in northeast Nebraska and exceeds 900 ft in a small area in central Nebraska (pl. 13).

OVERLYING UNITS IN THE PLAINS SUBREGION

The Western Interior Plains aquifer system does not crop out anywhere in the Plains subregion. Scattered outcrops may exist in the foothills of the Rocky Mountains. The Western Interior Plains confining system is at the land surface in much of the eastern part of the Plains area but is directly overlain by the High Plains aquifer farther west or by glacial drift and loess in eastern Nebraska and northeastern Kansas.

The Great Plains aquifer system is directly overlain by the Great Plains confining system in most places and by the High Plains aquifer, glacial drift, or loess along its eastern margin (fig. 42). The Great Plains confining system is as much as 8,000 ft thick (fig. 43). 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 Tertiary and Quaternary sediments (Weeks and Gutentag, 1981). Where present, its character permits hydraulic connection with adjacent units.

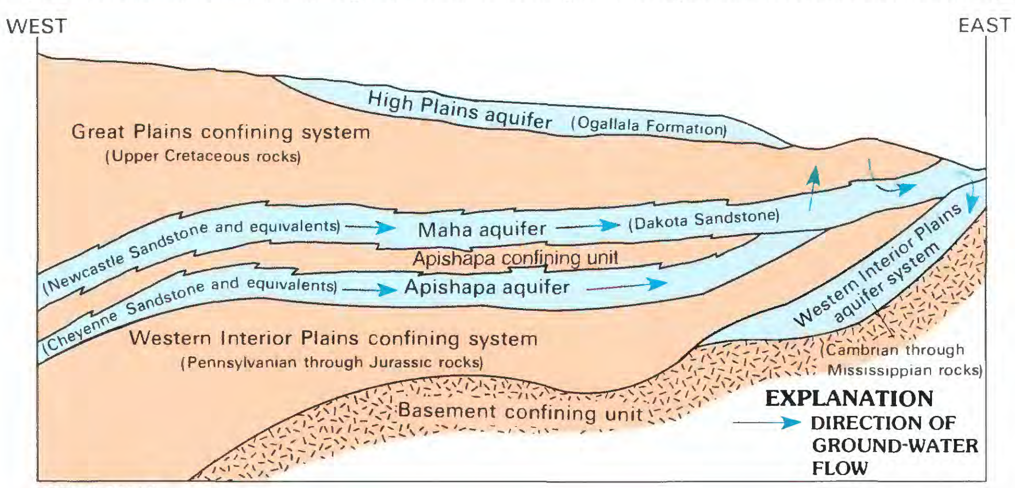


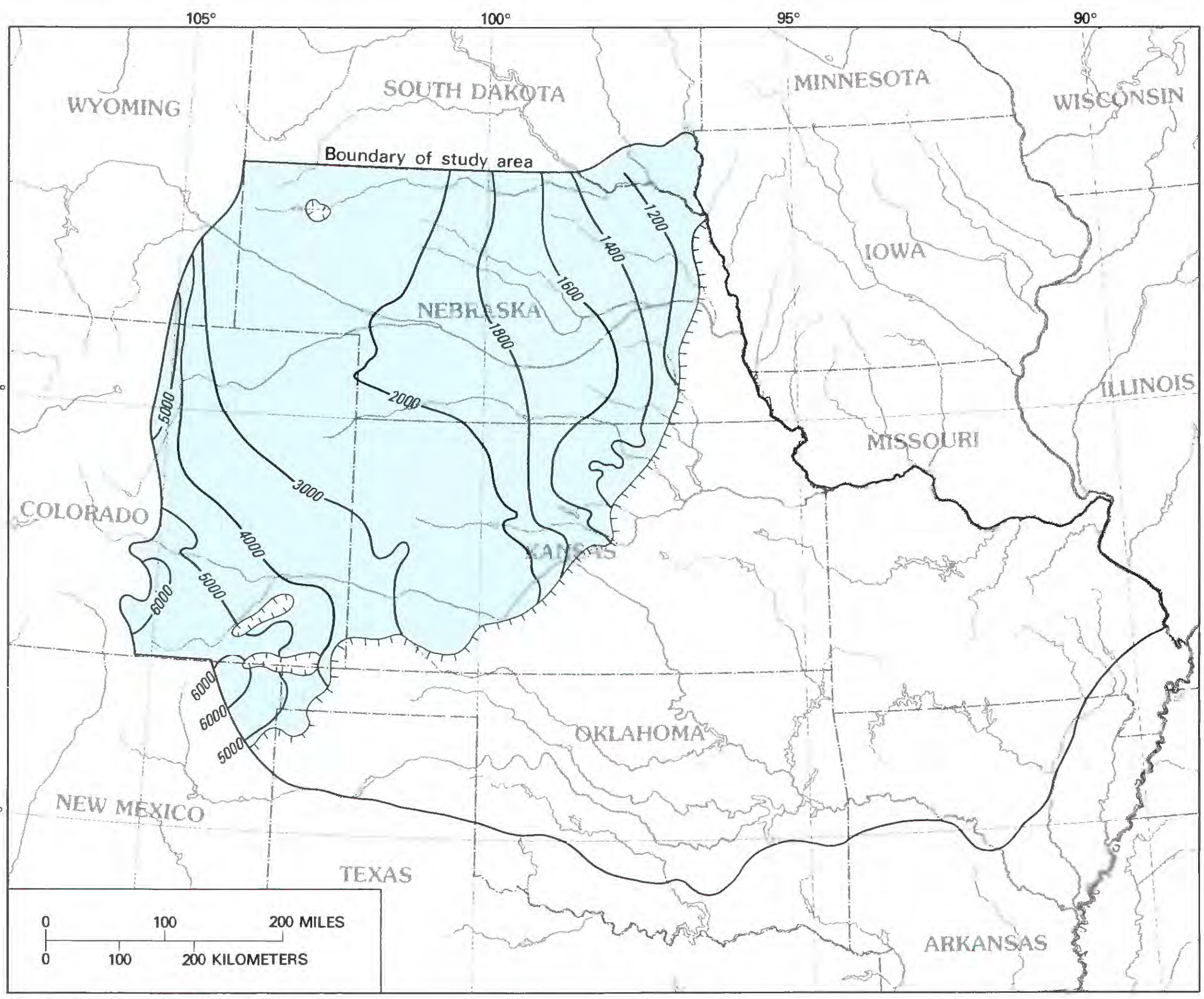
FIGURE 38.—Maha and Apishapa aquifers, Great Plains aquifer system. Section extends across Nebraska from the intersection of North Platte River and Wyoming-Nebraska Stateline on the west to Missouri River at northernmost extent of Nebraska-Iowa Stateline on the east.

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

OZARK SUBREGION

The Ozark subregion (figs. 44, 45) 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 gentle regional topographic low from northeastern Oklahoma to the Missouri River in central Missouri (fig. 45).

In general, ground water flows outward from a topographic high along an axis from the St. Francois Mountains in southeastern Missouri to the tri-State corner of Missouri, Arkansas, and Oklahoma. Flow is also outward from a topographic ridge of the Boston Mountains in northwestern Arkansas. The Ozark Plateaus aquifer system is underlain by the basement confining unit that is composed mostly of igneous and metamorphic crystalline rocks. The base-



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

EXPLANATION

—3000— POTENTIOMETRIC CONTOUR—Shows altitude at which water would have stood in tightly cased wells. Contour interval, in feet, varies. Datum is sea level

EXTENT OF GREAT PLAINS AQUIFER SYSTEM

FIGURE 39.—Predevelopment potentiometric surface of the Maha aquifer, Great Plains aquifer system.

