Paleohydrology of the Central United States

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Chapter D

Paleohydrology of the Central United States

By DONALD G. JORGENSEN

U.S. GEOLOGICAL SURVEY BULLETIN 1989

STRATEGIC AND CRITICAL MINERALS IN THE MIDCONTINENT REGION, UNITED STATES

WARREN C. DAY and DIANE E. LANE, Editors

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miles	1.609	kilometers
square miles	2.590	square kilometers
degrees Fahrenheit (°F)	([1])	degrees Celsius (°C)

[1]°C=(°F–32)/1.8

STRATEGIC AND CRITICAL MINERALS IN THE MIDCONTINENT REGION, UNITED STATES

Paleohydrology of the Central United States

By Donald G. Jorgensen

Abstract

Paleohydrologic analysis of the Central United States indicates that from the end of the Precambrian to Late Cambrian time, unevenly eroded, fractured Precambrian crystalline rocks were exposed above sea level. From Late Cambrian through Middle Ordovician time, a transgressive, but cyclic, sea covered the area. During periods of sea encroachment, the sediments that were deposited underwent burial diagenesis, which generally decreased porosity and permeability of associated rocks. During most of Silurian and Devonian time, the sea receded, and the deposits underwent uplift diagenesis, which increased porosity and permeability, especially of the exposed rocks. However, at the end of the Devonian and during the Early Mississippian, nearly impermeable clay was deposited in the euxinic sea, forming a regional confining unit. Later, during Mississippian time, calcareous mud, which was deposited in the forming Anadarko and Ouachita basins, underwent burial diagenesis (which generally decreases permeability), especially rapid thermal alteration of organic material. At the same time, rocks in the Nemaha and the Colorado uplifts were undergoing uplift diagenesis (which generally increases permeability).

Tectonic activity reached its maximum during the Pennsylvanian. By Middle Pennsylvanian time, the sea had submerged most of the area, including the Ozark uplift. Large quantities of sediment, mostly shale, were deposited in the Anadarko and Arkoma basins. The rapid burial trapped slightly permeable material and resulted in geopressuring as the saturated sediments were buried more deeply. During the Late Pennsylvanian and Early Permian, the Ouachita uplift was higher than the Ozark uplift, thus creating a gradient down which water could flow from the Ouachita uplift through the Arkoma to possible discharge areas in the Ozark uplift. However, this is unlikely because the rocks below the Pennsylvanian shale in the Arkoma basin would have been deeply buried and thus would have been only very slightly permeable. During Permian time, the Ouachita uplift was leveled, Permian and Pennsylvanian rocks were eroded, and uplift diagenesis dominated the Ozark uplift and adjacent areas. During this time in eastern Missouri, the present-day Ozark Plateaus aquifer system formed adjacent to the St. Francois Mountains in the permeable Cambrian through Mississippian rocks, which had undergone extensive uplift and diagenesis. By the end of the Permian, sediments more than 20,000 ft thick had been deposited in the Anadarko and Arkoma basins and of a lesser thickness on the adjoining shelves. Burial diagenesis, especially rapid alteration of the organic material in the basins, dominated during Late Permian time.

During Triassic and Jurassic times, nearly the entire Central United States was above sea level. In general, the mild uplift diagenesis increased porosity and permeability.

During Cretaceous time, the sea returned to the central interior, deposited sediments in the forming Denver basin, and, in general, reestablished burial diagenesis. The Laramide orogeny raised the Rocky Mountains, creating an eastward tilt in the central interior. This regional uplift caused an eastward flow in the Great Plains aquifer system (mostly Lower Cretaceous sandstone) that exists today and initiated the present-day west-to-east flow of water throughout most of the Anadarko basin shelf in the Western Interior Plains aquifer system (mostly Cambrian through Mississippian rocks). However, there is a very slight radial flow of ground water outward from the geopressure zone in the Anadarko basin. Most water in the Western Interior Plains aquifer system is discharged upward to the water table or streams in the transition zone, which is a hydraulic boundary that separates the Western Interior Plains and the Ozark Plateaus aquifer systems.

Epigenetic mineral deposits are found on the western and southern flanks along the axis of the Ozark uplift. Although the source of the hot metal-bearing solution is not known, it is improbable that the fluid was part of an artesian flow system that transmitted water from a paleotopographic high, such as the Ouachita Mountains, during the Pennsylvanian Period, to the relatively lower lying areas along the Ozark uplift.

There are large hydrocarbon accumulations and a geopressure zone in the Anadarko basin. Relatively sparse hydrocarbon accumulations and no regional geopressure zone have been found in the Arkoma basin. The rapid burial by sediments in the Pennsylvanian and Permian Periods could have created the pressure that fractured the overlying rocks in the Arkoma basin, thus releasing hydrocarbons and water. Along the flanks of the Arkoma basin, relatively more permeable formations existed that could have transmitted fluids to areas on, and adjacent to, the axis of the Ozark uplift.

INTRODUCTION

Purpose and Scope

The purpose of this report is to describe the paleohydrology of the Central United States, especially the Ozark uplift and the Ouachita and Anadarko basins. Ground-water flow systems, water chemistry, and hydraulic properties of aquifers can be evaluated or estimated from paleohydrologic analysis—reconstruction of paleogeography, paleoclimate, and past heat-flow conditions to infer the hydrologic cycle. Special emphasis in this report is given to the geology of ground water, including the diagenetic processes that affect aquifers and the flow systems associated with them. Many diagenetic processes are a function of available energy, principally heat. Available heat within the upper crust of the Earth correlates with the tectonic setting of the rock material. The paleohydrologic approach is especially useful on the scale of continental and regional aquifers and has useful ancillary applications in evaluating potential for epigenetic mineralization or the occurrence of hydrocarbons.

This report represents a cooperative effort between the U.S. Geological Survey (USGS) Water Resources Division and the USGS Geologic Division and is a contribution to the USGS Midcontinent Strategic and Critical Minerals Project. This report relies substantially on the analysis of aquifers made as part of the U.S. Geological Survey Central Midwest Regional Aquifer-System Analysis (CMRASA) Study Program (Jorgensen and Signor, 1981; Sun, 1986).

Diagenetic Processes

Diagenetic processes in rocks can be divided into two broad groups—burial and uplift. Typically, burial diagenesis is associated with basin subsidence and (or) rise of sea level. Processes such as lithification, compaction, pressure dissolution and recrystallization, thermal alteration of organic material, and clay-layer transformation are included. In general, burial diagenesis results in a reduction in primary porosity and permeability; however, generation of carbon dioxide by thermal alteration of organic material typically results in an increase of porosity and permeability in selected rock sections (Al-Shaieb and Shelton, 1981).

Uplift diagenesis is associated with uplift and (or) sea-level recession. It generally increases porosity and permeability and includes such associated processes as weathering, near-surface dissolution, extension, and fracturing. Weathering and near-surface dissolution greatly increase both porosity and permeability. Uplift diagenesis also includes dolomitization in zones where sodium chloride water and calcium and magnesium bicarbonate water mix, such as in the shallow subsurface near coastlines (Hanshaw and Back, 1979); dolomitization usually increases permeability. Uplift generally is accompanied by a decrease in temperature and pressure in the rocks. These decreases can cause precipitation of cementing materials, such as calcite and silica, that decrease porosity and permeability. Unloading, uplift that typically results from erosion, causes extension or expansion by rebound of compression and thus extensional fracturing and microfracturing (Magara, 1981).

Certain physical diagenetic processes are typically related not only to the environmental conditions but to the rock type. Accordingly, it is useful to consider diagenetic processes as related to a specific rock type.

Carbonate Rocks

Calcareous sediments are preserved in warm seas. These sediments may be permeable, such as shell fragments, or have slight permeability, such as calcareous muds. Lithification of calcareous sediments occurs both above and below sea level (Hanshaw and Back, 1979) and alters hydraulic properties of the sediments. Areally extensive dolomitization typically occurs near shore where fresh ground water mixes with marine depositional water; dolomitization occurs as magnesium is substituted for calcium in calcite. Solution-fractured limestone and dolostone, which are typical of karst, are very permeable and, thus, are excellent aquifer materials (Stringfield and others, 1974; Babushkin and others, 1975; Parizek, 1976; Milanovic, 1979).

The important diagenetic processes that decrease porosity and permeability in carbonates are compaction, pressure dissolution, and cementation. Compaction by burial decreases porosity and markedly increases ductility of limestone. Consequently, limestone, which may be permeable near surface and form an aquifer, may be only slightly permeable at depth and form a confining unit. Compaction of dolostone also decreases its porosity, but it remains relatively brittle and retains some permeability even at depths in a basin (Handin, 1966). Pressure dissolution occurs at the contacts of grains; however, the carbonate may reprecipitate in adjacent pores. Calcite solubility increases with pressure and decreases with temperature. For normal geothermal and pressure gradients, solubility increases slightly with depth, thus allowing deep leaching of calcite by undersaturated water moving downward. Conversely, cementation by precipitation occurs if pressure is decreased or temperature is increased. Calcite cementation commonly is associated with outgassing of carbon dioxide of upward-moving water undergoing pressure reduction.

Siliceous Rocks

Siliceous rocks comprise most types of sandstone and most igneous and metamorphic rocks. The solubility of silica increases significantly with temperature and only slightly with pressure (Hem, 1970). Thus, ground water that moves downward and is not saturated with respect to silica can dissolve crystalline quartz and silicates, especially the more soluble amorphous silica. Conversely, ground water that moves upward can precipitate amorphous silica cement before crystalline quartz forms. Because solubility is only slightly affected by pressure, pressure dissolution and recrystallization are minimal with burial. Also, because sandstone remains relatively brittle with depth, porosity and permeability are attenuated by compression.

Shale and Clay

Shale and clay are greatly affected by compaction and thermal diagenesis of clay minerals. After being deposited in a marine environment, montmorillonite exchanges sodium, magnesium, and potassium for calcium, and water molecules are attached. Thus, porosity is greatly increased; permeability is not altered. Upon burial, porosity decreases as pore water is expelled by compaction. The fresher pore water is expelled before the slightly more saline water on the pore walls. As burial continues (increase in temperature and pressure), layer transformation of clay liberates lattice (intracrystalline) water in conjunction with the continued expulsion of pore water. Finally, upon further burial, mixed-layer montmorillonite and clay are dehydrated to illite.

Shale and clay layers act as membranes that filter ions as water moves through them and alters the chemistry of the ground water (Hanshaw and Back, 1972; Back, 1985).

Evaporites

With the exception of dolomite, evaporites typically are only slightly porous and permeable and are very ductile and not susceptible to fracturing. Also excepting dolomite, they are typically very soluble, markedly affecting water chemistry.

PALEOHYDROLOGY OF THE CENTRAL UNITED STATES

A summary of the geologic history and hydrology (paleohydrology) of the Central United States is presented in the following sections; special emphasis is given to the processes that resulted in the present hydraulic characteristics of the rocks, the water chemistry, and the flow systems in the Central United States and to the implications for the occurrence of epigenetic minerals and accumulations of hydrocarbons. A more detailed discussion, including stratigraphic correlation within the Central United States, can be found in Jorgensen and others (in press). A more generalized paleohydrologic description of the Central Nonglaciated Plain of North America was given by Jorgensen and others (1988), and a description of the paleohydrology of the Anadarko basin was given by Jorgensen (1988).

Paleohydrologic analysis of the Central United States relies substantially on an examination of evidence of paleogeograpic, paleoclimatic, and subsurface thermal conditions; that is, geologic conditions as dictated by plate tectonics. Most interpretations of the pre-Pangaea conditions are based on work reported by Bambach and others (1980) and of the post-Pangaea conditions on work reported by Dietz and Holden (1970). Other sources of information include the U.S. Geological Survey's paleotectonic investigations of geologic time systems, such as the Mississippian (Craig and Varnes, 1979), the Pennsylvanian (McKee and others, 1975), the Permian (McKee and others, 1967), the Triassic (McKee and others, 1959), and the Jurassic (McKee and others, 1956). Maps from the "Shell Atlas" (Cook and Bally, 1975) also are useful sources of information on the present extent of rocks.

The Central United States forms a reasonably distinct geohydrologic (CMRASA) study area on a subcontinental scale. The boundaries of the study area (fig. D1) are mostly hydrologic or flow boundaries, the origin of which can be determined by paleohydrologic analysis. The 370,000-mi^2 area extends from the foothills of the Rocky Mountains in Colorado to the Missouri and Mississippi Rivers in eastern Nebraska and Missouri and from the Siouxana arch in southeastern South Dakota to the Ouachita, Arbuckle, Wichita, and Amarillo uplifts of Arkansas, Oklahoma, and Texas (fig. D2).

Although the hydraulic connection between the rocks of the Rocky Mountains and the rocks of the study area is poor, the high elevation of the Rocky Mountains and the foothills provides the potential for gravity flow in the regional aquifers. The Missouri and Mississippi Rivers generally are sinks to the regional-aquifer systems; however, some reaches of the rivers receive recharge. The Siouxana arch is, in general, a boundary to lateral flow in pre-Cretaceous rocks. The Mississippi embayment is a strong sink to lateral flow from the Ozark Plateaus. The Arkansas Valley is a weak sink to the water from the Boston Mountains. In general, the Arbuckle, Wichita, and Amarillo uplifts are relatively impermeable boundaries to flow in the regional aquifers.

The Central United States is within the stable interior of the North American continent. Since Cambrian time, most of the area has undergone relatively gentle deformation, resulting in upwarp and downwarp of the Earth's crust over large areas. Structurally, the study area has been characterized by broad basins and arches (fig. D2). Accordingly, most folding of sedimentary rocks has been subtle, and few major fault zones of regional significance are present. Along the southern and western margins of the study area, however, strong

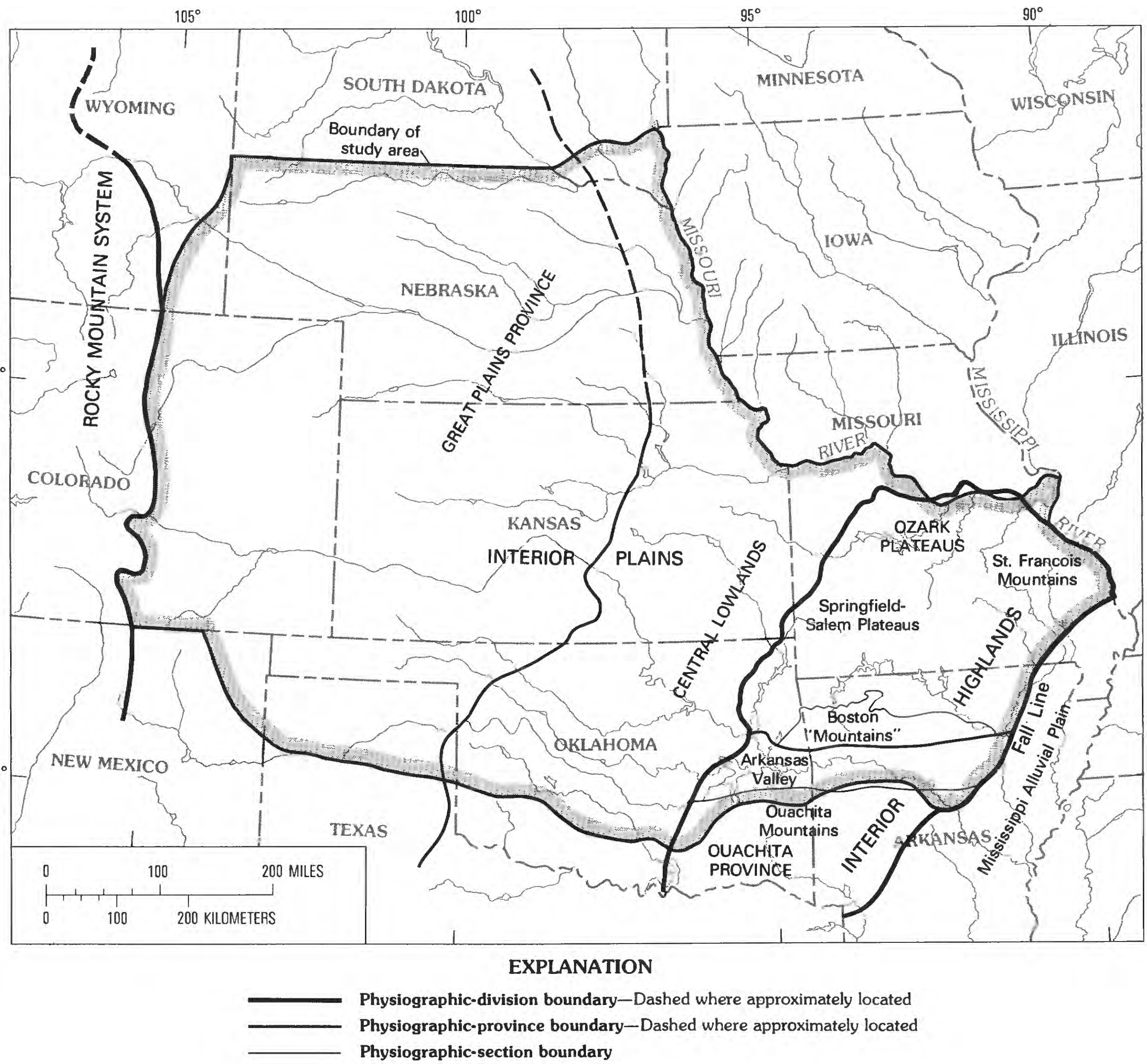


Figure D1. Physiographic subdivisions of the study area, Central United States (modified from Fenneman, 1946).

crustal deformation by mountain-building forces resulted in intense folding and faulting. This lateral change from simple to complex geologic structure was the major factor in defining the southern and western boundaries of the study area. The structural change is relatively abrupt in most locations but transitional in others.