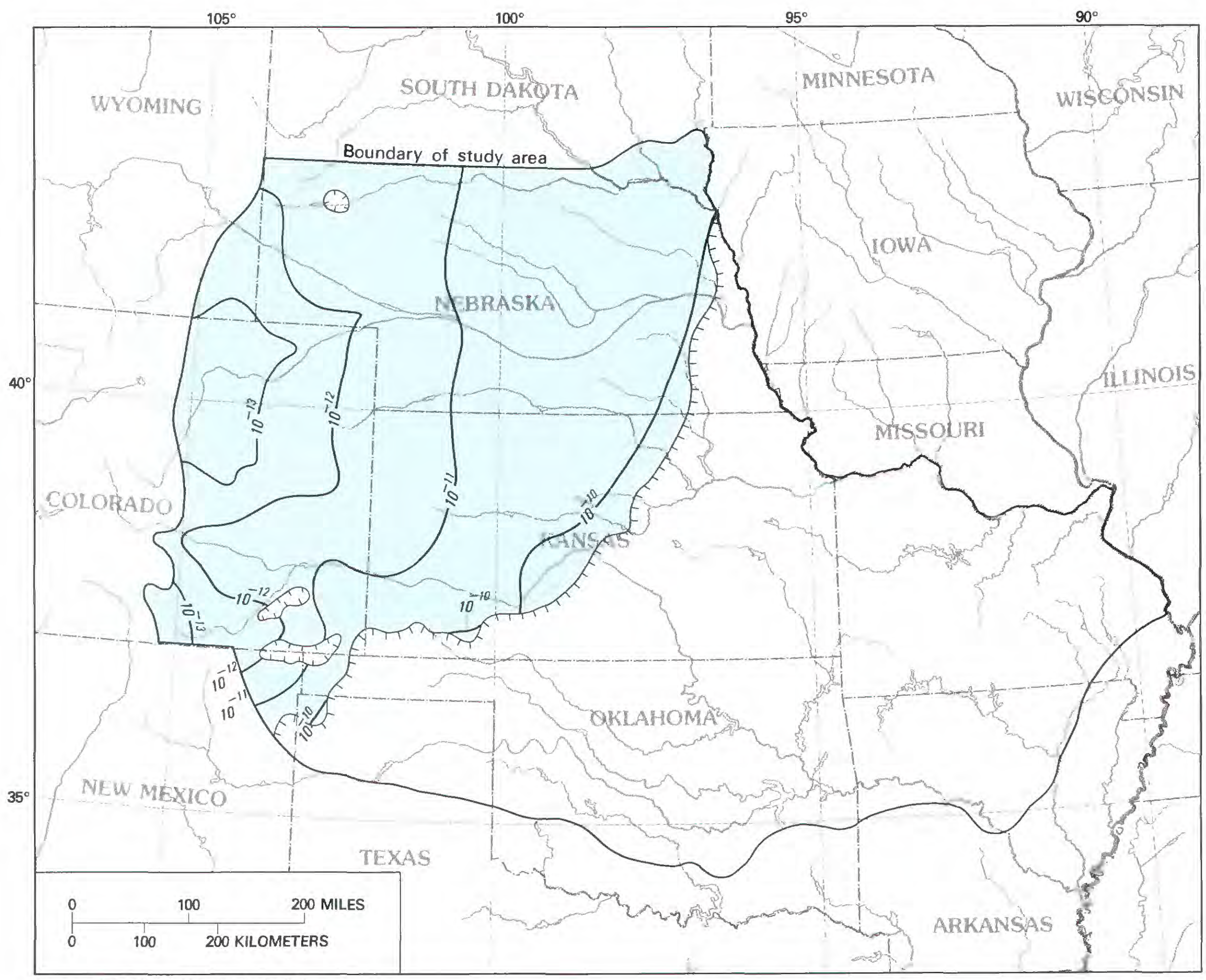
ment rocks are fractured and locally water yielding, such as in the St. Francois Mountains (fig. 44), but on a regional basis they are assumed to form the base of the regional flow system.

The altitude of the top of the basement ranges from more than 1,700 ft above sea level in the St. Francois Mountains to 15,000 ft below sea level in the Arkoma basin in Arkansas along the southern boundary of the Ozark subregion (pl. 3).

OZARK PLATEAUS AQUIFER SYSTEM

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

The geohydrologic units of the Ozark Plateaus aquifer system are composed of sedimentary rocks that range in age from Cambrian through Mississippian



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

EXPLANATION

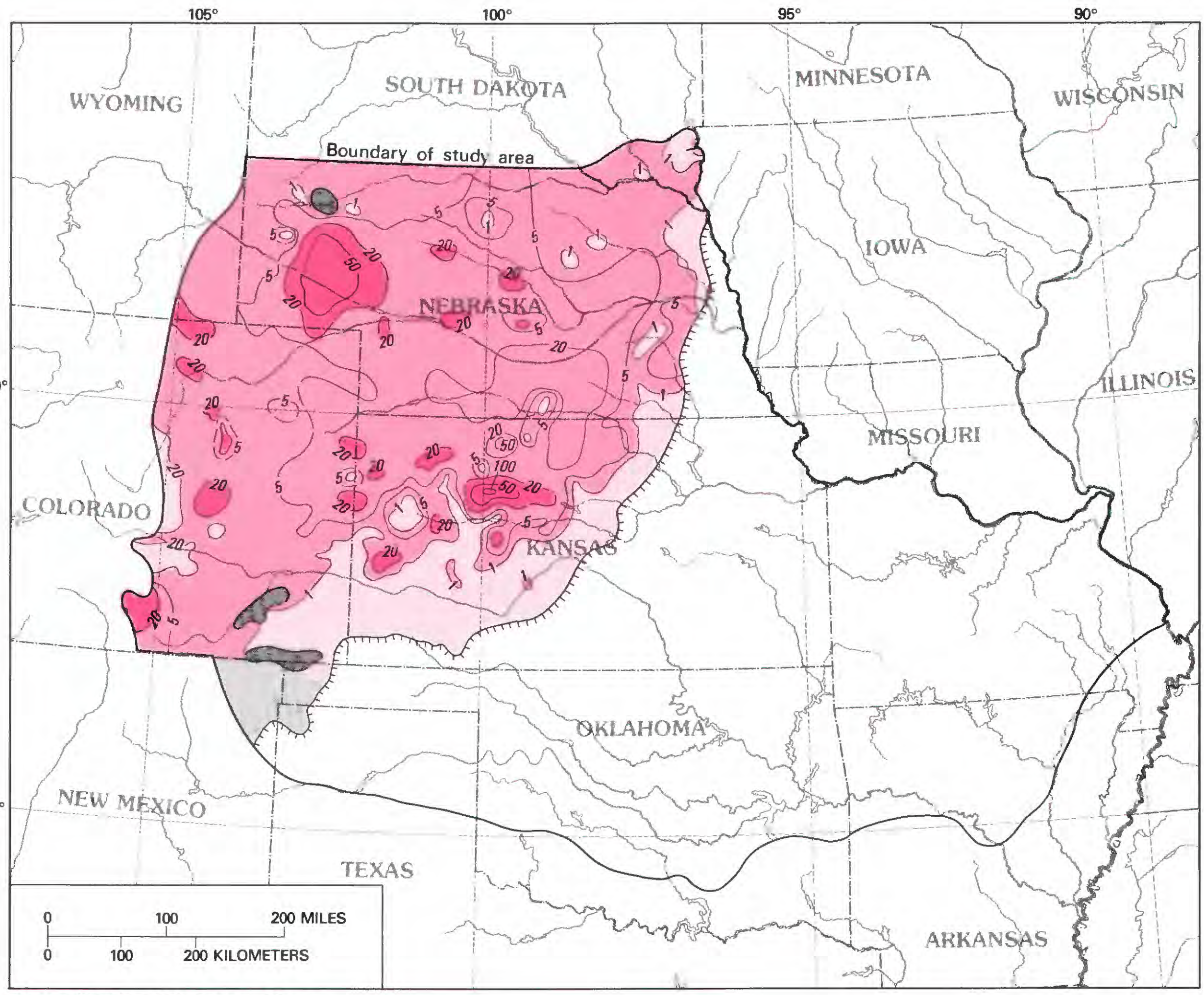
—10^{-13}— LINE OF EQUAL ESTIMATED PERMEABILITY—Value is the thickness-weighted mean horizontal intrinsic permeability. Interval, in feet squared, varies

⊥⊥⊥⊥⊥⊥⊥ EXTENT OF GREAT PLAINS AQUIFER SYSTEM

FIGURE 40.—Estimated regional intrinsic permeability of the Great Plains aquifer system.

(table 3). Boundaries between the geohydrologic units do not always conform to geologic-time divisions or to formation boundaries, but the delineated rock groups have similar hydrologic properties. All of the geohydrologic units that comprise the Ozark Plateaus aquifer system crop out in the Ozark Plateaus.

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



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

EXPLANATION

DISSOLVED-SOLIDS CONCENTRATION—Values in milligrams per liter

- 0 - 1,000
- 1,000 - 20,000
- More than 20,000
- No Data

—20— — LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION—Dashed where approximate. Interval, in thousands of milligrams per liter, varies

EXTENT OF MAHA AQUIFER

AREA WHERE GREAT PLAINS AQUIFER IS ABSENT

FIGURE 41.—Dissolved-solids concentrations in Maha aquifer water (modified from Leonard and others, 1983).

system to below the broad topographic low that extends from northeastern Oklahoma into central Missouri, and then leaks upward (fig. 31). The downdip flow extends to a depth of about 500 feet. 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 Missouri. In general, flow across the Fall Line is intercepted by streams, marshes, and drainage canals in the Mississippi Alluvial Plain.

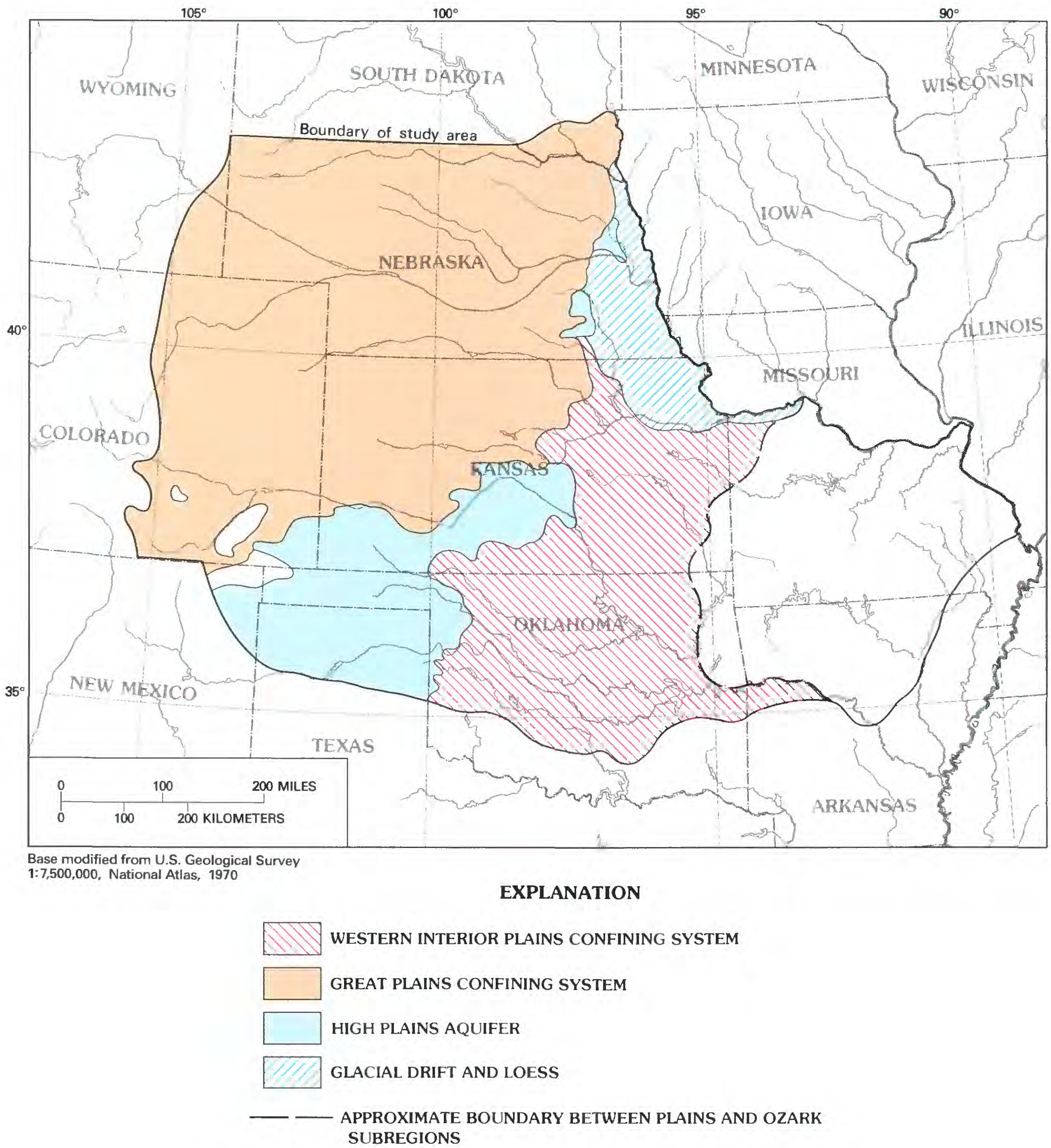


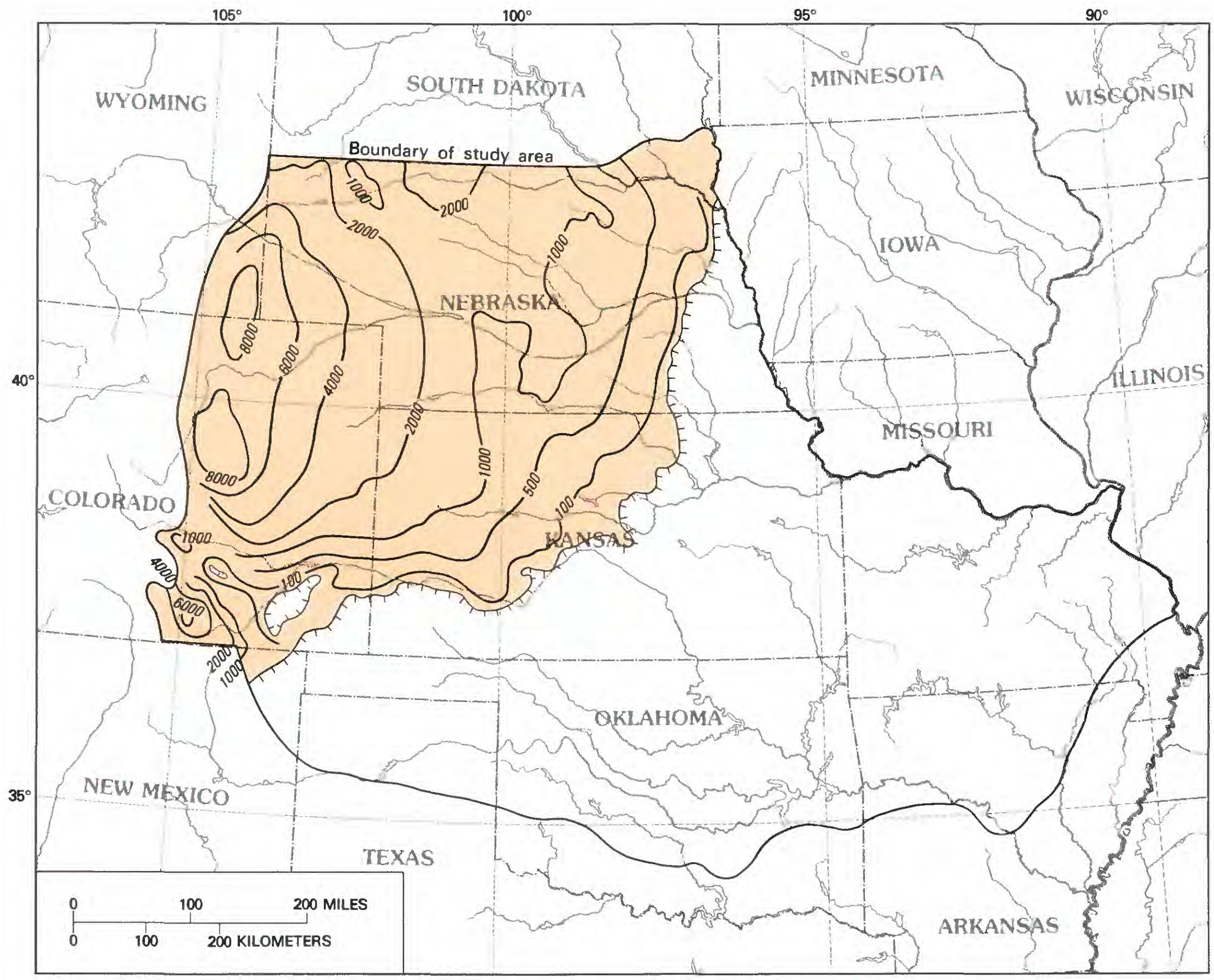
FIGURE 42.—Geohydrologic units overlying regional aquifer systems in the Plains subregion.

St. Francois Aquifer

The St. Francois aquifer, the lowermost geohydrologic unit of the Ozark Plateaus aquifer system, consists of water-bearing sandstone, dolostone, and other rock and rests on the basement confining unit. The aquifer crops out around the St. Francois Mountains for which it is named and is overlain by the St. Francois confining unit.