The present areal distribution of major time-stratigraphic units in the Central United States is shown in figure D3. Geologic sections (fig. D4) illustrate the general regional continuity of the units; the severest structural deformation is along the southern and western margins of the study area. Faulting was substantial in these areas (fig. D5) and, in general, has completely offset the water-bearing units. In contrast, most faults in the interior of the study area are not hydrologic boundaries because they have much less offset and hydraulic continuity exists across the fault faces.

Precambrian Time

The Precambrian rocks that underlie the Phanerozoic sedimentary rocks in the study area consist mainly of igneous and metamorphic rocks of various types that form a "basement complex." Deep burial of these rocks at most locations has precluded detailed knowledge of their nature. However, data compiled for the Midcontinent Strategic and Critical Minerals Project have resulted in new interpretations

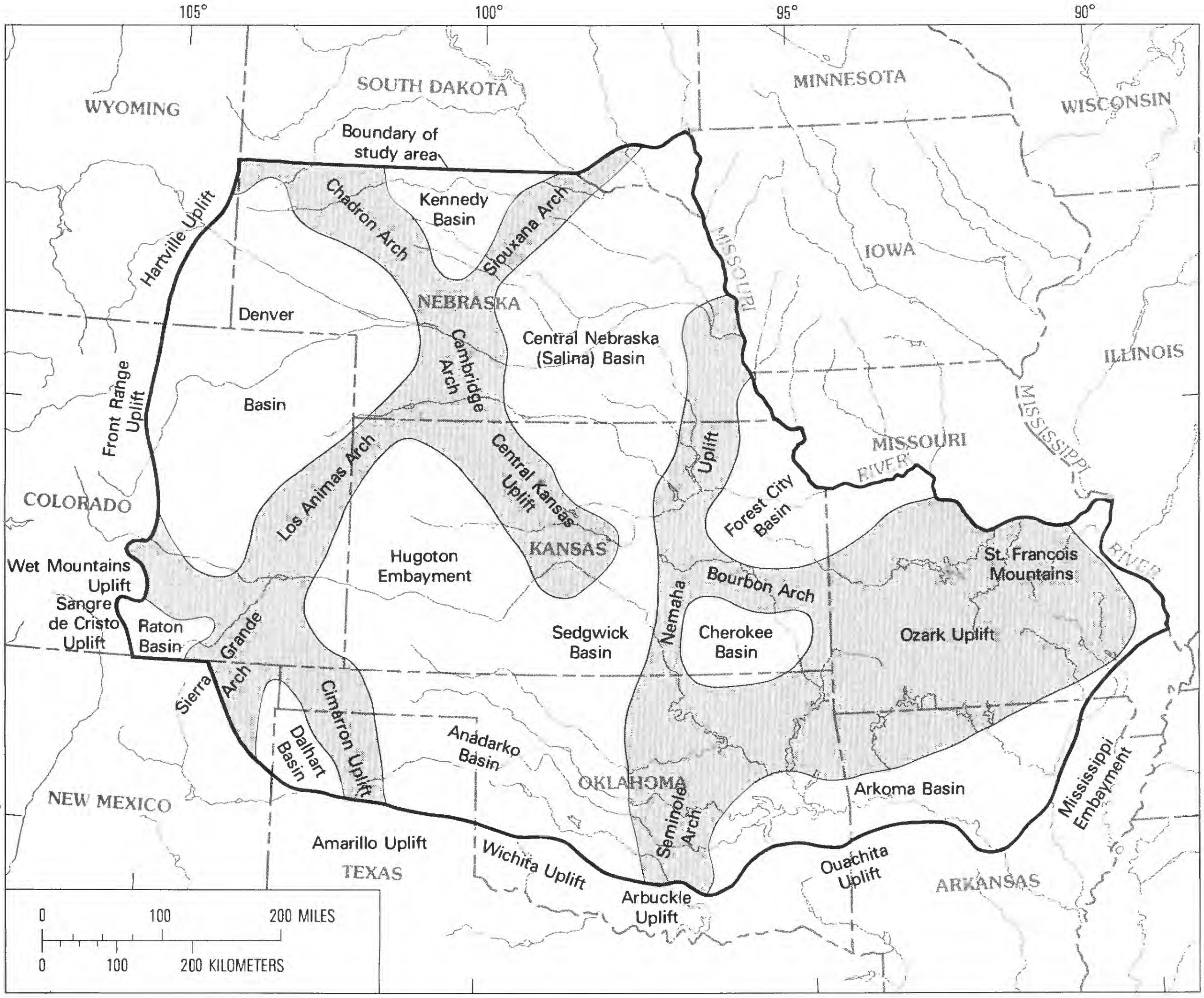


Figure D2. Major structural features in the study area, Central United States (modified from Carlson, 1963; Merriam, 1963; Oetking and others, 1967; Bennison and Chenowith, 1984; Renfro, 1973).

of the Precambrian geology of the study area (Sims, 1985). Sims and Peterman (1986, p. 488) reported:

> A major early Proterozoic orogen (Central Plains) more than 1,000 km long and at least 500 km wide has been delineated in the subsurface of Nebraska, Kansas, and Missouri as a result of a new compilation of Precambrian basement drill data in the northern midcontinent. The orogen is composed of metamorphic and granitoid rocks in the range of 1.63–1.8 Ga * * *.

Pratt and Sims (1987, p. 304) further related:

> The exposed and buried basement in the [north-central mid-continent] region is a collage of tectonic-stratigraphic terranes ranging in age from Archean to Middle Proterozoic * * *. Eight major terranes have been identified and delineated. From oldest to youngest, these are: Archean gneiss terrane, Late Archaen greenstone-granite terrane, Early Proterozoic Wisconsin magmatic terrane and associated epicratonic sedimentary rocks of the Penokean orogen, Early Proterozoic rhyolite-granite terrane of southern Wisconsin and east-central Minnesota, Early Proterozoic metamorphic and granitoid rocks of the Central Plains orogen, Middle Proterozoic St. Francois granite-rhyolite terrane, and Middle Proterozoic Midcontinent rift system * * *. The north-central Midcontinent basement is traversed by numerous northwest-trending tectonic zones interpreted as shears and characterized by cataclastic zones in the basement, by aligned granite and mafic intrusions of Middle Proterozoic age, and commonly, by faulting and folding in overlying Paleozoic rocks. The shears are believed to belong to a family of regional dextral transcurrent faults that are exposed farther north in the Lake Superior region and adjacent Canada.

Numerous other studies have yielded more site-specific information.

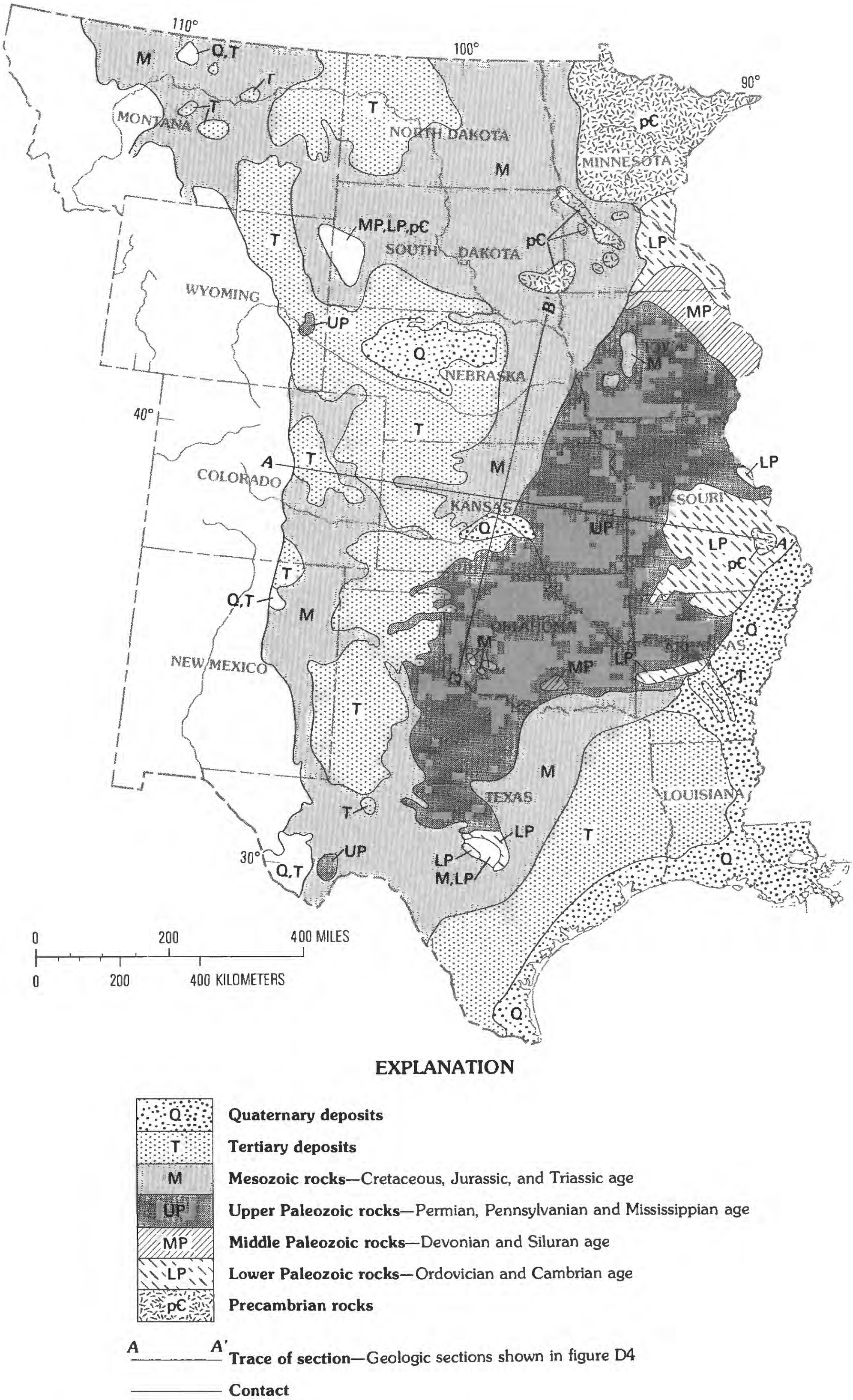


Figure D3. Regional geology of the Central United States (modified from Kinney, 1966).

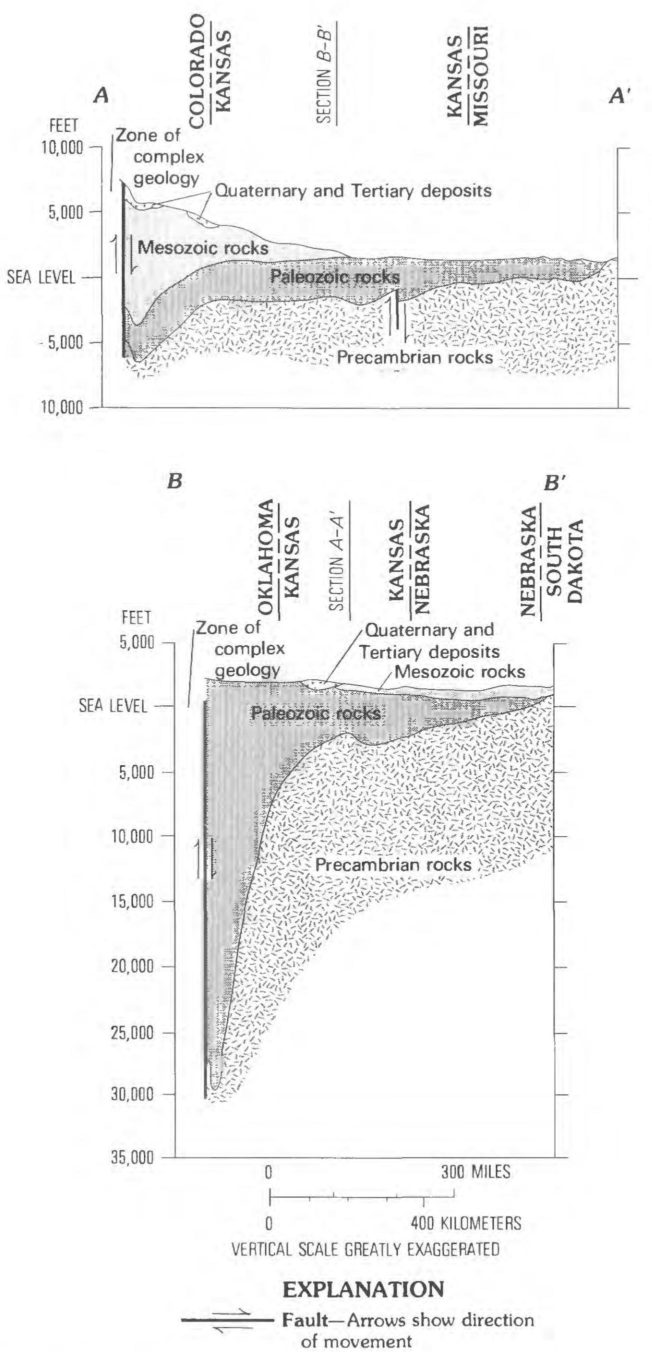


Figure D4. Regional geologic sections of the Central United States. Lines of section shown in figure D3.

Information concerning faults and fractures in the basement rocks is of special importance because they mark weak zones that were reactivated at various intervals during geologic time. The faults and fractures in the indurated rocks created anisotropic permeability and were paths for groundwater flow and dissolution. The orientation of faults, fractures, and other lineaments fluctuated somewhat during Paleozoic time but generally trended approximately N. 35° E. and N. 55° W.

Warner (1980) concluded that the Central United States was moderately mobile during the Precambrian. Large Precambrian faults are now oriented northwest-southeast. According to Warner (1980, p. 14), this alignment is the same as that of the boundary between metamorphic and igneous Precambrian rocks in the midcontinent region.

The Colorado lineament, extending from central South Dakota to eastern Colorado, may be one of several parallel faults along the Transcontinental arch that may have been started by Precambrian tectonic activity.

The Ozark uplift (fig. D2) formed a large land mass during the Precambrian, and by Cambrian time the mass, nearly 2,000 ft thick, was deeply eroded and faulted (Dake, 1930, p. 194). Precambrian faulting in the Ozark uplift area also was reported by Bridge (1930, p. 135). The core of the St. Francois Mountains is an epizonal granite batholith emplaced 1,500 million years ago and is part of a broad, largely subsurface belt of silicic igneous rocks of similar age that extends at least from Michigan through Oklahoma (Sides, 1978, p. 2). Lineaments in the Precambrian rocks mapped by Hayes (1962) are aligned N. 50° W. and N. 65° E. The greatest density of lineaments is associated with the St. Francois Mountains (El-Etr, 1967, p. 1).

On the basis of magnetic evidence in Kansas, Yarger (1982, p. 179) believed that block faults and possible dikes, which are usually associated with continental rifting, exist along the central midcontinent rift (also termed the "North American geophysical anomaly"). The rift in Kansas is west of, and runs parallel to, the Nemaha ridge (uplift), which extends from Nebraska through Kansas and into Oklahoma (fig. D6). It is not known why the rift of rather limited width did not develop further. Other site-specific investigations concerning basement rocks in structures in Kansas include those by Merriam (1963) and Steeples (1982).

In northeastern Oklahoma, Denison (1981, p. 26) outlined a series of parallel synclines and anticlines that are about 40 mi apart and trend N. 70° E. He also identified the Labette fault (not shown) and the ancestral Nemaha ridge as Precambrian structures. A Precambrian basin may have existed in southern Oklahoma. Recent seismic investigations imply that more than 20,000 ft of Precambrian sedimentary rocks underlie the Wichita Mountains (Brewer, 1982, fig. D26). Rifts along the present Arkoma basin (fig. D2) and the northern end of the Mississippi Alluvial Plain (fig. D1), which marks the subsurface Mississippi embayment, are believed to be late Precambrian in age (Schwalb, 1982; Houseknecht and Matthews, 1985).

Along the southern boundary of the study area in Oklahoma, the basement rock includes extrusive rhyolite rocks or intrusive granite of Early to Middle Cambrian age (Ham and others, 1964).