The St. Francois aquifer is used extensively as a source of water for domestic and public supply in the outcrop area. Well yields generally are 100 to 500 gal/min. The aquifer is not extensively used except near the outcrop area because in other areas the overlying Ozark aquifer yields more water at a shallower depth.

The St. Francois aquifer, at most locations, extends to the boundaries of the Ozark subregion. The altitude of the top and extent of the aquifer are shown on plate 14. The altitude of the aquifer ranges from more than 1,000 ft above sea level at the outcrop near the St. Francois Mountains to more than 7,000 ft below sea level in the Arkoma basin. Beyond the relatively small outcrop area (590 mi^2) in and near the St. Francois Mountains, the aquifer dips into the subsurface and is buried beneath the other units of the Ozark Plateaus aquifer system. The aquifer is missing in the subsurface at several isolated



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

EXPLANATION

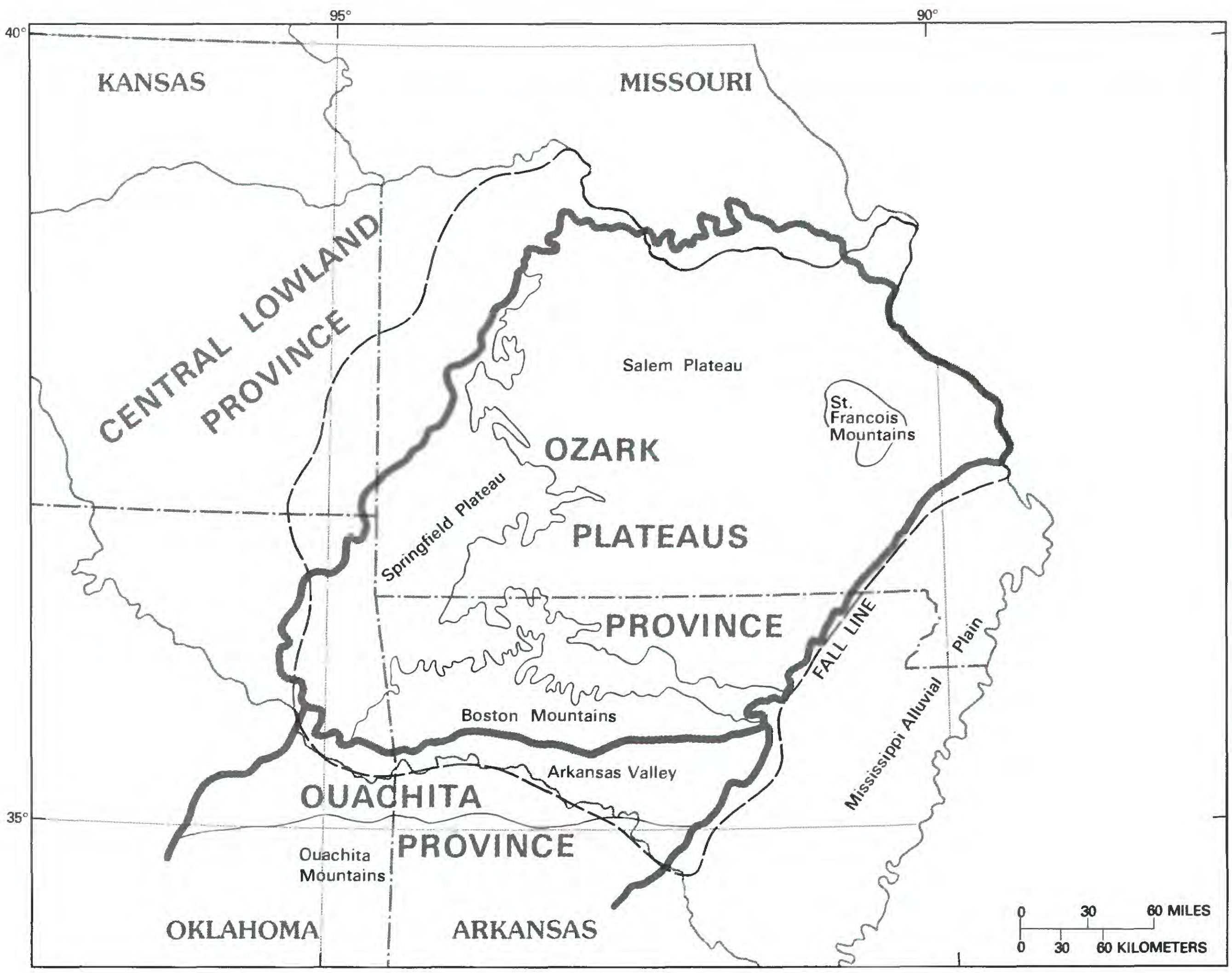
—2000— LINE OF EQUAL THICKNESS OF GREAT PLAINS CONFINING SYSTEM — Interval, in feet, varies

EXTENT OF GREAT PLAINS CONFINING SYSTEM

FIGURE 43.—Thickness of the Great Plains confining system.

areas surrounding the St. Francois Mountains. The aquifer dips as steeply as 150 ft/mi to the east toward the Illinois basin and south toward the Mississippi Alluvial Plain, where it is buried to a depth of more than 3,200 ft. To the west, the dip is more gentle and broken by a series of small basins.

The aquifer includes the Lamotte Sandstone and Bonneterre Dolomite and their equivalents of Upper Cambrian age (pl. 1, table 3). The Lamotte generally is a sandstone with some silt, and locally grades to arkose and conglomerate. It is the most permeable of the geologic formations within the aquifer. The overlying Bonneterre Dolomite is predominantly a coarse-grained dolostone, which contains numerous small cavities, resting on a sandy dolostone. Kurtz and others (1975) report that the Lamotte Sandstone and Bonneterre Dolomite are not present in extreme southwestern Missouri. In the western one-third of the Ozark subregion, the aquifer is composed of the Reagan Sandstone (a nearshore facies of the Lamotte Sandstone), and the Bonneterre Dolomite. The St. Francois aquifer is thickest (more than 1,000 ft) in the eastern part of the subregion near the Mississippi Alluvial Plain but generally is between 200 and 500 ft thick (pl. 15).



EXPLANATION

LIMIT OF OZARK SUBREGION

BOUNDARY OF PHYSIOGRAPHIC PROVINCES

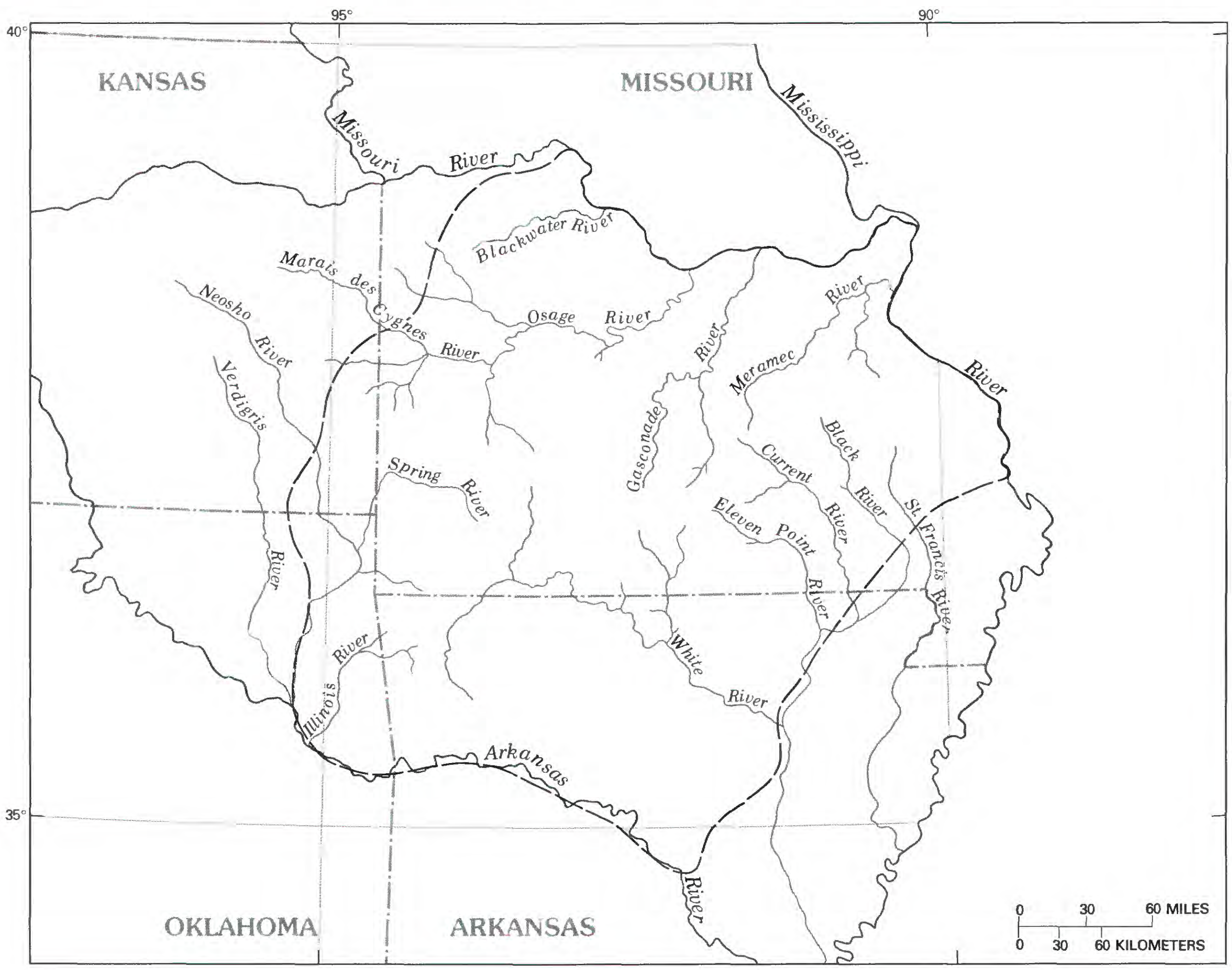
BOUNDARY OF PHYSIOGRAPHIC SUBDIVISIONS

FIGURE 44.—Physiographic features of the Ozark subregion.

Generally, both the Lamotte and Bonneterre are permeable and yield water to wells; however, water yields from the Lamotte Sandstone generally are greater than those from the Bonneterre. Estimates of hydraulic conductivity, based on specific-capacity data, range from 1×10^{-4} to 1×10^{-6} ft/s in and near the outcrop area and tend to decrease away from the outcrop area. Little is known about the hydraulic properties of the Reagan Sandstone because few water wells are drilled deep enough to penetrate the formation; however, it is believed to be hydrologically similar to the Lamotte.

The hydraulic head of the St. Francois aquifer is mostly topographically controlled. The aquifer is recharged from infiltration of precipitation through the soil zone at the outcrops. The aquifer also is recharged by flow from the fractured Precambrian rocks of the basement 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 downdip from the outcrop area. However, exact areas of this discharge are not known because the hydraulic head in the aquifer is known only at the outcrop area.

Few data are available on the chemistry of water in the aquifer; however, the data available indicate that the water is not dissimilar to that of the overlying Ozark aquifer, probably because the confining unit separating the aquifers is thin and leaky.



EXPLANATION

— — LIMIT OF THE OZARK SUBREGION

FIGURE 45.—Drainage features of the Ozark subregion.

TABLE 3.—*Generalized correlation of stratigraphic units to geohydrologic units in most of the Ozark subregion*

Geohydrologic unit		Principal stratigraphic unit(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	Moorfield 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	*Choteau Group and Chattanooga Shale	Lower Mississippian and Upper Devonian
	Ozark aquifer	Clifty Limestone, Penters Chert, Lafferty Limestone, St. Clair Limestone, Brassfield Limestone, Cason Shale, Fernvale Limestone, Kimswick 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 Dolomites, Davis Formation	Upper Cambrian
	St. Francois aquifer	Bonneterre Dolomite and Lamotte Sandstone	Upper Cambrian
Basement confining unit		Mostly igneous and metamorphic rock	Precambrian

*Designated Choteau Limestone by the U.S. Geological Survey.

Chemical analyses of water samples collected from the St. Francois aquifer in the outcrop area indicate dissolved-solids concentrations of 220 to 450 mg/L.

ST. FRANCOIS CONFINING UNIT

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 formations in the Upper Cambrian Elvins Group—the Davis Formation, the Derby Dolomite, and the Doe Run Dolomite (table 3).

The extent and altitude of the top of the confining unit are shown on plate 16. Well-log data are insufficient to define the top of the unit in much of its extent; however, where there are insufficient data, contours are drawn so that the altitude of the top of the St. Francois confining unit is consistently lower than the top of the overlying Ozark aquifer for which there are more data. The unit crops out in about a 400 mi^2 area around the St. Francois Mountains and dips steeply away from the St. Francois Mountains at a rate of as much as 150 ft/mi, except to the west where the dip is more gentle. Most of the small isolated areas within the Ozark subregion where the St. Francois confining unit is not present in the subsurface are coincident with or near areas where the underlying St. Francois aquifer also is not present.

The thickness of the St. Francois confining unit, as determined from well-log data, ranges from nearly zero to 730 ft. The maximum thickness of the unit is in northwestern Arkansas (pl. 17). The confining unit generally is thicker to the northeast of the St. Francois Mountains and to the southeast where it dips below the Mississippi Alluvial Plain. The unit is thinner in western Missouri (ranging from 0 to 300 ft), and the stratigraphic rock units pinch out a few miles west of the Ozark subregion in eastern Kansas and northeastern Oklahoma. The confining unit thins abruptly at the St. Francois Mountains where the confining rocks have been removed by erosion.

The shale content of a confining unit commonly is used as an indicator of the effectiveness of the confining unit. Although this generally is a good indicator because shale is generally less permeable than most rock types, other factors, such as presence of fractures, can negate the water-impeding ability of the shale. Shale in the St. Francois confining unit exists as distinct beds and usually is distributed throughout the limestone and dolostone mass as thin layers or beds. Thus, the confining ability of the unit also is dependent on the degree of cementation of the carbonate rock and the abundance of both fractures and solution openings.

The amount of shale within the St. Francois confining unit ranges from 0 to more than 40 percent and generally is less than 30 percent (pl. 18). The Davis Formation contains the largest percentage of shale of the three geologic formations. The data used to determine the percentage of shale were derived primarily from the hundreds of insoluble-residue analyses on file at the Missouri Division of Geology and Land Survey. Because the clay is reported to be from thin clay beds, insoluble-residue results should represent the percentage of shale. However, most data used to determine the percentage of shale in southeastern Kansas and northeastern Oklahoma were obtained from borehole geophysical logs.

The Davis Formation is not part of the St. Francois confining unit at isolated locations in west-central and south-central Missouri. The Davis Formation thins to the southwest and becomes more clastic in a facies change to the Reagan Sandstone (Thacker, 1974). The Derby and Doe Run Dolomites are more uniform in thickness and are part of the confining unit at nearly all locations.

Generally, substantial secondary porosity and permeability have not developed in the limestone and dolostone of the Davis Formation or in the Derby and Doe Run Dolomites. The fine-grained nature of the dolostones is the probable reason for the slight permeability of the confining unit even in regions devoid of shale. However, the confining unit is more likely to be leaky in these areas as compared to areas with a large percentage of shale. There is evidence from well cores that the upper part of the Derby and Doe Run Dolomites is permeable along a northwest-trending reef zone passing through south-central Missouri. Because the Davis Formation is absent in part of the reef zone, it is possible that the underlying St. Francois aquifer and the overlying Ozark aquifer locally are hydraulically connected. Fracture zones are evident in the Derby and Doe Run strata and may increase leakance locally, especially in the vicinity of faults. However, in Arkansas, the faults mostly have been sealed.

Ozark Aquifer

The Ozark aquifer is mostly composed of water-bearing dolostone and is the most permeable and the most extensively used aquifer in the Ozark subregion. The aquifer with the exception of the St. Francois Mountains area, is at land surface or nearly at land surface throughout most of the area that generally is termed the "Ozark area" or the "Ozarks." The aquifer is accordingly called the Ozark aquifer because of the association with the Ozarks. The rocks of the aquifer are fractured dolostone with some limestone, sandstone, chert, and shale. The dolostone contains solution cavities. 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 with numerous streams and springs.

Stratigraphically, the aquifer is present in Upper Cambrian through Middle Devonian rocks (table 3). The basal formation of the Ozark aquifer is the Potosi Formation. In eastern Missouri, the upper boundary of the aquifer is coincident with the base of the Maquoketa Shale, which usually is underlain by the Kimmswick Limestone. West and south of the extensive outcrop area of the aquifer, the base of the Chattanooga Shale is the upper boundary of the aquifer.