In summary, all investigators have found the Precambrian basement rocks faulted and fractured. The fractures cause anisotropic permeability and are avenues of groundwater flow. In addition, the basement surface represents a

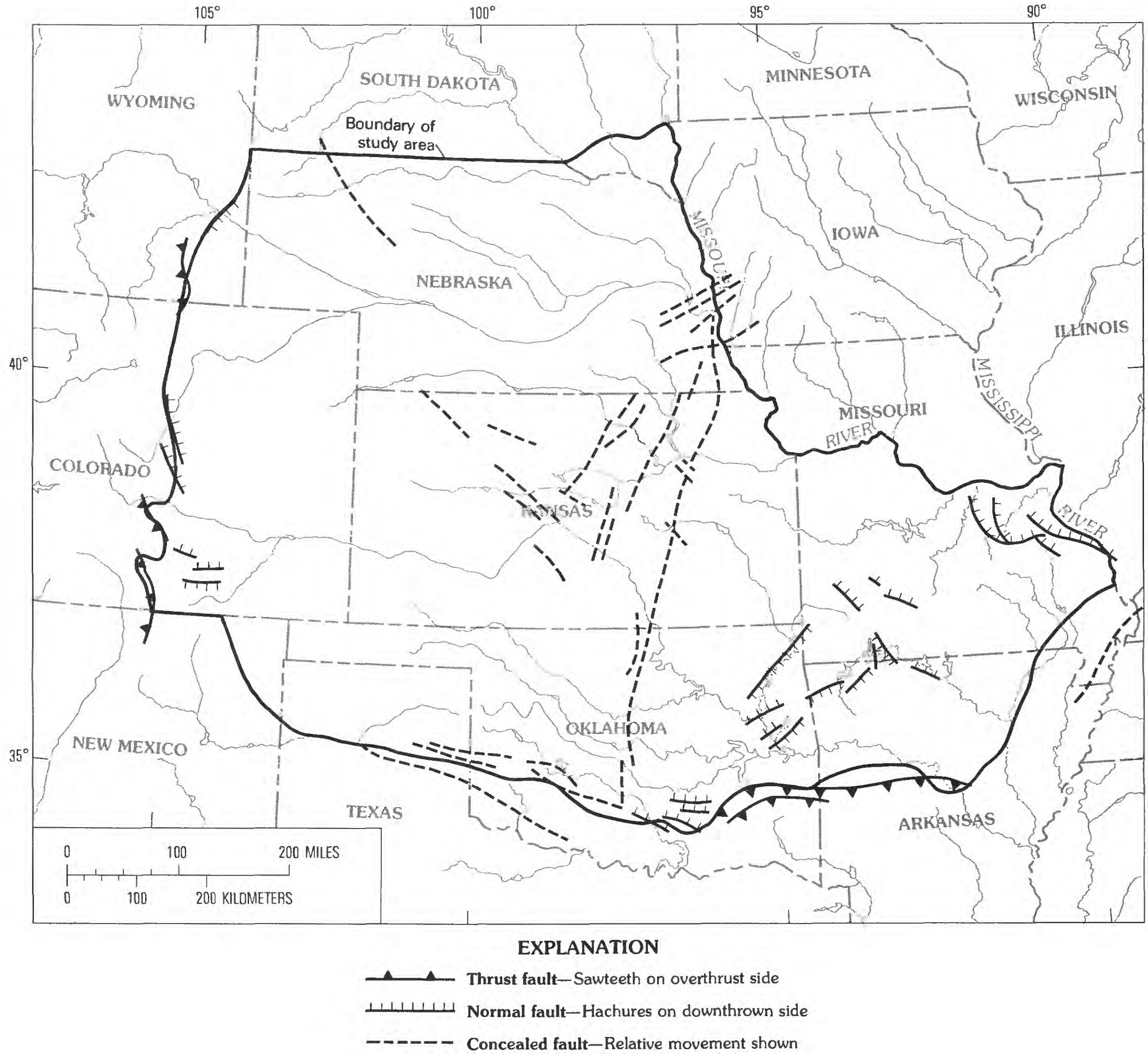


Figure D5. Major fault zones in the study area, Central United States (modified from King, 1968; Sims, 1985).

major unconformity (resulting from a long period of erosion or nondeposition). The permeable broken or weathered rock on the basement surface, which is sometimes termed "granite wash," typically forms a permeable zone.

Paleozoic Time

From the beginning of the Cambrian through the Middle Cambrian, the Central United States was above sea level, Precambrian rocks were being eroded (fig. D6), and no high mountains existed. The climate was probably warm and wet. During the Late Cambrian, this area, except for the Transcontinental arch and small islands (fig. D7), was inundated by a marine sea of normal salinity. The first deposits were permeable nearshore sand, which became the Lamotte Sandstone, the Sawatch Quartzite, and the Reagan Sandstone; in some areas, calcareous mud was deposited along with the sand. The thickest sediments were deposited in a subsiding basin that extended from central Oklahoma through central Arkansas. The advances of the sea were interrupted by periods of recession, during which uplift diagenesis occurred and calcareous mud was lithified to limestone and sand to sandstone. During the periods of recession the saline water deposited with the sediments probably was flushed from the Cambrian mantle and subjacent

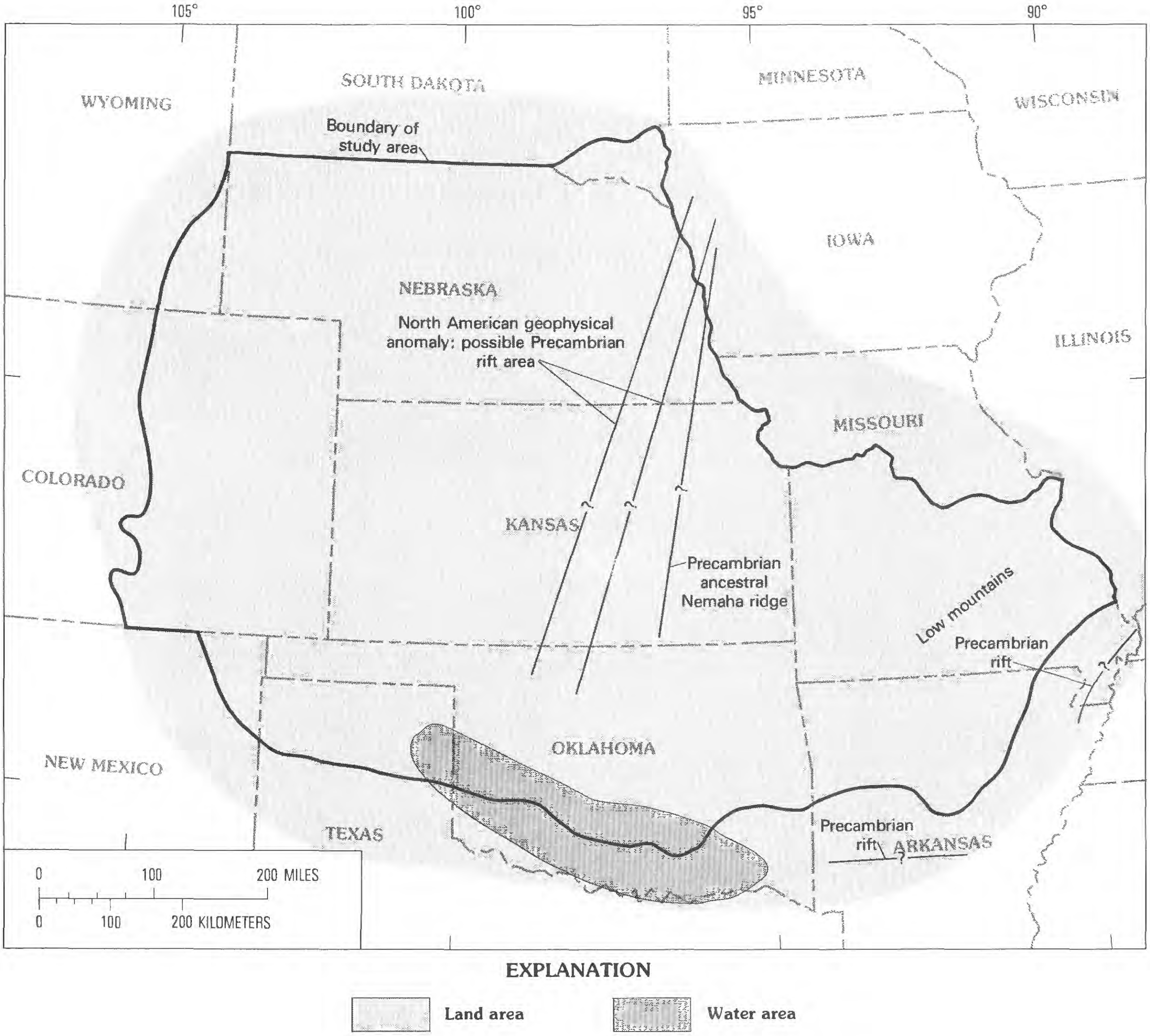


Figure D6. Early Cambrian geography of the study area, Central United States.

rocks in the positive (land) areas. Erosion removed overburden load and resulted in extensional fracturing. The fracturing created secondary permeability and, more importantly, paths along which dissolution, especially of calcareous material, occurred. At some locations, especially those near coastlines, rocks containing saline water were in contact with fresh ground water from the land masses; this commonly resulted in dissolution and dolomitization, which generally increased permeability.

During Ordovician time, the Oklahoma-Arkansas basin continued to subside, and the upward movement of the Ozark uplift was renewed. The climate was likely warm and humid. Calcareous mud was the predominant shallow-water sediment. In these areas, sediment accumulated to a thickness in excess of 6,000 ft and burial diagenesis ensued. Compaction of the sediments squeezed water from the rock, reducing primary porosity. At depths of 5,000 ft or more, thermal diagenesis of organic material and the production of carbon dioxide, water, and hydrocarbons at a slow to moderate rate could be expected on the basis of normal geothermal gradient (25 °C/km). Smectite was transformed to illite, and water was probably released. The resulting carbon-dioxide-rich fluids, in turn, would have dissolved selected carbonate and siliceous material along their pathway, thus selectively increasing secondary porosity and permeability.

During Late Cambrian time the sea was cyclic, so most Ordovician sediments adjacent to the Ozark uplift were nearshore calcareous mud (largely algal lime), sand, and some clay (figs. D8–D10). Calcareous mud was lithified to limestone, especially during periods of sea recession, and the

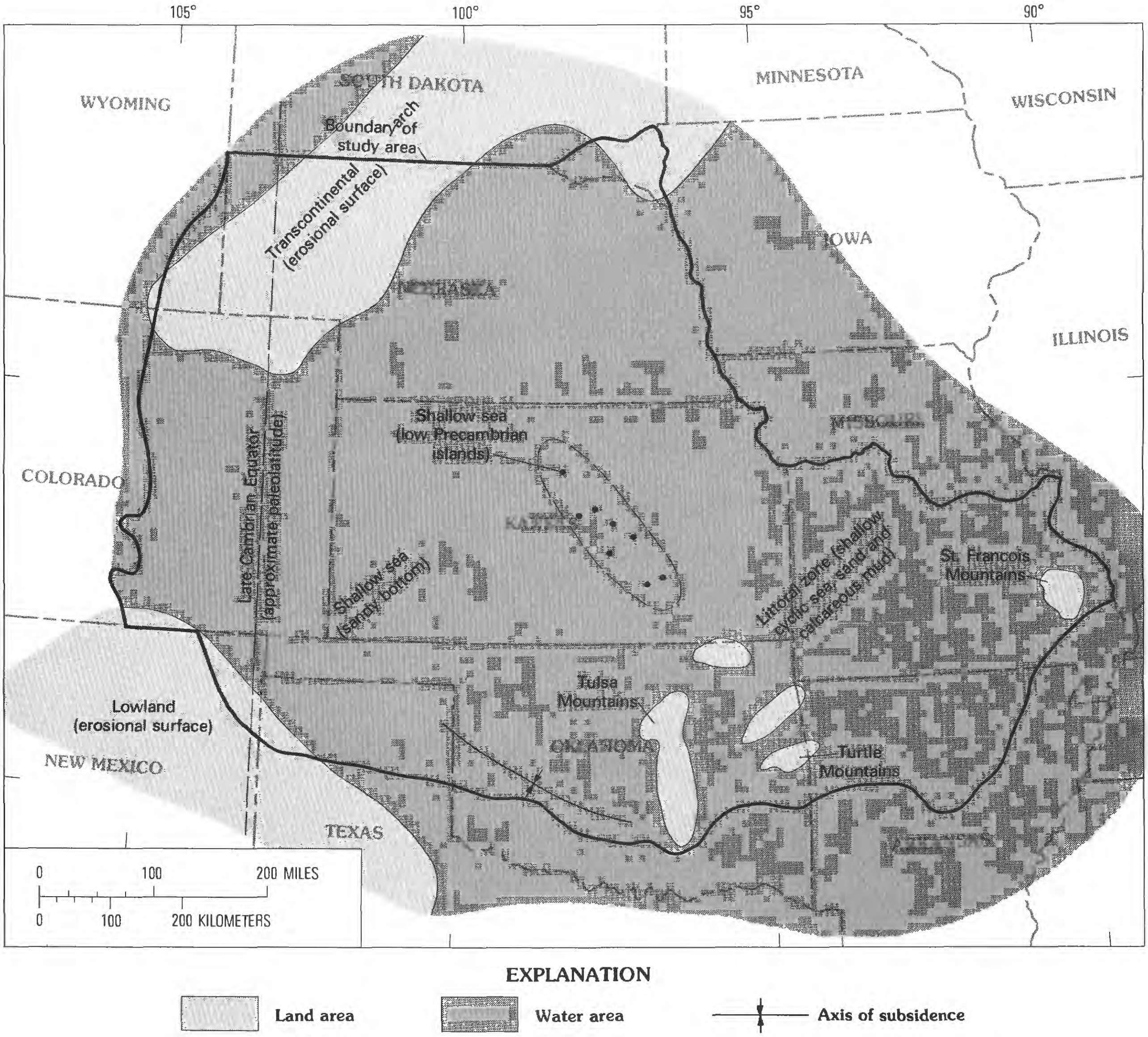


Figure D7. Late Cambrian geography of the study area, Central United States.

limestone was dolomitized near coastlines. Erosion removed sediments and decreased stress, which resulted in extensional fracturing that created paths for dissolution of carbonate and other rock material, especially by near-surface ground water of meteoric origin. Most processes increased porosity and permeability.

During the Silurian and Devonian Periods, nearly the entire study area, except for southern Oklahoma, northern Arkansas, and the present Salina basin in central Kansas, was uplifted (figs. D11, D12) and uplift diagenesis predominated. The exposed rocks on the extensive warm, wet lowlands were severely eroded. The removal of large quantities of pre-Silurian rock resulted in unloading, extensional fracturing, and other types of uplift diagenesis. Regional-flow systems of ground water of meteoric origin developed and flushed the existing formational water from the Cambrian and Ordovician rocks in and adjacent to the extensive land areas. Near-surface dissolution of carbonate material greatly increased the permeability of the exposed rocks.

At the end of Devonian time or possibly during very early Mississippian time, the warm equatorial transgressing sea is believed to have completely submerged the area, except for parts of Colorado and Wyoming (fig. D13). The land subsided and was tilted regionally as the remnant ocean off Laurussia (Laurasia of Bambach and others, 1980) was being thrust below Gondwana. Sands were deposited near the shore, and extensive clay was deposited offshore in the euxinic sea. This extensive and only slightly permeable clay restricted fluid flow from the underlying carbonate rocks to the overlying sediments.

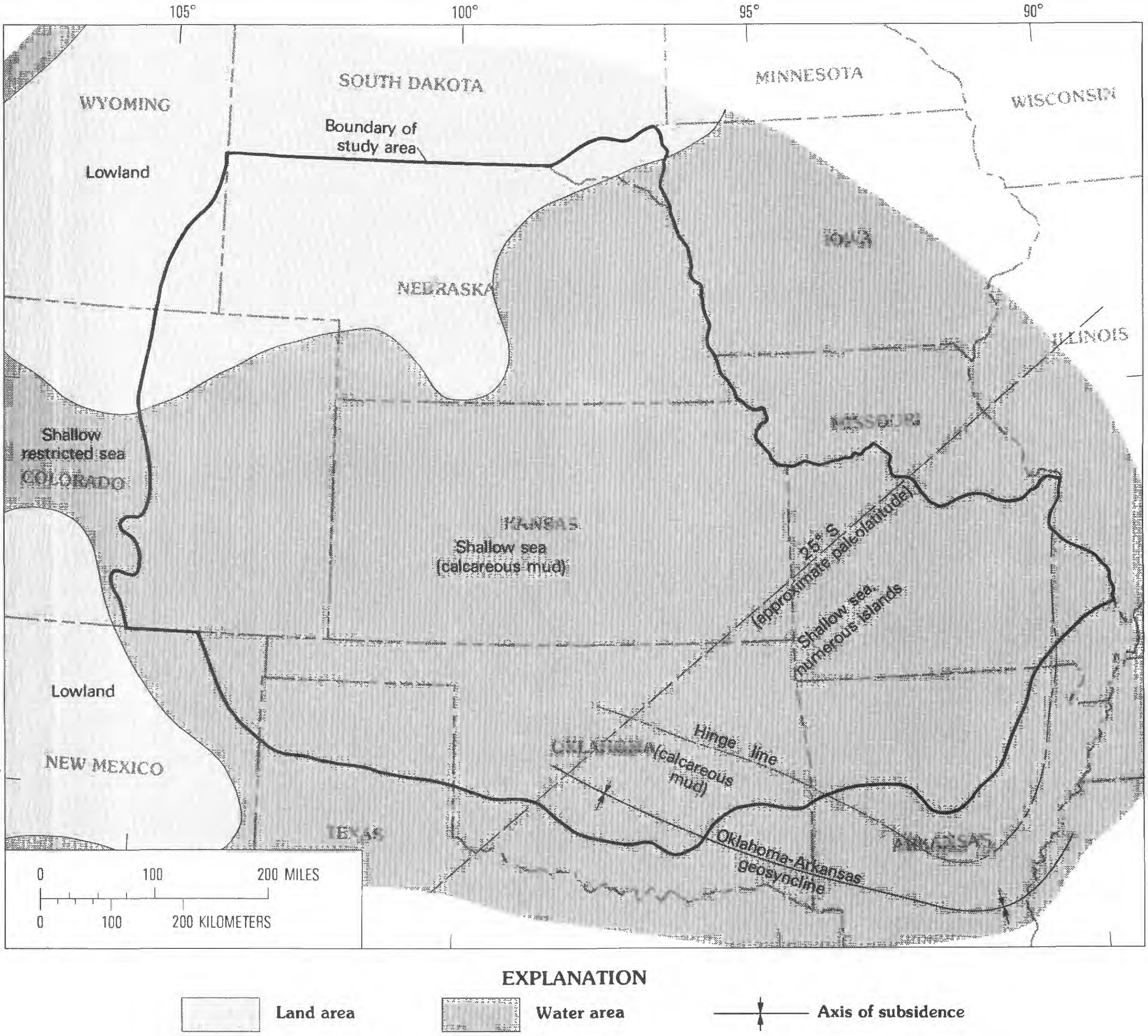


Figure D8. Early Ordovician geography of the study area, Central United States.