The altitude of the top of the Ozark aquifer is shown on plate 19. Where the aquifer dips into the subsurface, it is generally overlain by Upper Devonian rocks of the Ozark confining unit; however, in the north-central part of the Salem Plateau (fig. 44) the aquifer is in direct contact with as much as 200 ft of Pennsylvanian shale, which is a confining material.

Near the Fall Line along the Mississippi Alluvial Plain, the aquifer dips to the southeast at about 45 ft/mi. In eastern Kansas and western Missouri, the aquifer dips to the west at about 14 ft/mi. A ridge of the Ozark aquifer extends southwestward and can be recognized by the surface expression of a chain of island-like outcrops extending from southwest Missouri into northeast Oklahoma. This ridge approximates the axis of the Ozark uplift. In northern Arkansas, the regional dip is about 26 ft/mi southward and increases to about 175 ft/mi or more near the southern boundary of the subregion.

The Ozark aquifer is the thickest (typically about 1,000 ft) geohydrologic unit in the Ozark subregion (pl. 20). In southeast Kansas, the aquifer thickness ranges from about 700 to 1,200 ft. The thickness is less uniform within short distances in northeastern Oklahoma where Precambrian topographic relief affected the thickness of sediments that today are rocks of the Ozark aquifer. The aquifer is only 270 ft thick near the Oklahoma-Kansas border where the basement confining unit directly subcrops beneath the aquifer.

The hydraulic conductivity of the Ozark aquifer has been estimated from specific-capacity data and has been inferred from the density of fractures and the degree of development of solution openings. In general, the more that rocks have been uplifted, the more they have been fractured, the more dissolution along the fractures has occurred, and correspondingly, the greater the hydraulic conductivity. The areas of greatest hydraulic conductivity are concentrated along a line trending westward from the St. Francois Mountains where the hydraulic conductivity may be as much as 1×10^{-3} ft/s. In areas where dissolution has occurred and springs are numerous, the hydraulic conductivity is extremely large and locally exceeds 1×10^{-1} ft/s. Hydraulic conductivity of near-surface aquifer material is more developed in the valleys as compared to the interfluves. Hydraulic conductivity decreases to the south to as little as 1×10^{-8} ft/s near the southern boundary of the subregion.

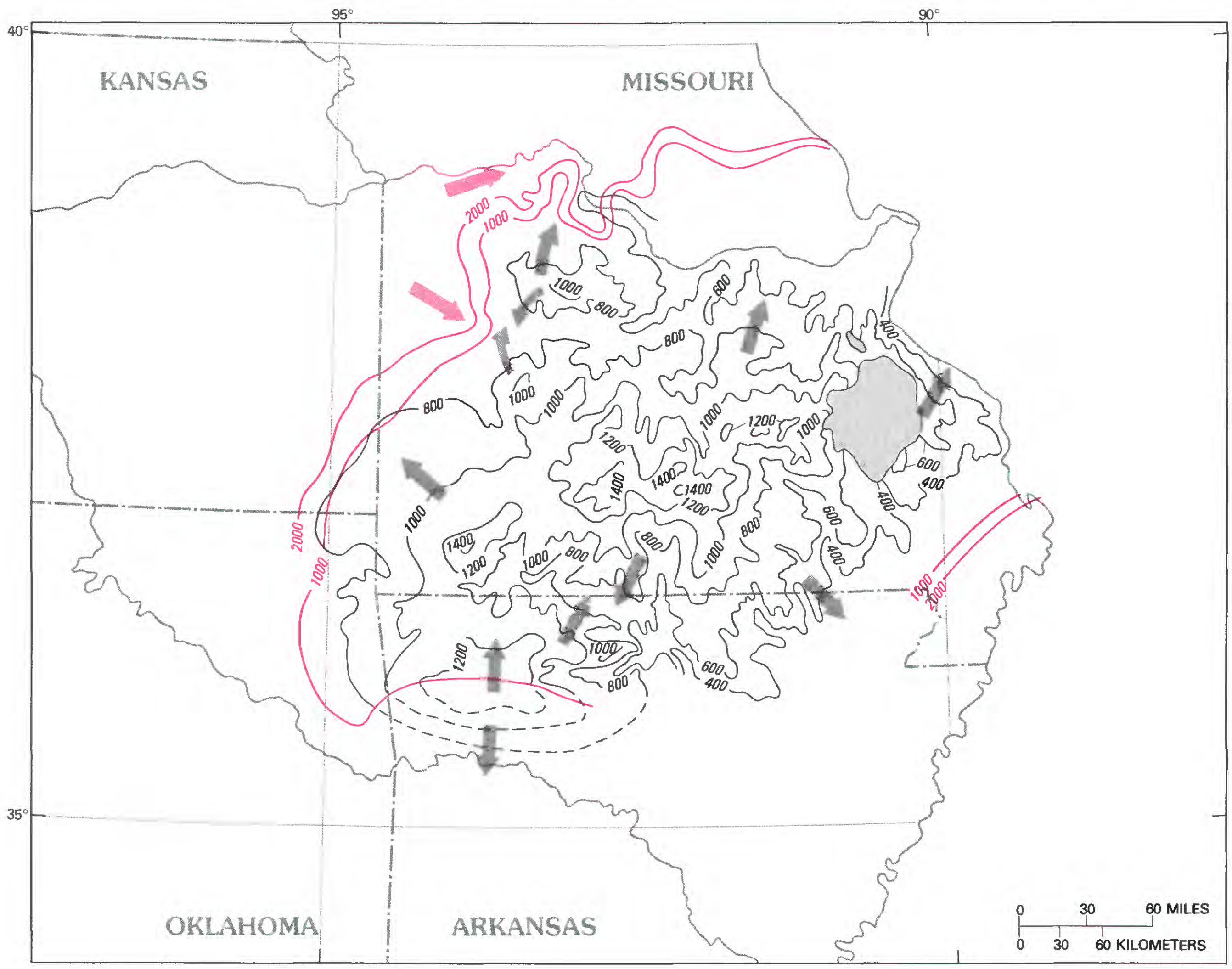
The Potosi Formation is the most permeable Cambrian formation within the aquifer. This massive dolostone contains numerous druse cavities lined with finely crystalline quartz. It has a relatively uniform thickness (about 100 to 300 ft) throughout much of the area, and an extensive network of solution channels has developed along fractures. The overlying Eminence Dolomite is also a Cambrian formation with lithology similar to the Potosi, but secondary porosity has not been developed to the same degree.

The lower part of the Gasconade Dolomite and the Roubidoux Formation, which are Ordovician rocks, are important water-yielding zones, especially in the southern and southwestern parts of the Ozark subregion (Harvey, 1980; Lamonds, 1972). The Gasconade is primarily dolostone but contains a major water-bearing sandstone member (Gunter Sandstone Member) that extends throughout northwestern Arkansas and southern Missouri. The Roubidoux Formation is a sandy, cherty dolostone with sandstone beds that generally are water bearing. The stratigraphic sequence from the Jefferson City Dolomite through the Smithville Formation mostly consists of dolostone with minor shale, chert, and sandstone. These formations generally are not as permeable as the lower rocks, the Gasconade Dolomite and the Roubidoux Formation. Of the Ordovician rocks younger than the Smithville Formation, the St. Peter Sandstone is the most important water-bearing formation. It is a clean, quartzose sandstone with little indication of bedding in the eastern part of the Ozark subregion, but it is slightly shaly in the western part. The remainder of the Ordovician formations are dolostone and limestone with minor shale and sandstone, with the exception of the Cason Shale in Arkansas and the equivalent Sylvan Shale in Oklahoma. These latter formations are distinct shale units with minor dolomitic sandstone. The shale layers are competent and fractured, and do not yield water to wells but allow regional leakage of water. None of the younger Ordovician rocks are important regional sources of water, but the Kimmswick Limestone, the Plattin Limestone, and the Joachim Dolomite yield small quantities of water to domestic wells.

Limestone and chert of Silurian and Devonian age are the uppermost rocks in the Ozark aquifer in the north-central and southern part of the subregion. The rocks are less permeable than the lower rocks in the aquifer and generally are not used as a water source. The rocks are fractured but have lesser hydraulic conductivity because solution-channel permeability has not been well developed. The Mississippi Alluvial Plain adjacent to the Fall Line is a major discharge area. In general, most water flowing across the Fall Line is intercepted by streams, drainage canals, and marshes adjacent to the Fall Line.

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 (figs. 45, 46), and hundreds of springs have developed. Typically, flow in these springs is local because most recharge to springs is in the upland intervalley areas and is discharged in nearby stream valleys. The Mississippi River valley is a major regional discharge area for regional flow from the Ozark aquifer. The Missouri River valley east of Saline County, Missouri (not shown), also is a major discharge area.

In southwest Missouri, southeast Kansas, and northeast Oklahoma, flow in the Ozark aquifer is outward to the periphery or boundary of the subregion. This western boundary is marked by the broad, gentle physiographic low that extends around the western edge of the Ozark Plateaus. The Western Interior Plains confining system is the surficial material in the physiographic low and overlaps the Ozark Plateaus aquifer system, of which the Ozark aquifer is a part. Water flows upward through the confining system. The leakance of the confining system controls the quantity of upward leakage out of the Ozark Plateaus aquifer system to the physiographic low. In northern Arkansas, most flow is through the permeable zones of the Roubidoux Formation and the Gunter Sandstone Member of the Gasconade Dolomite. Along the Oklahoma-Arkansas State line, flow is toward the broad physiographic low in northeast-



EXPLANATION

AQUIFER ABSENT

—600— — POTENTIOMETRIC CONTOUR— Shows altitude at which water level would have stood in tightly cased well. Dashed where approximate. Contour interval 200 feet. Datum is sea level

—2000— LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION— Interval 1000 milligrams per liter

MAJOR DIRECTION OF REGIONAL FLOW IN OZARK AQUIFER

MAJOR DIRECTION OF FLOW IN WESTERN INTERIOR PLAINS AQUIFER SYSTEM

FIGURE 46.—Predevelopment potentiometric surface of the Ozark aquifer.

ern Oklahoma. In general, north of the Boston Mountains in Arkansas, regional flow is northward toward the potentiometric low associated with the White River drainage. To the south of the Boston Mountains, flow is inferred to be toward the Arkansas River valley. In this area, the rocks of the Ozark Plateaus aquifer system are beneath a thick confining system and substantial secondary permeability has not developed.

Ozark Confining Unit

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 that it confines. The leaky confining unit is composed mostly of shale, shaley limestone, and limestone. The formations generally included are the Upper Devonian Chattanooga Shale and the Lower Mississippian Chouteau Group (designated Chouteau Limestone by the U.S. Geological Survey) (table 3). Not all of the geologic formations in the confining unit are present everywhere in the Ozark subregion. Commonly in the western and southern part of the subregion, only the Upper Devonian shale and the Lower Mississippian shale and limestone are included in the confining unit. In extreme eastern Missouri, Ordovician, Silurian, and Devonian formations are included as part of this confining unit.

The Ozark confining unit is missing from the subsurface in small localities in southeast Kansas, southwest Missouri, northeast Oklahoma, and northwest Arkansas (pl. 21). The formations of the confining unit also are absent in the subsurface throughout a large area in the northern part of the Salem Plateau and along the Mississippi Alluvial Plain where the rocks have been removed by erosion. The altitude of the confining unit ranges from more than 1,500 ft above sea level at outcrops to more than 5,000 ft below sea level in the Arkansas River valley in Arkansas.

The thickness of the Ozark confining unit ranges from near zero to more than 1,600 ft in the Ozark subregion (pl. 22). At most locations the unit is less than 100 ft thick and, therefore, is relatively thin in comparison to other geohydrologic units in the Ozark subregion. The confining unit is thinnest in a narrow west-trending belt from southwest Missouri to southeast Kansas, where wells penetrate less than 10 ft of the confining unit. To the south of this belt, the unit gradually thickens except at scattered locations in northeast Oklahoma and southwest Missouri where the unit is locally absent. The sequence of rocks has been identified and named as a confining unit on the basis of regional hydrologic relations. However, local lithologic and thickness variations can increase the leakance to the degree that confinement is minimal. The shale content of the Ozark confining unit, which is an indicator of the degree of confinement, ranges from 0 to 100 percent (pl. 23).

Along the northeastern boundary of the Ozark subregion, the confining unit is lithologically more complex than elsewhere in the subregion. Limestone predominates in this area; shale also is present in significant quantities, and sandstone is present in minor quantities. The thickness of the major shale formations may total as much as 100 ft. Many of the limestone formations also have included shale. In the northern and northwestern parts of the subregion, the lithology varies from mostly shale to mostly limestone, depending on the presence or absence of the three formations of the Chouteau Group (table 3). Southward, the confining unit is represented solely by the Chattanooga Shale.

Springfield Plateau Aquifer

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 unit. The aquifer is the uppermost unit of the Ozark Plateaus aquifer system and at most locations overlies the Ozark confining unit.

Water from the aquifer is used extensively for stock and domestic purposes in the outcrop area. The aquifer also is present in the subsurface south of the Boston Mountains in Arkansas. In this area, the water in the aquifer contains more than 1,000 mg/L dissolved solids, probably because near-surface permeability has not been developed, and thus, the slow-moving water probably dissolves minerals as it passes through the confining unit. The aquifer south of the Boston Mountains is unused because of greater dissolved-solids concentrations and small well yields.

The Springfield Plateau aquifer includes several Mississippian formations. In northwest Arkansas, the most permeable zone is in the Boone Formation and the St. Joe Limestone Member of the Boone. Elsewhere, the aquifer includes several minor limestone formations from the basal Pierson Formation, which is equivalent to part of the Boone Formation, to the uppermost Moorefield Formation. The Moorefield Formation is included as part of the Springfield Plateau aquifer in northeastern Oklahoma. The shale content of the Moorefield Formation increases in northern Arkansas, where the formation is considered part of the overlying confining unit. In the southwestern part of the Ozark subregion, the Springfield Plateau aquifer includes the rocks from the basal part of the Boone Formation through the Moorefield Formation. The Boone Formation is similar to the Burlington and Keokuk Limestones and is moderately permeable. Outcrops of the aquifer typically do not form karsts in Oklahoma, but springs have developed in the solution openings along fractures.

The Springfield Plateau aquifer crops out around the western and southern perimeter of the Salem Plateau and along the axis of the Ozark uplift. In western Missouri, the top of the aquifer dips west to northwest into the subsurface at about 11 ft/mi (pl. 24). The dip increases to about 30 ft/mi in northeastern Oklahoma near the Kansas border. At the extreme southwest edge of the subregion and beneath the Boston Mountains in northern Arkansas, the southward dip of the aquifer is as much as 140 ft/mi. The aquifer is not present in the area adjacent to the Mississippi Alluvial Plain (fig. 44) nor in the subsurface at two small areas near the western edge of the Springfield Plateau and at the southern and southwestern edge of the subregion in Arkansas and Oklahoma. To the west and south, the Springfield Plateau aquifer is thicker than the relatively uniform thickness of 100 to 400 ft that is present throughout most of the subregion (pl. 25).

In southwestern Missouri and eastern Kansas, the more important geologic formations in the aquifer, due to their relatively greater thickness and permeability, are the Burlington and Keokuk Limestones. These two formations are both of medium to coarsely crystalline bedded limestone and contain abundant gray chert, mainly in the form of nodules. Dissolution of the very soluble limestone along fractures has created an extensive network of permeable channels, which in many cases have been enlarged to the point where the rock matrix has collapsed, producing caves and other large karst features with extremely large permeability. The underlying Fern Glen Limestone and Pierson Formation, which are equivalent to part of the Boone Formation (pl. 1), are moderately permeable but are not as thick as the Burlington and Keokuk Limestones and do not contain extensive networks of solution channels.

Hydraulic-conductivity values from aquifer tests of 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 mostly recharged 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. In the western part of the area, the aquifer receives upward discharge from the Ozark aquifer. In the eastern part of the outcrop area, conditions are reversed, and water is discharged downward to 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 layers 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 junction of the 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.

SUMMARY

The 370,000-mi^2 study area 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 of Arkansas and Oklahoma. This report describes the major regional aquifers within the study area and their geologic framework within the Cambrian through the lower sandstones in the Cretaceous rock section.

From the end of the Precambrian to Late Cambrian time, the study area was above sea level, and an uneven erosional surface had developed. The crystalline rock was fractured by the resultant stresses from large compressive forces from the north and south, and northwest- and northeast-trending lineaments were formed.

From Late Cambrian through Middle Ordovician time, a transgressive but cyclic sea covered the area. The first deposits were mostly permeable sand followed by slightly permeable calcareous mud consisting of aragonite and algal remains. During periods of uplift above sea level or sea-level recession, uplift diagenesis occurred, which in general greatly increased porosity and intrinsic permeability. Uplift diagenesis includes dissolution of minerals in rocks along fractures, dolomitization of limestone near shorelines where fresh ground water and salinewater mix, and extensional fracturing that results from removal of overburden by erosion.