The most important characteristic of the Mississippian Period was the active tectonism that initiated the large structural features that were to affect geology and hydrology. These features include the Colorado-Wyoming uplift, the Anadarko basin, the Nemaha uplift (ridge), and the Arkoma basin (Ouachita trough) (fig. D13). Calcareous sediments were deposited in the shallow equatorial seas over the clay until Late Mississippian time.

Generally, Late Mississippian time was characterized by a cyclic, but recessive, sea; by the end of the Mississippian, only the deepest parts of the Anadarko basin were submerged (fig. D14). Burial diagenesis, including thermal alteration of organic material, continued in the deeply buried rocks in the geologic basins. This resulted in the generation of water, carbon dioxide, and hydrocarbons. The low pH of the water caused the selective dissolution of calcareous material and resulted in the selective increase in porosity and permeability. Elsewhere, lithification, erosion, fracturing, and dissolution occurred. Karst topography in a fresh ground-water system developed on the calcareous sediments and rocks in Colorado and the Ozark Mountains.

The Pennsylvanian climate was wet and warm because the area was astride the Equator. The Pennsylvanian sea was cyclic, but generally advancing, and by early Middle Pennsylvanian time had covered the Ozark Mountains. During Pennsylvanian time large compressive stresses continued to develop, primarily north to south, as the Laurussia and Gondwana plates continued to collide. These stresses were relieved by downwarping, faulting, and folding. The east-central part of the study area remained stable at or above sea

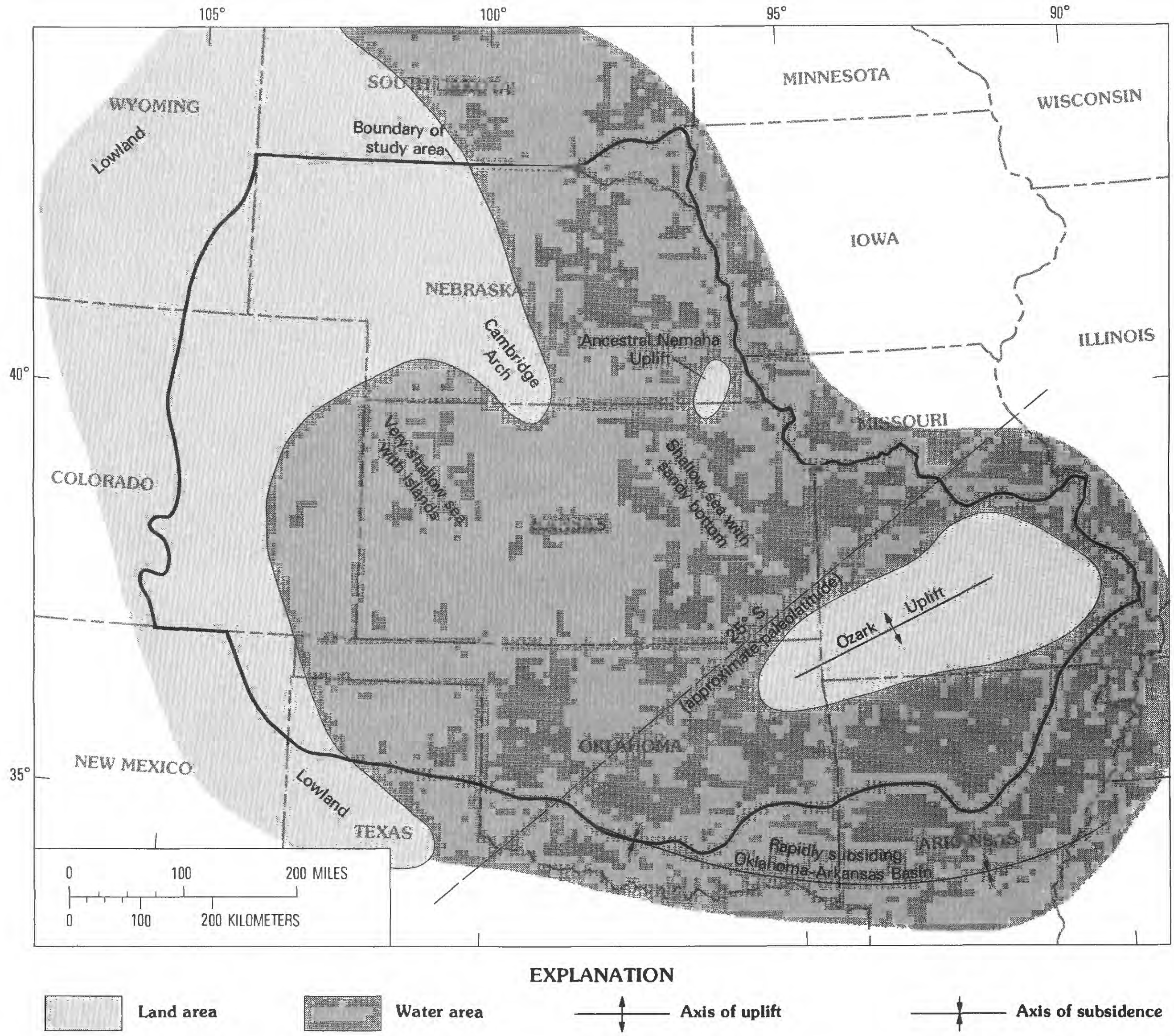


Figure D9. Middle Ordovician geography of the study area, Central United States.

level, and most uplifts were in a wide arcuate belt along the western and southern boundaries of the study area. Uplifts included the Front Range, Apishapa, Sierra Grande, Amarillo, Wichita, Criner, Arbuckle, Ouachita, Ozark, Nemaha, and Cambridge–Central Kansas (figs. D15, D16). Subsidence was mostly in the Ouachita trough (Arkoma basin) and in the Anadarko basin adjacent to the zone of faulting contiguous to the Amarillo, Wichita, and Arbuckle uplifts. The Arkoma basin is a foreland basin, the ancillary Anadarko basin is similar to a foreland basin, and the Ouachita uplift is an orogenic belt associated with the Arkoma basin subduction complex. Volcanism is not known to be associated with either the Arkoma or the Anadarko basins. Modern prototypes of foreland basins have normal geothermal gradients. The geothermal gradient of a modern subduction complex not associated with volcanism, such as a volcanic arc, is assumed to be greater than average.

Most Pennsylvanian sediments deposited in the cyclic sea were clay, sand, and calcareous mud. In the eastern part of the area, a large volume of organic material accumulated, especially during Middle Pennsylvanian time. Rapid deposition of clay and sand in the Anadarko basin is likely to have trapped water with the sediments, thus creating the geopressure zone in the Early Pennsylvanian (Morrowan) sediments (Breeze, 1970). Further rapid burial accompanied by an increase in temperature may have caused thermal pressuring of the trapped water. Similar material in the Arkoma basin also was deposited rapidly; however, no evidence of an extensive geopressure zone is known. Pre-Pennsylvanian rocks were buried to depths of about 20,000 ft in the

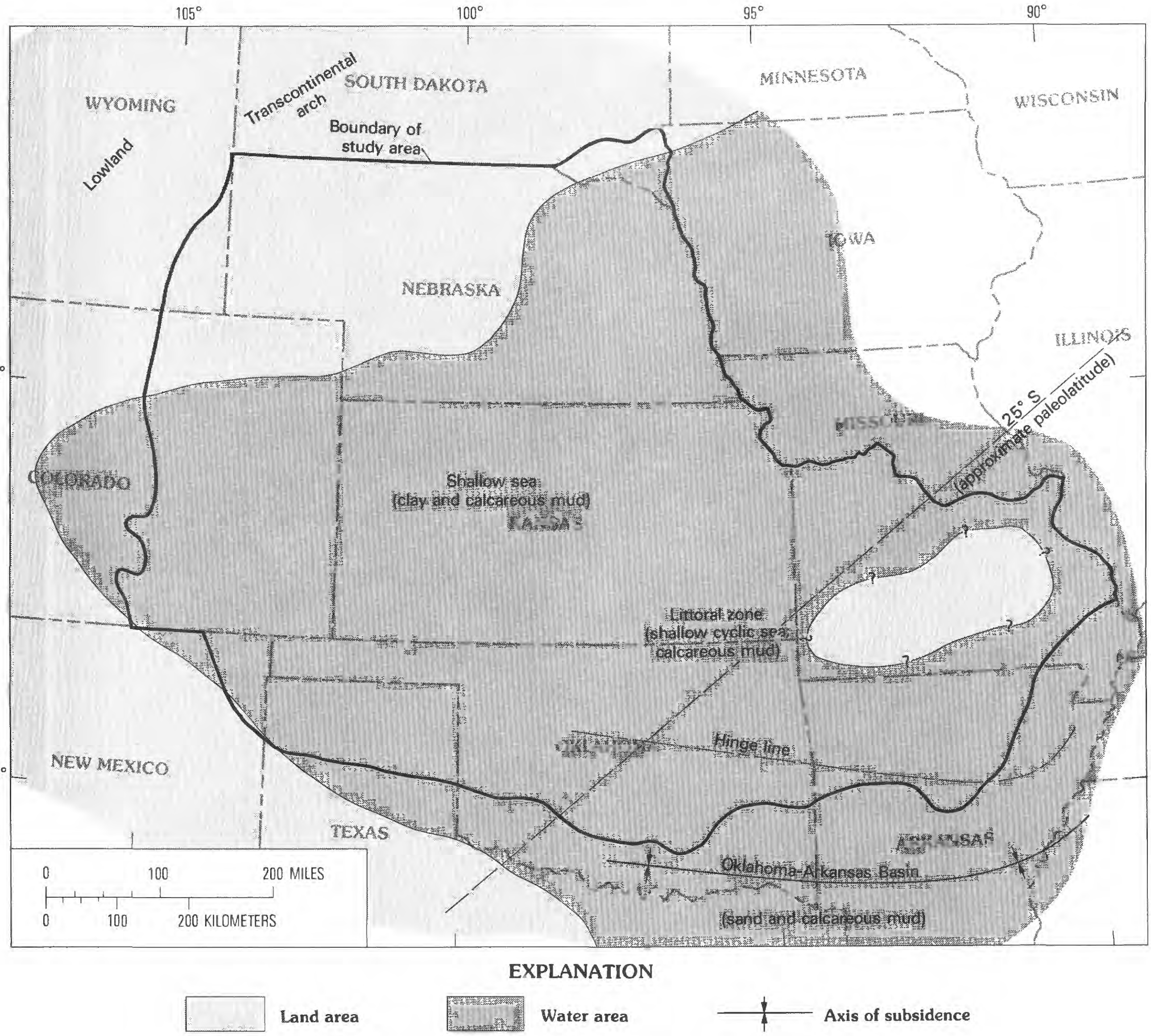


Figure D10. Late Ordovician geography of the study area, Central United States.

Anadarko and Arkoma basins. Thermal diagenesis in the deeply buried rocks would have been rapid and nearly complete. The deep burial reduced primary porosity but would have increased secondary porosity and permeability in selected strata. Adjacent to the Front Range, the Amarillo, and the Wichita uplifts, permeable arkosic sediment was deposited in a band a few tens of miles in width. Fresh ground water from the adjacent uplifts moved through the arkose deposits but probably not into the deep basinal deposits. By the end of the Pennsylvanian, the Ouachita uplift had raised the entire Ozark-Ouachita area above sea level.

During earliest Permian time, the Ouachita uplift was at a higher elevation than the Ozark uplift. Thus, there was potential for water moving from the Ouachita uplift to discharge areas in the Ozark uplift. However, this flow was unlikely because the rocks in the Arkoma basin were deeply buried beneath thick shale layers; consequently, permeability would have been very slight.

The Permian Period was a time of reduced tectonic activity compared to the Pennsylvanian. The Early Permian sea, like the Late Pennsylvanian sea, was cyclic. During the Early Permian (Leonardian time and earlier), regional tilting upward to the east, which was associated with the Ouachita and Appalachian orogenies, closed the seaway across the Ozark Mountains (fig. D17). These mountains between Laurussia and Gondwana were high enough to disrupt the subtropic easterly winds and to create an intense rain shadow that caused a dry, hot climate on the Laurussia side (Central United States) and a wet climate on the Gondwana side (Eastern United States) (Bambach and others, 1980). The

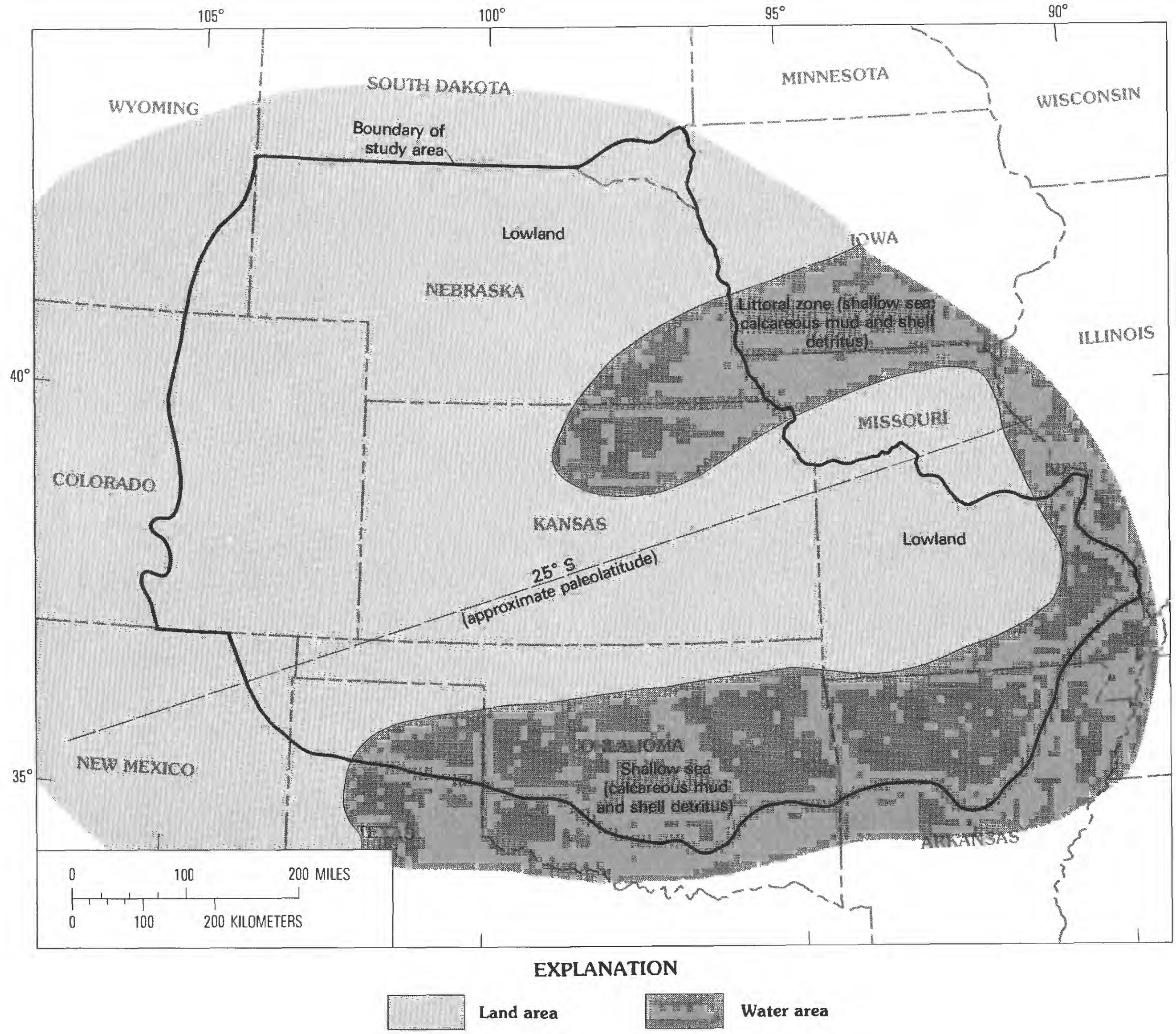


Figure D11. Early Silurian geography of the study area, Central United States.

closing of the seaway restricted circulation and resulted in extensive evaporite precipitation over nearly the entire Central United States (fig. D17). In addition to the regional tilting, uplift of the Ozark area continued. Tensional stresses associated with uplift and later with extension caused by the erosional unloading resulted in major fracturing of the pre-Pennsylvanian carbonate rocks. The Ouachita Mountains were rapidly eroding or subsiding, and by the end of Early Permian time little relief remained.

The widespread erosion of the Ouachita uplift and uplifted rocks over the Arkoma basin may have resulted in extensive fracturing. However, it is more likely that the rapid burial of the water-saturated rocks and the accompanying increase in temperature resulted in thermal pressuring of the water and hydrofracturing. The fractures may have been avenues that allowed the upward escape of the connate water that had been heated by either its deep burial or a heat source. The hot fluids escaping upward may have caused thermal diagenesis of the overlying organic material of Pennsylvanian age. This would also explain the paleogeothermal gradient indicated by a decrease in the rank of the Pennsylvanian coals away from the Ouachita uplift. If this were the case, then it also would explain the absence of extensive geopressure areas in the Arkoma basin. The Anadarko basin has an extensive geopressure zone preserved in the absence of extensive fractures.

Tectonic activity in Colorado continued from the Pennsylvanian into the Permian. Arkosic sediments continued to be deposited along the Front Range, Apishapa, and Sierra Grande uplifts. In Oklahoma, the Anadarko basin continued

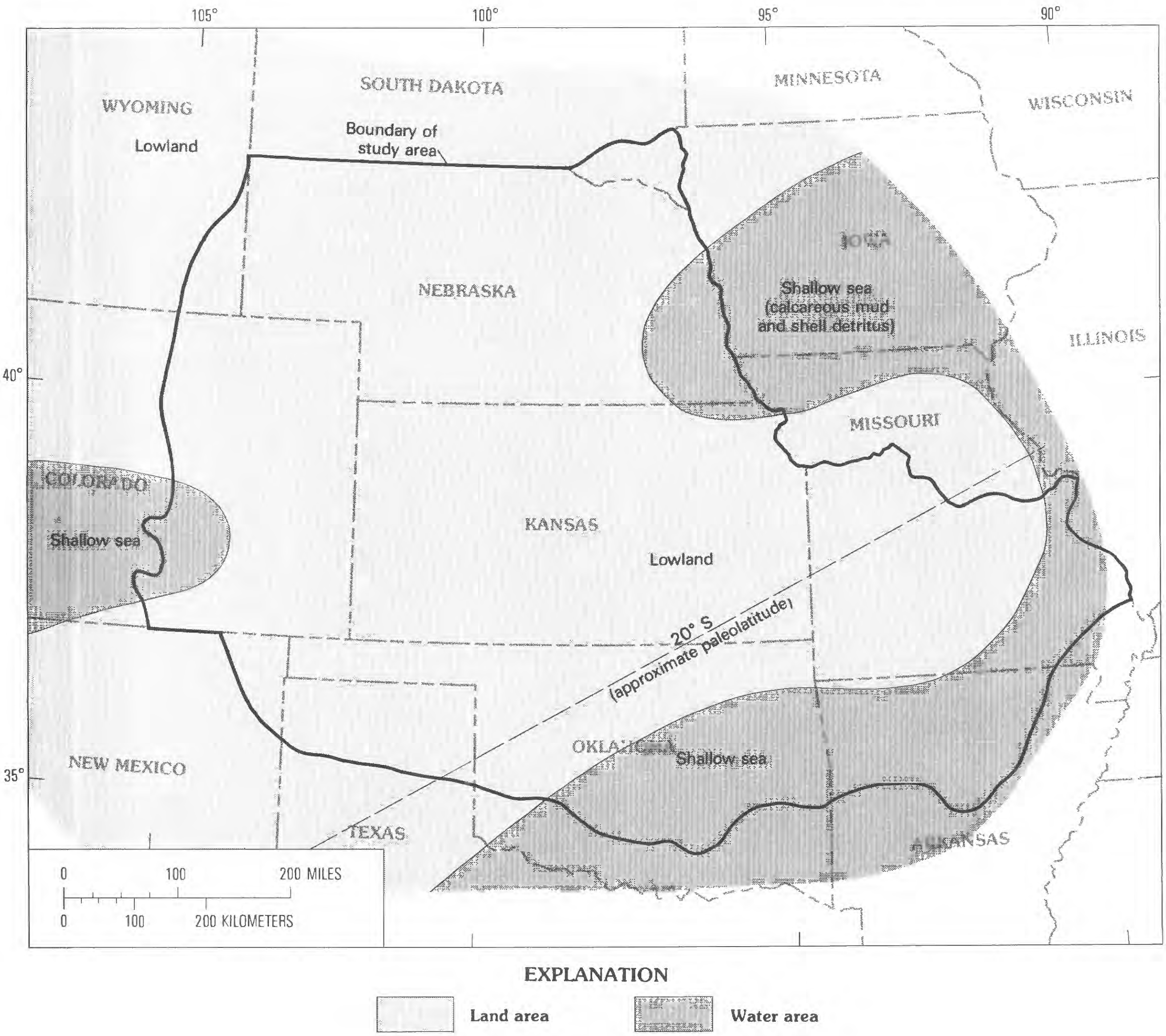


Figure D12. Early Devonian geography of the study area, Central United States.

to subside and the Wichita uplift continued; detritus from the Wichita uplift was the predominant source of sediment.

The sea retreated to the west during Late Permian time as the study area continued to be tilted upward to the east. At the end of the Permian, more than 20,000 ft of Pennsylvanian-Permian sediments, which were mostly shale, sandstone, limestone, and evaporites, had been deposited in the Anadarko basin. The sandstone layers are relatively permeable in comparison to the evaporite layers and shale. The limestone layers are relatively permeable at depths of less than 5,000 ft, but at depths of greater than 10,000 ft limestone is ductile and permeability is greatly reduced. The shale and evaporite layers restricted flow to and from the subjacent pre-Pennsylvanian rocks. It is not known if the Pascola arch, a post-Early Permian uplift in southeastern Missouri and northwestern Tennessee (Bethke, 1986), was associated with the Permian regional tilting in the Ozark area or was possibly a Mississippian-Pennsylvanian foreland arch. At the end of the Permian, Pennsylvanian rocks around the St. Francois Mountains in the Ozark area were being eroded. As the Pennsylvanian shale and other rocks were removed from the higher altitudes, a regional ground-water flow system developed in the highly fractured and permeable rocks of Cambrian and Ordovician age. The extent of the Ozark flow system was controlled by topography and by the extent of the overlying confining shale layers.

Mesozoic Time

Sediments were deposited during the Early Triassic only in northeastern Colorado and western Nebraska. Red clay,

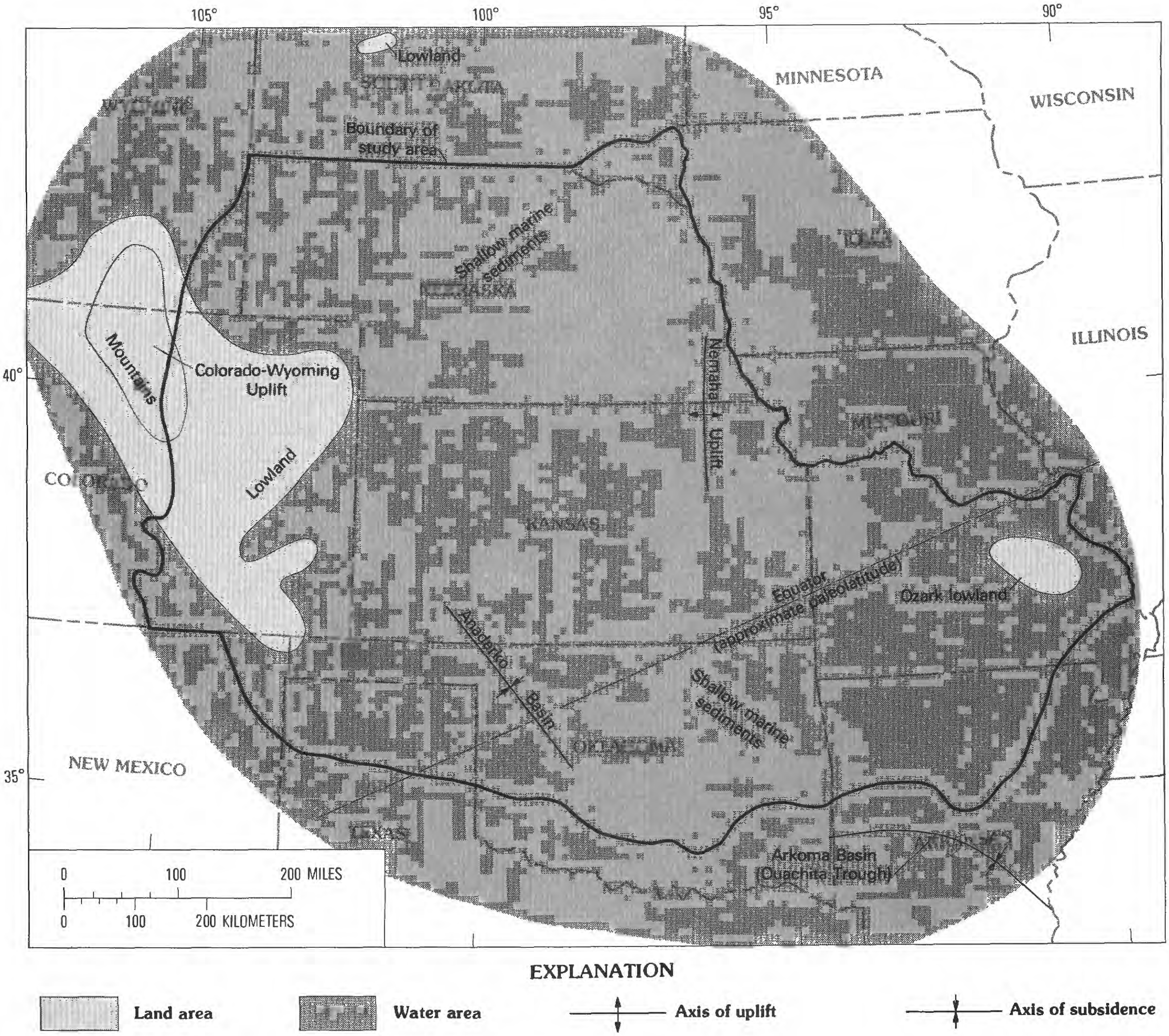


Figure D13. Early Mississippian geography of the study area, Central United States.

calcareous mud, and dolomite were deposited in a sea that had restricted circulation. As during the Late Permian, the uplifts of central Colorado were being eroded rapidly, and the sediments were deposited in the freshwater lake in the Dockum basin (fig. D18). Stress probably changed from compressive to tensional during the Triassic as a precursor to the movement of the North American plate away from Pangaea. In general, during the Triassic land within the Central United States had little relief and was not a significant source of sediment. The continued removal of the slightly and very slightly permeable Pennsylvanian and Permian rocks on and along the Ozark Plateaus increased the extent of the Ozark flow system. The permeability of the exposed carbonate rocks increased mostly as the result of weathering and near-surface dissolution.

Most of the study area was above sea level during Jurassic time; however, a sea in which clay and sand were being deposited existed in the western part of the area. Subsidence along the present Mississippi embayment was such that the Jurassic sea encroached into the new lowland. It is not known if this subsidence was a product of the breakup of Pangaea. The Ozark flow system continued to expand as it had during the Triassic. At the end of the Jurassic and the beginning of the Cretaceous, nearly the entire study area was above sea level and was undergoing uplift diagenesis. This was ended by a rapid transgression of the Cretaceous sea from the north and the south. Moderately permeable fine-grained sand and intercalated clay were deposited on alluvial plains or in near-shore estuaries by the advancing sea. As the sea advanced, clay replaced sand as the predominant

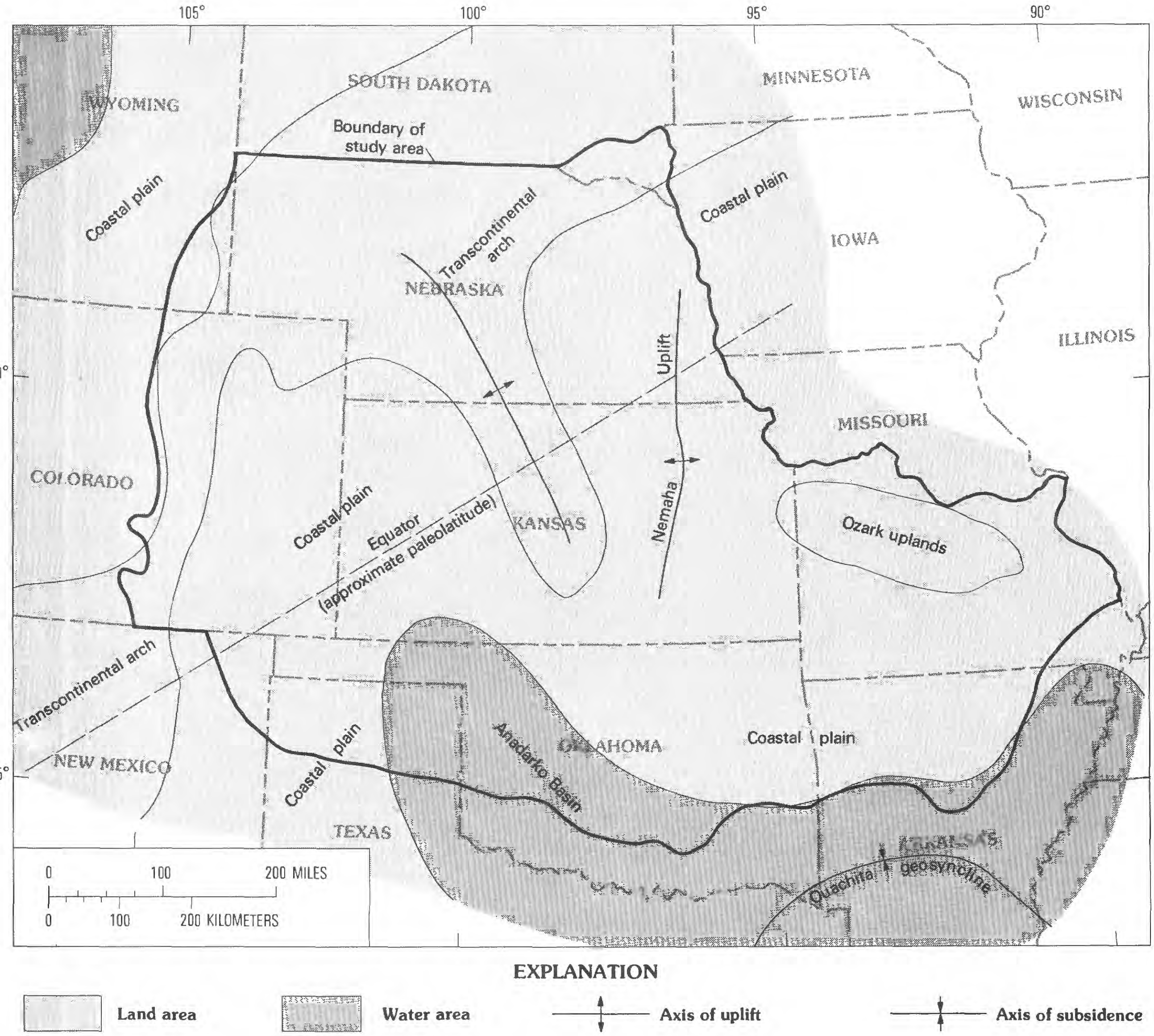


Figure D14. Late Mississippian geography of the study area, Central United States.

sediment. This relatively impermeable clay, which today forms the Kiowa Shale and equivalents, restricted vertical flow to the aquifer material below. Although the exact extent of the Kiowa sea is unknown, it likely covered the entire study area with the exception of part of the Siouxana arch and the Ozark Plateaus (fig. D19). Clay deposition was ended by a recession of the sea, which was, in part, the result of the regional uplift of the eastern part of the study area.

The erosional trend was terminated by a second sea advance that started during the Early Cretaceous. The transgressing sea resulted in deposition of the sand that is the parent material of the Dakota Sandstone. However, as the sea and, thus, the shore moved farther inland, clay replaced sand as the predominant sediment. The maximum extent of the sea is not known, except that it extended beyond the present Dakota Sandstone and may have covered most of the western part of the study area.