During most of Silurian and Devonian time, nearly the entire area was above sea level, except for southern Oklahoma and northern Arkansas. Again, uplift diagenesis greatly increased porosity and intrinsic permeability of the rocks. At the end of the Devonian or at the beginning of Early Mississippian time, a transgressing sea covered most of the area, and clay was deposited.

Calcareous mud was the dominant sediment deposited during much of Mississippian time. Tectonic activity increased as evidenced by uplifts, such as the Colorado–Wyoming and the Nemaha uplifts. Subsiding basins, such as the Arkoma and Anadarko, received large quantities of sediment that covered the older rocks, thus causing burial diagenesis. Processes of burial diagenesis include compaction, thermal diagenesis of organic materials, thermal diagenesis of clay, and pressure dissolution at grain contacts with recrystallization in pores. In general, burial diagenesis decreased primary porosity and intrinsic permeability; however, CO_2-rich water, a product of thermal diagenesis, selectively increased secondary porosity and permeability by local dissolution of carbonate minerals.

Tectonic activity reached its maximum during Pennsylvanian time and decreased during the Permian. Uplifts, such as the Front Range, Apishapa, Criner, Amarillo, Wichita, Arbuckle, Ouachita, Ozark, Nemaha, and Cambridge–Central Kansas, were active. The Arkoma and Anadarko basins continued to subside and received as much as 20,000 ft of sediments. The dominant sediment was clay, with lesser calcareous mud, sand, and evaporite minerals. During the Permian, the eastern part of the area was tilted upward; the sea receded; and regional ground-water flow commenced from east to west. In the Ozark uplift area, a ground-water flow system began around the St. Francois Mountains.

During Triassic and Jurassic time, the eastern part of the study area was above sea level, and uplift diagenesis was active again. However, during the Early Cretaceous, a transgressive but cyclic sea deposited permeable sand and slightly permeable clay over the western and central parts of the study area. During Late Cretaceous, clay was deposited in thick layers and burial diagenesis occurred throughout most of the area. At the end of the Cretaceous and into the Tertiary, major uplifts, such as the Rocky Mountains, were formed as part of the Laramide orogeny. Uplifts in the west accompanied the regional tilting of the study area downward to the east. Regional ground-water flow from west to east started in the Lower Cretaceous sandstone and in pre-Pennsylvanian rocks. In the Ozark area, the ground-water flow system near the St. Francois Mountains continued to expand as Pennsylvanian and Permian rocks were removed by erosion.

The geohydrologic units generally correlate with the regional stratigraphic units, except adjacent to major structural features and in other areas of complex stratigraphic relations. The major exception is along and adjacent to the physiographic boundary between the Interior Plains and the Interior Highlands. At this location, the Western Interior Plains aquifer system and the Ozark Plateaus aquifer system are laterally adjacent. In general, water flow in the Western Interior Plains aquifer system is very slow from the west to the east. The mostly fresh ground-water flow system originating in the Ozark Plateaus extends outward until it meets the saline ground-water flow system that underlies most of the western part of the Interior Plains. The approximate boundary of the transition zone between these two flow systems is marked by a broad low in the potentiometric surface that is nearly coincidental with a broad topographic low. Water in both aquifer systems moves upward to the water table, springs, or streams in the topographically low area. The areas underlain by the two regional flow systems are referred to herein as the Plains subregion and the Ozark subregion.

The Plains subregion contains three major regional-geohydrologic systems. These systems, in ascending order, are the Western Interior Plains aquifer system, the Western Interior Plains confining system, and the Great Plains aquifer system, all overlying the basement confining unit. Overlying these geohydrologic units are the Great Plains confining system and the High Plains aquifer.

Rocks of the Western Interior Plains aquifer system consist mostly of dolostone, limestone, and shale of Cambrian through Mississippian age. The geohydrologic units in the aquifer system are hydraulically connected. At most locations, the aquifer units are permeable and water yielding except in deep basins where permeability is greatly decreased. The aquifer system is several thousand feet thick in the Anadarko and Arkoma basins. The aquifer system contains saline water and brine with dissolved-solids concentrations of about 10,000 to more than 200,000 mg/L. Intrinsic permeability ranges from 10^{-11} to 10^{-17} ft^2.

The Western Interior Plains confining system confines water flow to and from the Western Interior Plains aquifer system at nearly all locations including the deep basins. The thick confining system consists of layered shale, limestone, sandstone, and evaporite deposits of Late Mississippian through Jurassic age. The thickness of the confining system decreases from about 20,000 ft in the Anadarko basin to nearly zero along the periphery of the Ozark Plateaus where it crops out.

The Great Plains aquifer system overlies the Western Interior Plains confining system and contains two regional aquifers and one confining unit. Both aquifers are composed predominantly of water-bearing Lower Cretaceous sandstone and are separated at most locations by a shale confining unit. Most recharge occurs in southeastern Colorado and northeastern New Mexico. Ground water flows east-northeast from these western recharge areas to discharge areas in central Kansas and eastern Nebraska.

The Apishapa aquifer, the lower of two aquifers in the Great Plains aquifer system, is composed of permeable, slightly cemented, medium-grained to very fine grained sandstone of the Cheyenne Sandstone and its equivalents. Aquifer thickness ranges from 0 to 400 ft, but 100 to 200 ft is typical. The Apishapa confining unit restricts water movement between the Apishapa aquifer and the overlying Maha aquifer. The confining unit, which is typically less than 100 ft thick, mostly is composed of slightly permeable Kiowa Shale and equivalents. Intrinsic permeability ranges from 10^{-13} ft^2 in the Denver basin to more than 10^{-10} ft^2.

The Maha aquifer is the upper aquifer of the Great Plains aquifer system and is more extensive than the underlying Apishapa aquifer. The Maha aquifer consists of permeable sandstone of the Dakota Sandstone and its equivalents. Dissolved-solids concentrations range from about 1,000 mg/L along outcrops in southeastern Colorado, central Kansas, and eastern Nebraska to more than 20,000 mg/L in western Nebraska.

The Great Plains confining system overlies and restricts flow to and from the Great Plains aquifer system and the overlying High Plains aquifer or to and from the near-surface water-table aquifer. The confining system mostly consists of very slightly permeable Cretaceous shale. The extensive confining system, which is more than 8,000 ft thick in the Denver basin, generally thins eastward.

The Ozark subregion approximately corresponds to the Ozark Plateaus and adjacent areas of the Interior Plains and Ouachita physiographic provinces. The Ozark Plateaus aquifer system, which is underlain by the basement confining unit, is located within the Ozark subregion. In general, freshwater flows outward from the central area of the Ozark Plateaus to the periphery, where the water is discharged upward. The basement confining unit consists of igneous and metamorphic rocks that generally are fractured, saturated, and locally yield water to wells.

The St. Francois aquifer, which is the lowest aquifer of the Ozark Plateaus aquifer system, is composed of water-bearing Upper Cambrian rocks, mostly sandstone that directly overlies the basement. The aquifer is more than 1,000 ft thick near the Mississippi Alluvial Plain, but typically is 200 to 500 ft thick. The St. Francois confining unit, which overlies and confines the St. Francois aquifer, is composed of Upper Cambrian shale, siltstone, dolostone, and limestone, and it is leaky as it transmits a considerable amount of water.

The Ozark aquifer, the largest and most widely used aquifer in the Ozark subregion, is composed mostly of water-bearing Upper Cambrian through Middle Devonian fractured dolomitic rocks. The aquifer is typically about 1,000 ft thick and is the thickest unit of the Ozark Plateaus aquifer system. The Ozark confining unit restricts the movement of water between the Ozark aquifer and the overlying Springfield Plateau aquifer. The confining unit includes Upper Devonian and Lower Mississippian shale.

The Springfield Plateau aquifer is composed of fractured and water-bearing Mississippian limestone. Aquifer thickness is as much as 1,500 ft, but thicknesses of 100 to 400 ft are typical. The aquifer is overlain to the west by beds of very slightly permeable shale of Pennsylvanian age. The shale confines or restricts water movement between the Springfield Plateau aquifer and the water table. At most locations, such as along the eastern boundary of the Ozark subregion, the shale restricts upward flow from the Springfield Plateau aquifer. Pennsylvanian shale also overlies the aquifer south of the Boston Mountains. In this area permeability of the aquifer material is very slight, and the quantity of water flowing to the south is very small.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1993-583-411

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