Near the end of the Cretaceous, many areas, such as the Front Range, were rapidly uplifted as part of the Laramide orogeny. This orogeny was caused by the north-northeast compression associated with the collision of the Farallon and North American plates. Back-arc basins formed to the east of the Rocky Mountains (a collision arc). Thermal gradients greater than 20 °C per 100 m in the Rocky Mountains would have been likely. Thermal gradients that exceeded 6 °C per 100 m were probable in the back-arc basins, such as the Denver basin. During most of the Late Cretaceous, clay was the predominant sediment. Maximum sedimentation, which ranged from 3,000 to 8,000 ft, was in the Denver basin. Back-arc basins typically have greater than normal

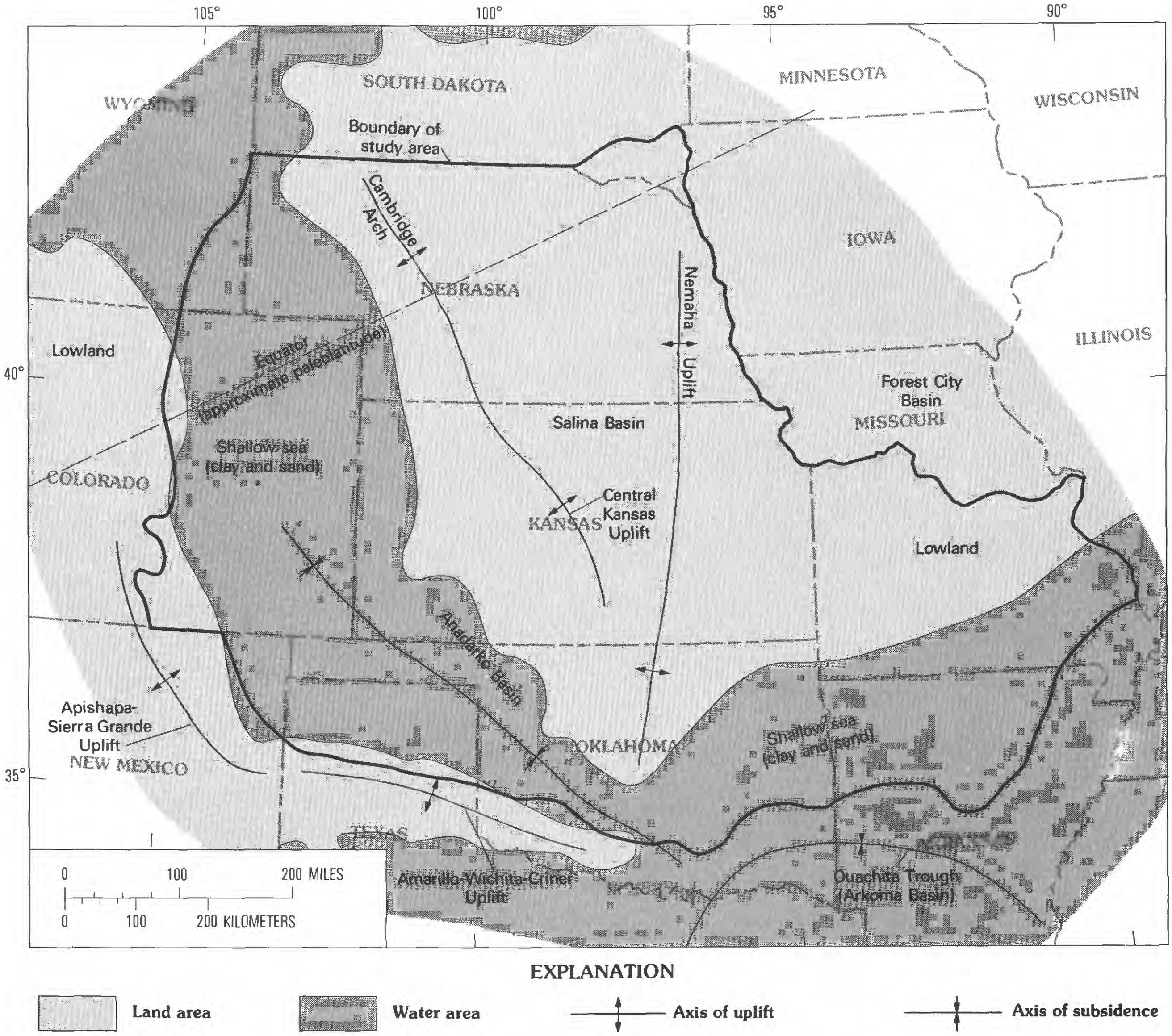


Figure D15. Early Pennsylvanian (Morrowan) geography of the study area, Central United States.

geothermal gradients (Rutherford and Quershi, 1981; Piggott, 1986). Burial diagenesis acted from the late Early Cretaceous through most of the Late Cretaceous. Compaction resulting from burial reduced primary porosity and permeability; however, thermal diagenesis may have selectively increased permeability locally in the buried Lower Cretaceous sandstone.

At the end of Cretaceous time, the sea receded northward as the western part of the area was tilted farther upward. Ground water started to flow from west to east in the Lower Cretaceous sandstone layers, except possibly in the deepest parts of the Denver basin, where only slight water movement could be expected. Similarly, water started to flow from west to east in the underlying Cambrian through Mississippian rocks, except in and adjacent to the geopressure zone in the Anadarko basin.

Cenozoic Time

The Laramide orogeny continued into Tertiary time as evidenced by mountain building in central Colorado and Wyoming. Extensive erosion of the uplifts resulted in deposition of widespread, thick permeable alluvial material (parent material of the Ogallala Formation) on the plains. The deposition further enhanced burial diagenesis in the Denver basin and the western part of the study area. With time, the Laramide mountain building ended, and the erosion of alluvial material in the plains commenced as the stress changed from compression to tension in the study area. The thickness of Tertiary material removed probably exceeded 2,000 ft. The present water-bearing Ogallala Formation (fig. D20) is an erosional remnant of the much more extensive deposit. Presently, the thickness of the Ogallala ranges from nearly

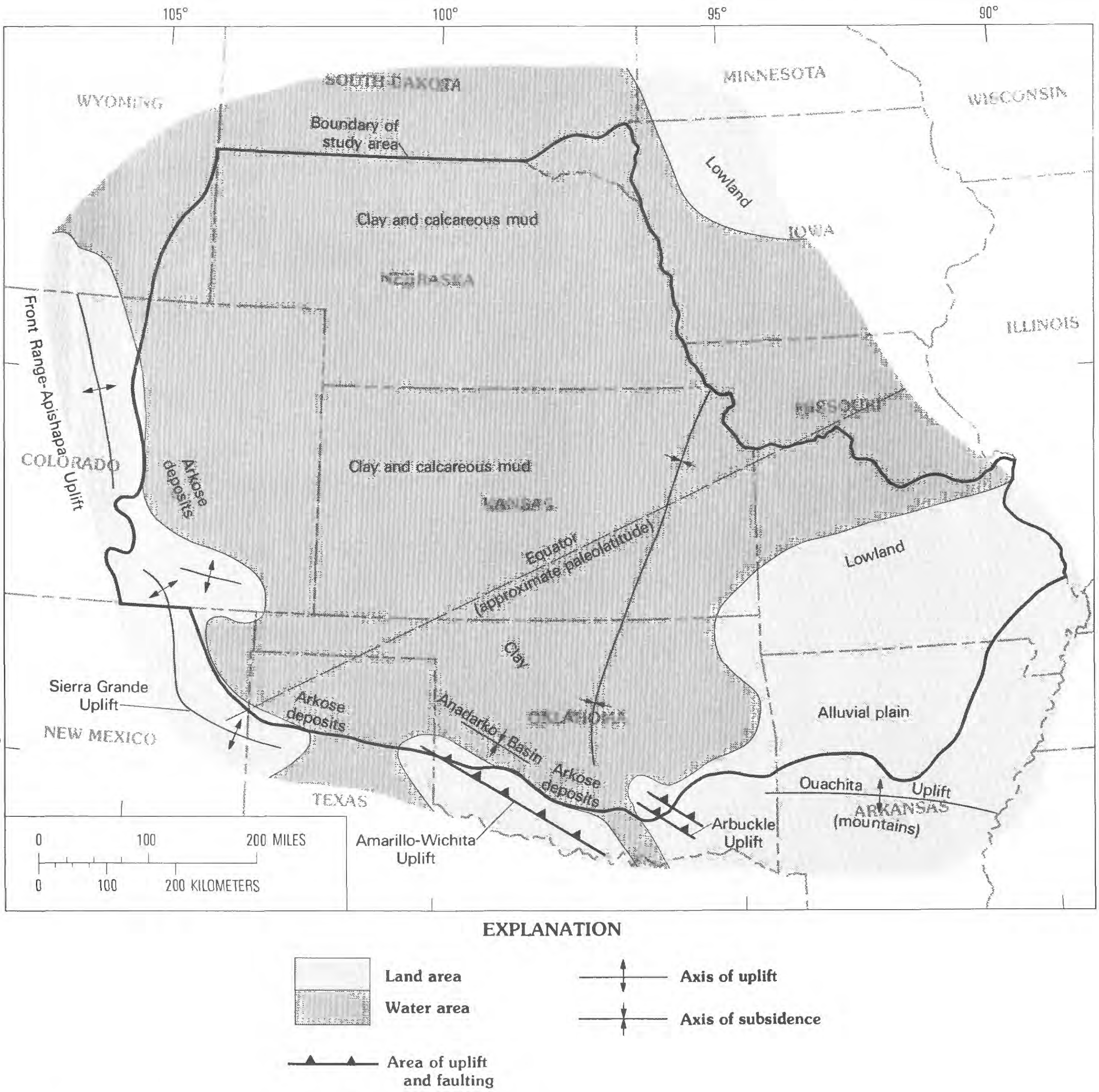


Figure D16. Late Pennsylvanian geography of the study area, Central United States

0 to 1,000 ft; a 100- to 200-ft thickness is typical. The Ogallala Formation is immediately underlain by Cretaceous and older rocks, except in west-central Nebraska, where the Ogallala overlies older undifferentiated Tertiary material (Weeks and Gutentag, 1981).

The unloading caused by the erosion of more than 2,000 ft of Cenozoic sediments over the Denver and Anadarko basins resulted in expansion of the rock mass and reduction 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 (underpressured). Removal of sediments in the Anadarko basin also reduced pore pressure, which resulted in underpressuring over the flanks of the basin and a reduction of geopressure in the geopressure zone. The rate of generation of carbon dioxide from thermal alteration of organic material was reduced.

In the eastern part of the study area, erosion continued to remove Pennsylvanian and Permian rocks from the Ozark area. This removal further extended the Ozark flow system, which was developing outward from the St. Francois Mountains.

At the end of Tertiary time, the sea retreated north to the Williston basin in North Dakota and south to the Ouachita

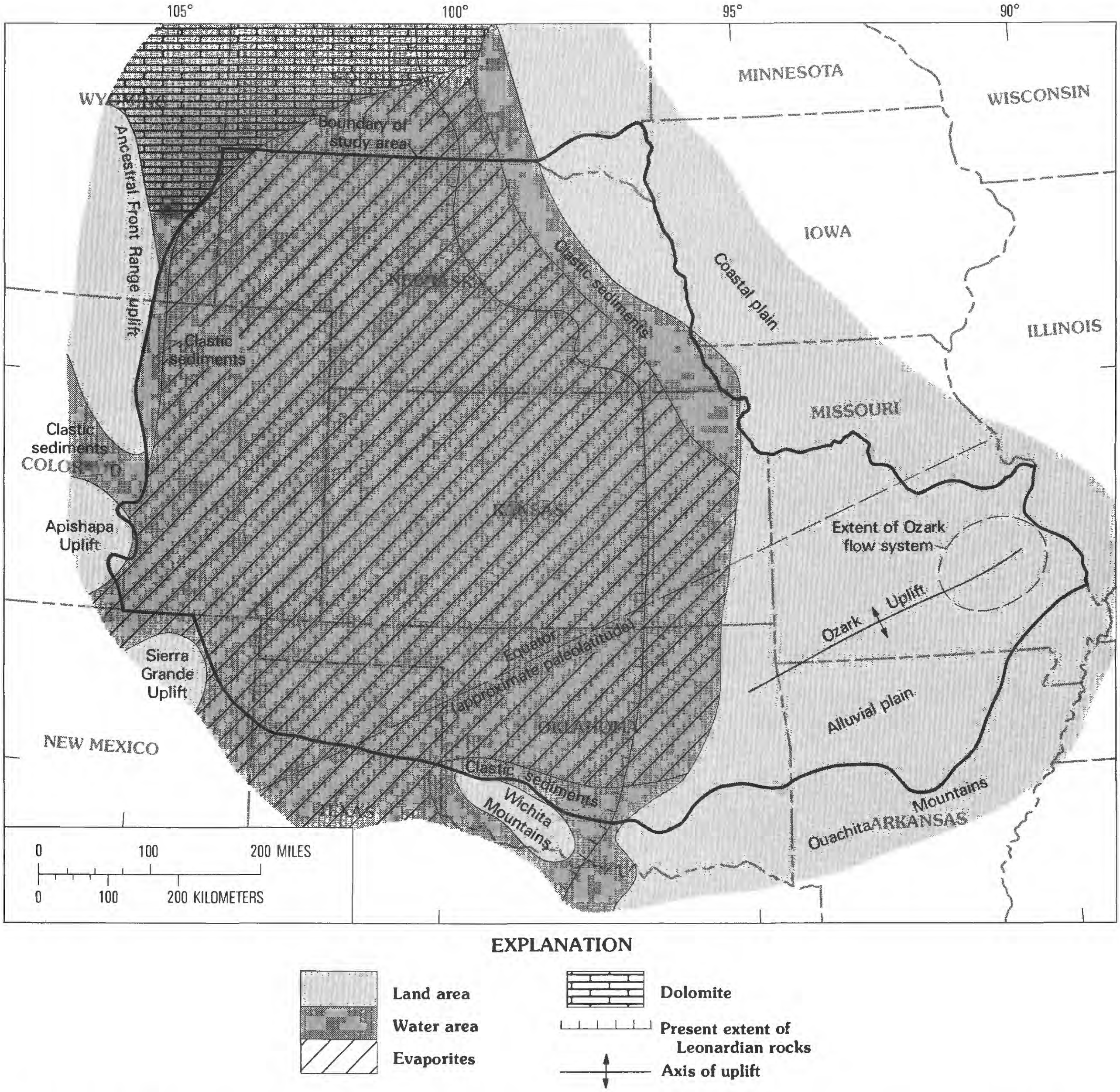


Figure D17. Early Permian geography of the study area, Central United States (modified from McKee and Oriel, 1967).

fold belt 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. Drainage patterns similar to those of the present were established, and organic material was abundant.

The Quaternary Period has been marked by episodes of extensive glaciation that alternated with much warmer interglacial periods. Although glaciation directly affected only the northeastern edge of the study area (fig. D20), the climatic changes affected the entire study area. The advance and retreat of the glaciers were accompanied by lowering and raising of sea level. The change in sea level directly affected the near-surface water levels in rocks and the base level of erosion, altering pore pressure in the subsurface. The glaciers also altered the regional topography and, in turn, the direction of ground-water flow. The cyclic loading and unloading by the ice affected the distribution of stresses and probably caused some additional fracturing of competent rocks. The unglaciated part of the study area underwent erosion and associated diagenetic changes.

PRESENT-DAY REGIONAL HYDROLOGY

Present-day regional aquifer systems (fig. D21) in the Central United States are the Ozark Plateaus, the Western

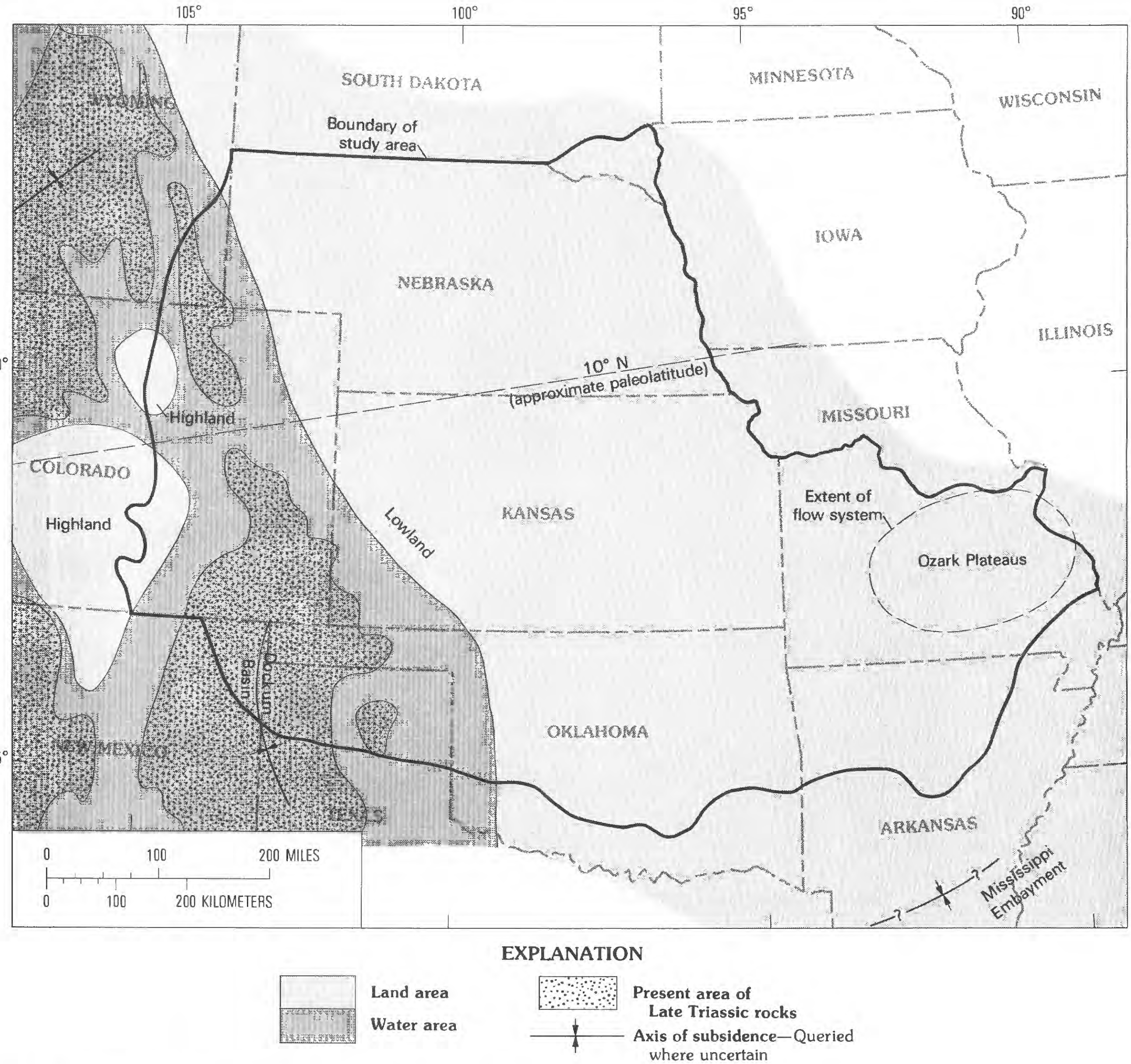


Figure D18. Late Triassic geography (maximum sea) of the study area, Central United States.

Interior Plains, and the Great Plains. The High Plains aquifer, which consists largely of the Ogallala Formation (fig. D20), a regional aquifer, also is present in the study area.

The Ozark Plateaus aquifer system (fig. D22) consists of the Ozark, St. Francois, and Springfield Plateau aquifers. In general, ground water in the Ozark Plateaus flows outward from the areas having a higher water-table, which are associated with high land, toward the Missouri River, the Mississippi River, the Mississippi embayment, and the broad lowland, which is approximately coincidental with the Central Lowland (figs. D1, D23, D24). The aquifer system is composed mostly of water-bearing dolostone, limestone, and sandstone of Cambrian and Ordovician age. Because the area has undergone several episodes of uplift and has been above sea level nearly continuously since Ordovician time, except for a small part of Pennsylvanian time, the rocks are well fractured and solutioned and have well-developed anisotropic permeability. The eastern extent of the flow system is controlled partly by the extent of the beds of Pennsylvanian shale and limestone that form a confining system (fig. D24), and the western extent of the Ozark Plateaus aquifer system is approximated by the extent of the water that contains less than 1,000 mg/L of dissolved solids as is shown by the preliminary interpretation in figure D25. The data shown in figures D23–D25 indicate the presence of a transition zone where water from the Ozark Plateaus aquifer system meets saline water of the Western Interior Plains aquifer system. The transition zone

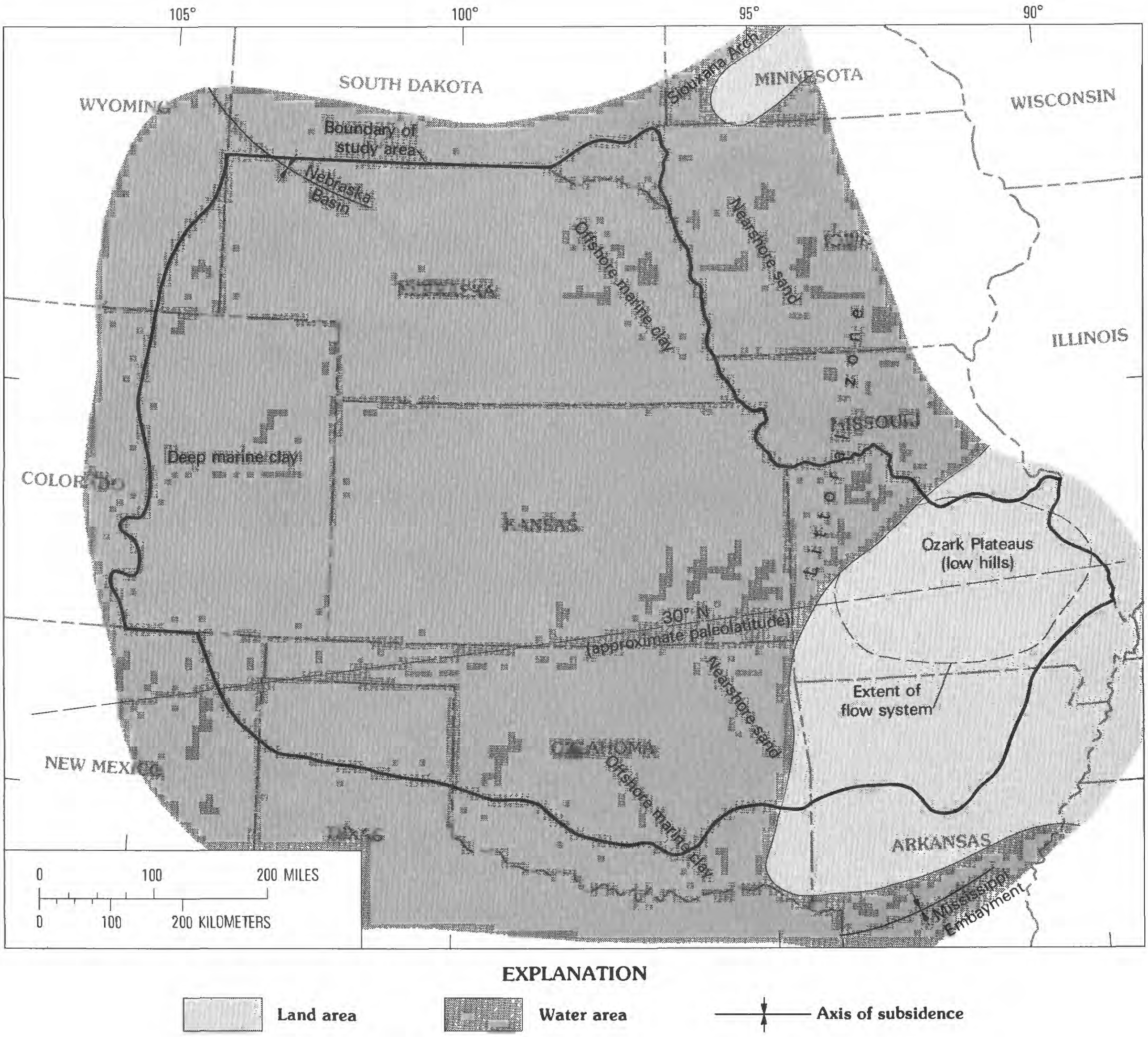


Figure D19. Early Cretaceous geography (maximum sea) of the study area, Central United States.

is a diffused saltwater-freshwater interface and forms a hydraulic boundary to lateral flow, thus separating the two flow systems.

The Western Interior Plains aquifer system, which is similar to the Ozark Plateaus aquifer system, also includes Cambrian-Mississippian dolostone, limestone, and sandstone. Flow in the aquifer system is mostly, but not entirely, topographically controlled. In general, flow is southeast from Nebraska towards the transition zone in west-central Missouri and from the west across Colorado and Kansas towards the transition zone in southeastern Kansas and northeastern Oklahoma. In the Anadarko basin, a trivial amount of water flows outward from the geopressure zone in the overlying Early Pennsylvanian sandstone and shale (see the 3,000-ft contour in northern Texas and western Oklahoma, fig. D23). The presence of the geopressure is proof of the very slight permeability of the deeply buried rocks in the Anadarko basin. The Western Interior Plains aquifer system contains saline water and brines; in several areas concentrations of dissolved solids exceed 200,000 mg/L (fig. D25).

Permeability data for the Western Interior Plains aquifer system are scarce because no information from water wells is available. The only available data are from drill-stem tests that were conducted in oil and gas reservoirs. In general, these reservoirs have anomalous hydraulic characteristics in relation to regional aquifers. However, regional zones of relative permeability can be predicted from paleohydrologic considerations. Areas that have undergone only burial diagenesis probably have only very slight permeablity. Similarly, areas that have undergone extensive uplift diagenesis

Figure D20. Mountains of the Laramide orogeny, present extent of the Ogallala Formation, and extent of glaciation.

over long periods of time are relatively permeable to very permeable. Accordingly, the information shown in figures D6–D19 can be collated to make a map showing relative permeability for Cambrian and Ordovician rocks (fig. D26). Area 1 has the most permeable rocks because it has undergone nearly continuous uplift diagenesis since Ordovician time. Areas 2 and 3 have undergone considerable uplift diagenesis, especially during Mississippian time. Area 4 was uplifted during most of the Silurian and the Devonian. Area 5 is an area in which the rocks have never been exposed since deposition and, thus, have undergone virtually no uplift diagenesis. Area 6 is similar to area 5 except that rocks have undergone extreme burial diagenesis and have very slight permeability. Model analysis of the aquifer systems described as part of the study area indicates that the distribution of relative permeability shown in figure D26 is appropriate (Donald C. Signor, oral commun., 1988).

The brines within the Western Interior Plains aquifer system (fig. D25) are of unknown origin. They are not solely connate water because they are present in some areas that have been above sea level at certain times, such as during the Devonian, and, thus, should have been flushed with fresh ground water. Other possible origins of the brines may have been a solution of dissolved evaporites, an evaporative brine, or a filtration brine. The present-day flow system (from west to east) has existed since the Laramide orogeny; thus, the

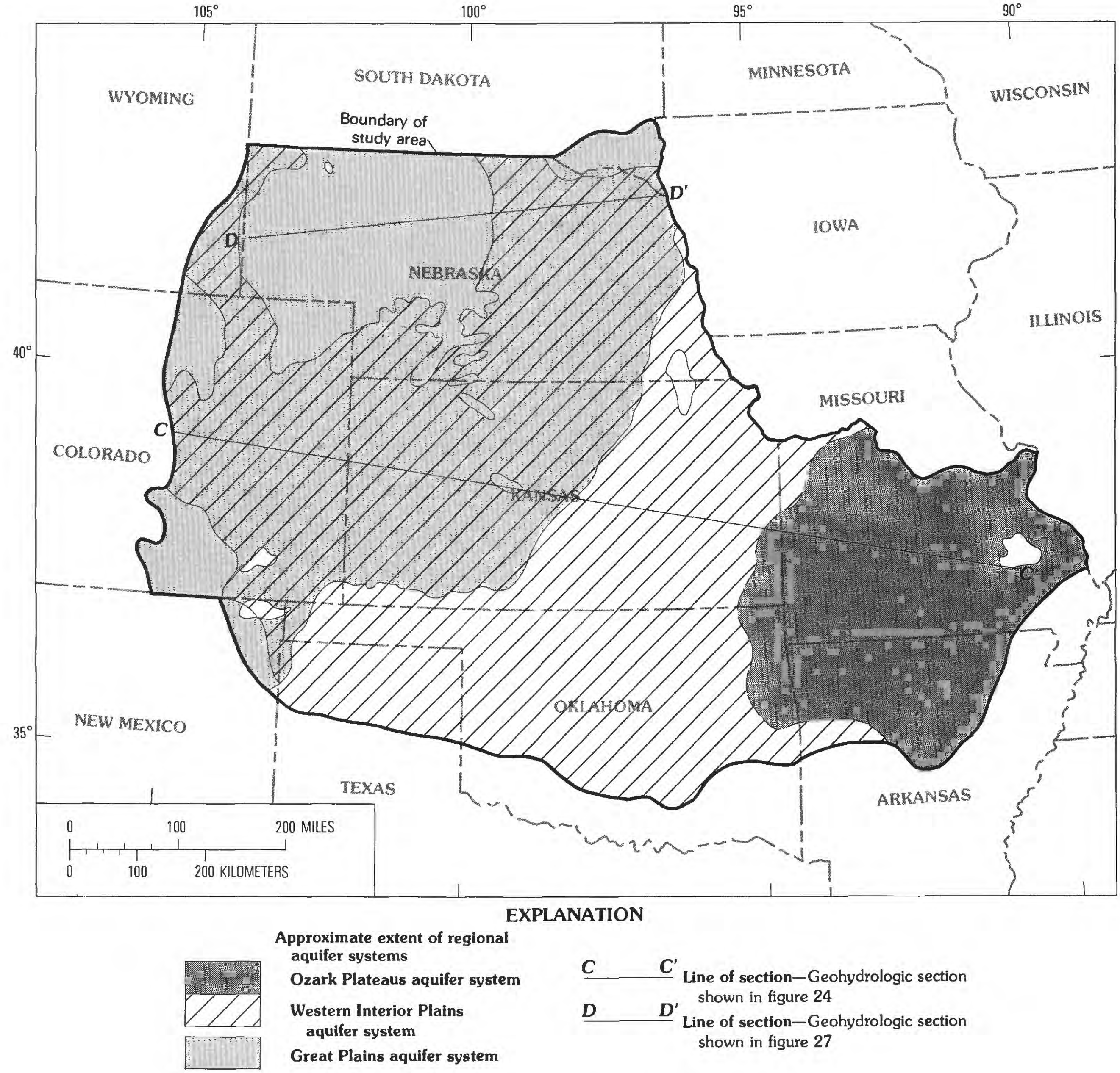


Figure D21. Present-day regional aquifer systems of the study area, Central United States.

brines are believed to be older than 65 million years. During post-Permian time and before the Laramide orogeny, the flow direction was probably from east to west.

The Great Plains aquifer system extends from northern Canada to New Mexico and is in and adjacent to the Great Plains (Helgesen and others, 1982; Leonard and others, 1983; Jorgensen and Signor, 1984). It consists predominantly of water-bearing Lower Cretaceous sandstone and, in the study area, contains two aquifers (fig. D27): The upper aquifer (the Maha) generally comprises the Newcastle and Dakota Sandstones and their equivalents; the lower aquifer (the Apishapa) generally consists of the Cheyenne Sandstone and its equivalents.

The paleohydrologic history of the Great Plains aquifer system is much simpler than that of the Western Interior Plains aquifer system. In general, burial diagenesis acted on the Lower Cretaceous sandstone units until after the Laramide orogeny began. Since the start of the Laramide orogeny at the end of the Cretaceous period the aquifer system has been in an uplifted area. However, in general, the aquifer system has not been exposed, except for nearby present-day outcrop areas. Therefore, the permeability

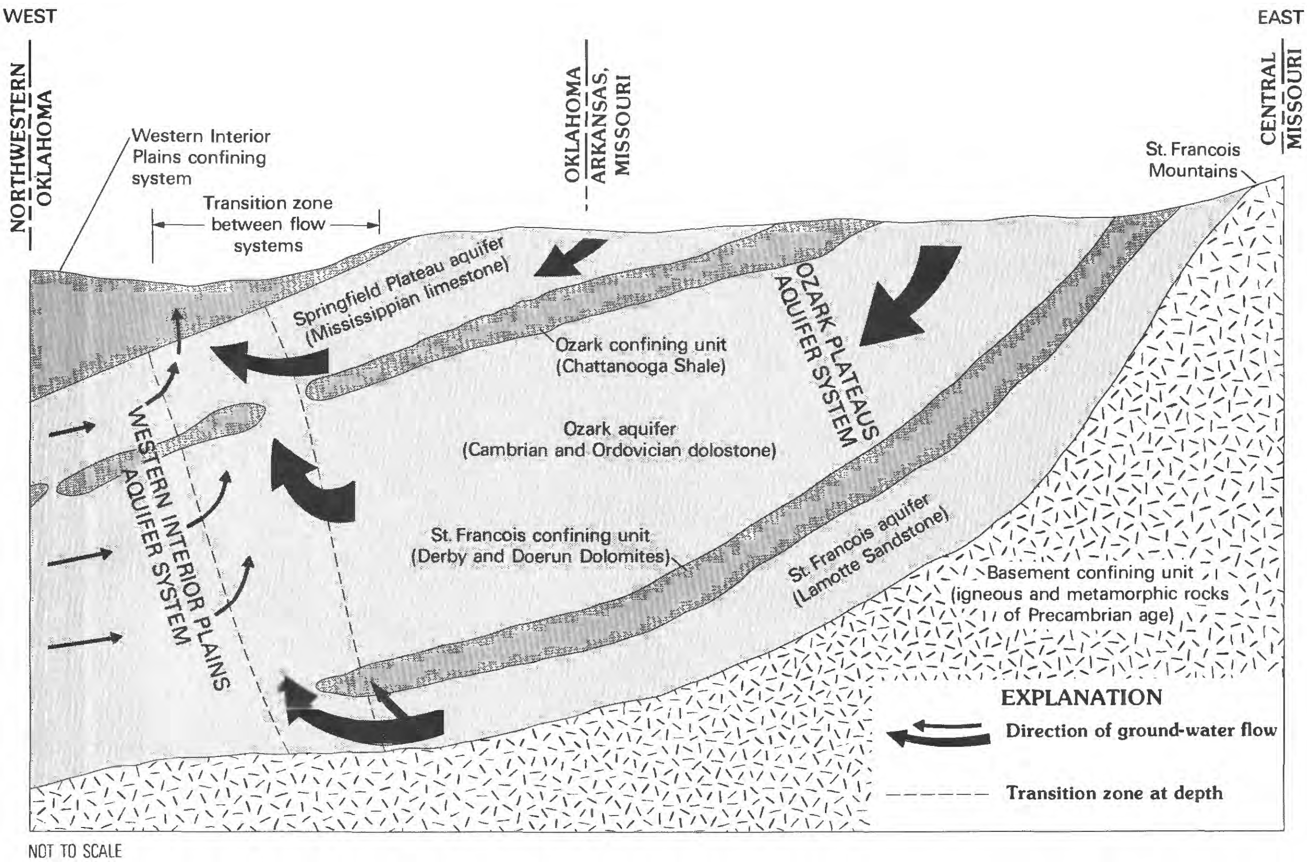


Figure D22. Major aquifers in the Ozark Plateaus, Central United States.

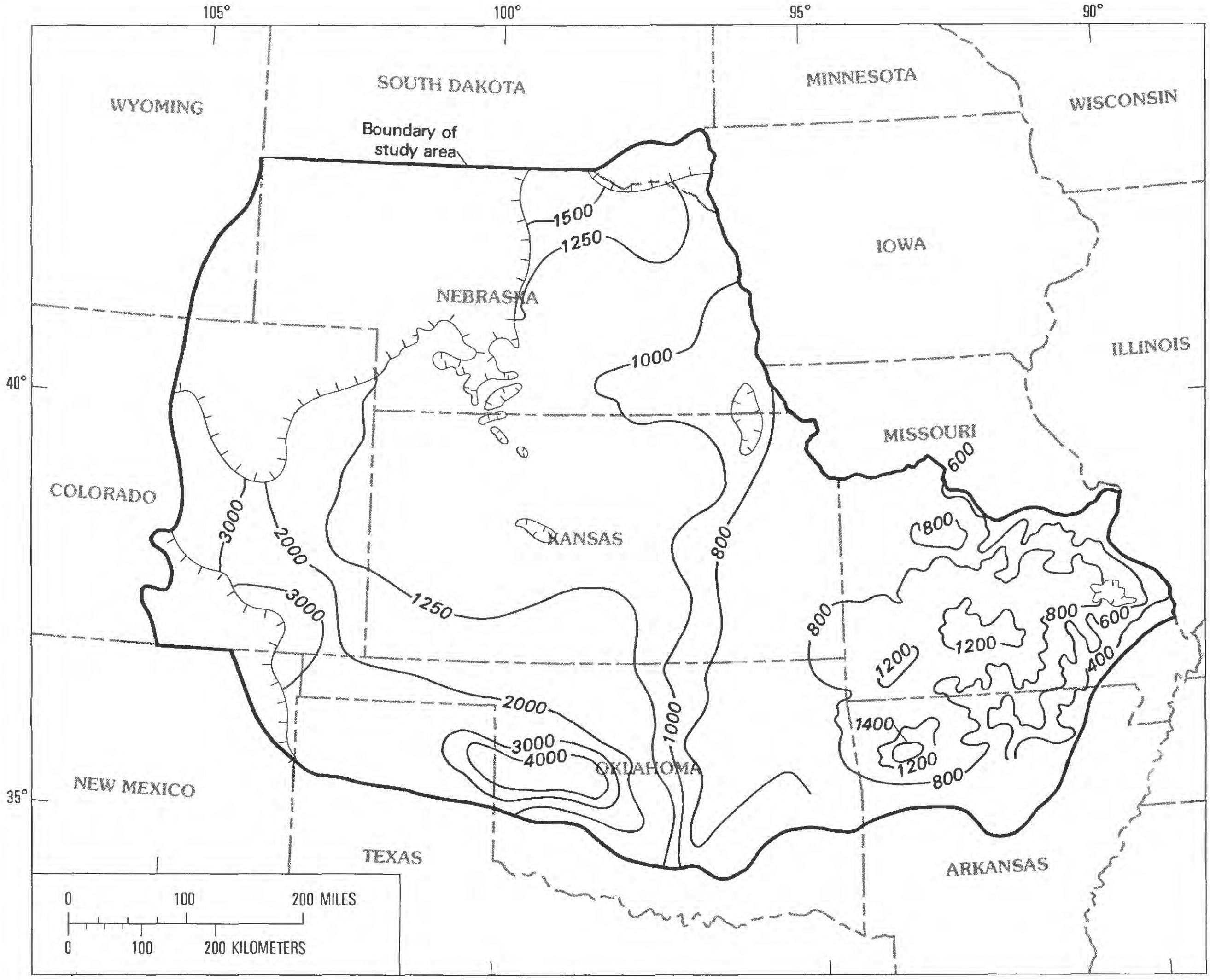
distribution in the aquifer system is mostly the result of earlier burial diagenesis. Consequently, permeability decreases rather uniformly with depth.

The High Plains aquifer extends from South Dakota to northern Texas. This surficial water-table aquifer is composed of slightly cemented sand and gravel of the contiguous Tertiary Ogallala Formation (fig. D20), unconsolidated alluvial deposits of Quaternary age in central and eastern Kansas (not shown), and some Pleistocene sediments in eastern Nebraska (Weeks and Gutentag, 1981). The aquifer is recharged by infiltrating precipitation. Natural discharge is to springs along streams that dissect the aquifer. The hydraulic properties are mostly genetic and have not been greatly altered by diagenesis.

EPIGENETIC MINERALIZATION AND HYDROCARBON ACCUMULATION

Epigenetic mineralization and accumulation of hydrocarbons generally are closely related to water movement. Paleohydrologic analysis is used to determine the likely source and occurrence of water, which is the most probable carrier for dissolved metals, dissolved organic material, and hydrocarbons. Moving water also is an effective mechanism for the transfer of heat; heat transfer by advection in water is much more rapid than heat transfer by conduction through the matrix of the rock.

Extensive Mississippi Valley–type mineral deposits (epigenetic) exist on the edge of the Ozark uplift (fig. D9). An excellent overview of mineralization in the Ozark Mountains is given by Leach and Rowen (1986). Of special interest are the minerals in the Tri-State area of southeastern Kansas, northeastern Oklahoma, and southwestern Missouri, as well as the deposits that are found mostly south of the axis of the uplift in northwestern Arkansas and southern Missouri, including the Viburnum trend. The exact age of these deposits is not known, but some dating techniques indicate they are very early Permian (Desborough and others, 1985). Different sources of the hot metal-bearing solutions—basinal fluids being squeezed out of the deep parts of the Arkoma and (or) the Anadarko basins or artesian (gravity flow) systems of water moving from a paleogeographic high, such as the Ouachita uplift—have been considered. In general, the mineral deposits are found in permeable or relatively permeable rocks of Cambrian through Pennsylvanian age. Whether the hot saline source water represents one episode or several is not known. It is generally believed that hot saline fluids migrated under pressure updip toward the axis of the Ozark uplift until an area of high permeability,



EXPLANATION

Extent of Cambrian and Ordovician rocks

—600— **Line of equivalent-freshwater head**—Shows approximate altitude of equivalent-freshwater head. Datum is sea level

Figure D23. Predevelopment equivalent freshwater head in Cambrian and Ordovician rocks in the study area, Central United States (modified from Jorgensen and others, 1986).

reduced temperature, and slight pressure was encountered, at which point mineral deposition occurred.

The source of the hot metal-bearing solution or solutions is not known. However, it is unlikely that the solution or solutions were part of an artesian system transmitting flow from the Ouachita uplift through the Arkoma basin to the Ozark uplift. The rocks below the Pennsylvanian strata in the center of the Arkoma basin had undergone nearly continuous burial diagenesis, were not permeable, and, therefore, did not readily transmit water laterally. Similarly, it is unlikely that the hot saline fluids were water squeezed laterally from the deeper part of the Anadarko basin. Sediments in the Anadarko basin, like those in the Arkoma basin, always had been undergoing burial diagenesis and, thus, were not permeable and did not transmit the fluids. The presence of the geopressure zone in Early Pennsylvanian (Morrowan) and all pre-Pennsylvanian rocks in the deeper part of the basin is evidence that significant quantities of fluids have not escaped.

Even though the source fluids were not transported laterally from the deeper parts of either the Arkoma or the Anadarko basin, the fluids, whatever their source, could have traveled updip along the flanks of these basins. By Late Pennsylvanian time, permeability had developed along the

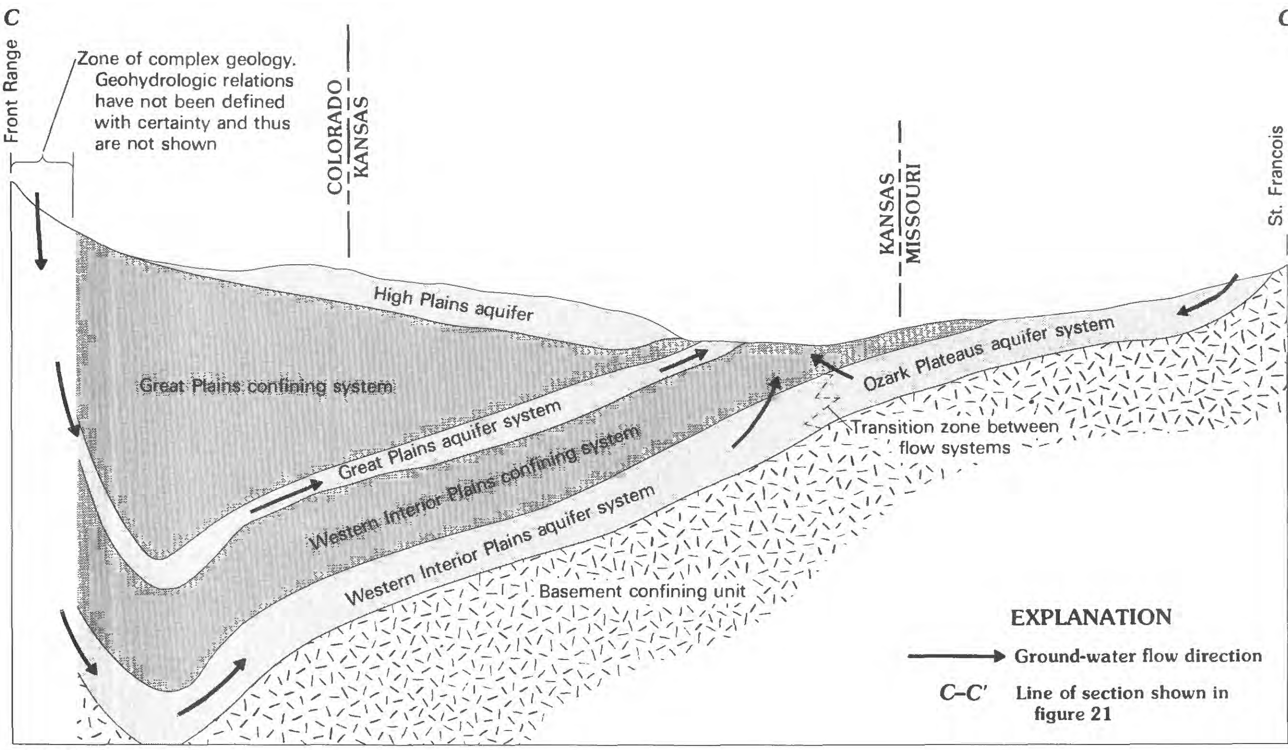


Figure D24. Major geohydrologic units in the Plains and the Ozark subregions, Central United States.

flanks of the Ozark uplift before fluid invasion because the area had undergone several long periods of uplift diagenesis (fig. D26). These permeable Mississippian and older rocks were overlain by relatively impermeable and ductile shale of various thicknesses, which would have acted as an upper confining layer. The effectiveness of the overlying confining layer decreased updip toward the Ozark uplift because the shale thickness decreased rapidly updip.

Sharp (1978) tested several hypotheses related to fluid movement by using a one-dimensional energy-momentum numerical model. One hypothesis indicated that faulting during Late Pennsylvanian to Permian time resulted in a rupture of a vast reservoir of hot fluids under excess pressure, which, in turn, rapidly moved laterally to the outcrop areas associated with the Ozark uplift. This hypothesis seems more likely than either the hypothesis postulating gravity flow through the Arkoma basin from the mountains associated with the Ouachita uplift during Pennsylvanian and Permian time or the hypothesis postulating that hot fluids associated with the Ouachita orogeny moved laterally long distances through the deep sediments in the Arkoma basin. The last two hypotheses are unlikely because, as stated above, permeable formations are not believed to have been present in the deeper parts of the basin.

The grade of the Pennsylvanian coal decreases with distance away from the Ouachita Mountains (Wilson, 1961; Damberger, 1974). In general, the coal that has undergone the most extensive thermal alteration is above the deepest part of the Arkoma basin. The coal grades from anthracite near the Ouachita Mountains to bituminous coal northward. Reconstruction of the depth of burial of the Pennsylvanian coal indicates that because it was never buried deeply enough to have been heated to anthracite grade, assuming normal geothermal gradient, there must have been another source of heat. The anthracite is in a foreland basin, so the rate of heat flow should have been normal. However, because the adjacent Ouachita uplift was an orogenic area, heat flow in the area would have been greater than average. According to studies of thermal maturity of carbon material in the Ouachita Mountains by Houseknecht and Matthews (1985), heat flow was greater than normal. Possibly, rapid subsidence in the Arkoma basin resulted in thermal pressuring of the water to such an extent that it caused widespread hydrofracturing and dissipated the hot water upward. The calculated temperature of water at the bottom of the Arkoma basin, assuming a normal geothermal gradient, is roughly consistent with that needed to thermally alter the coals above. Along the flanks of the Arkoma basin, hot fluids could have escaped laterally updip in those formations that were highly permeable, so trapped hydrocarbons could have escaped with the thermal water. This may explain why the production of hydrocarbons is relatively less in the Arkoma basin than in the adjacent Anadarko basin and why a regional geopressure zone does not exist.

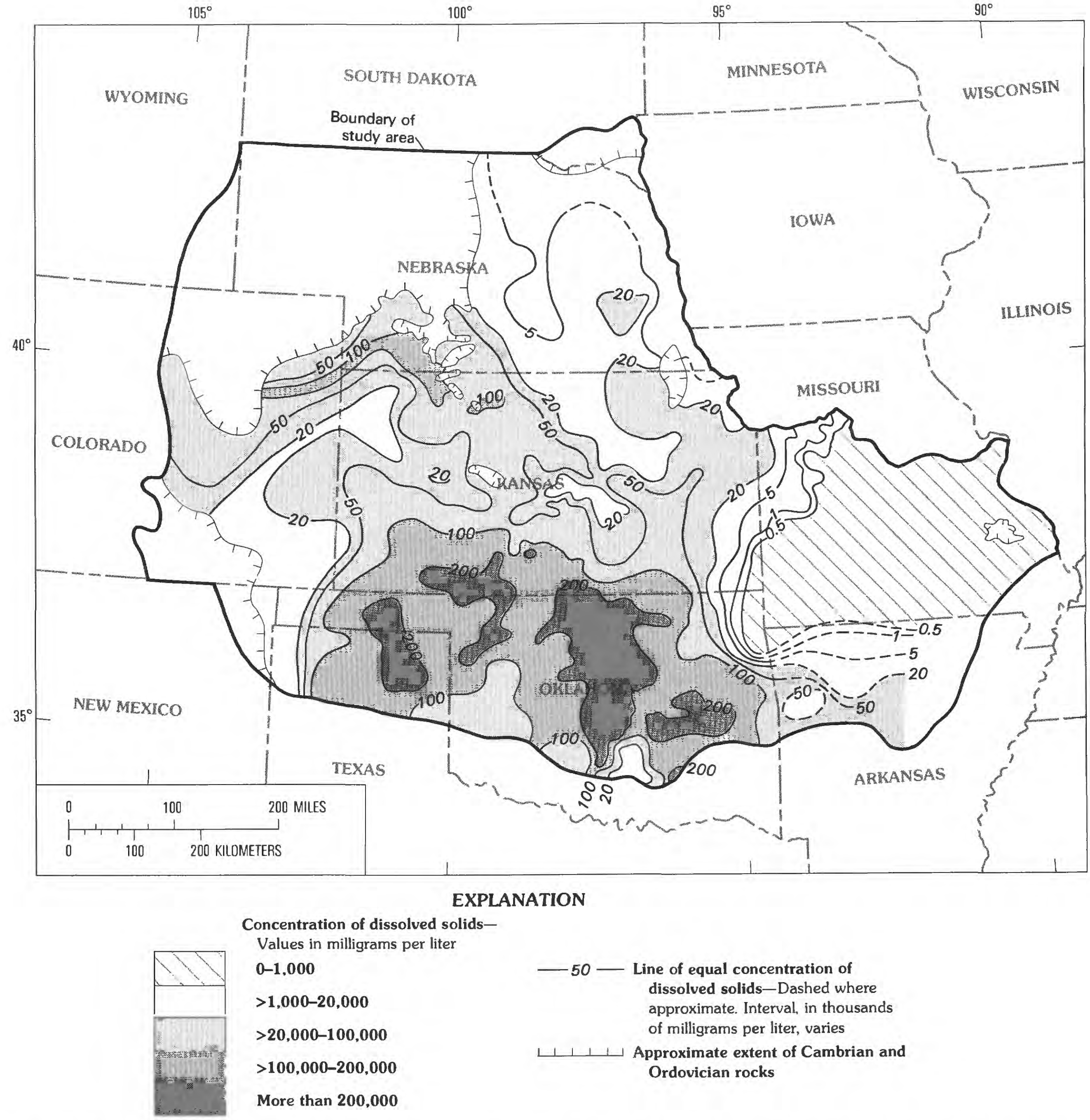


Figure D25. Concentration of dissolved solids in water from Cambrian and Ordovician rocks (preliminary) in the study area, Central United States.

The deep part of the Anadarko basin is geopressured below the Early Pennsylvanian (Morrowan) sediments. Unlike the Arkoma basin, an areally extensive geopressure zone exists in the Anadarko basin. A study of thermal maturity in the Anadarko basin (Schmoker, 1986) did not indicate greater than normal heat flow. It is possible that, unlike the Arkoma basin, thermal pressuring was not as great in the Anadarko basin, and, thus, hydrofracturing and the release of pressure did not occur. Accordingly, an accumulation of natural gas in a geopressure zone area is likely, and accumulations of oil and natural gas should exist in permeable pockets within the relatively impermeable regional confining layer above the geopressured rocks.

SUMMARY

The Central United States is defined as the 370,000-mi^2 area that extends from the foothills of the Rocky Mountains

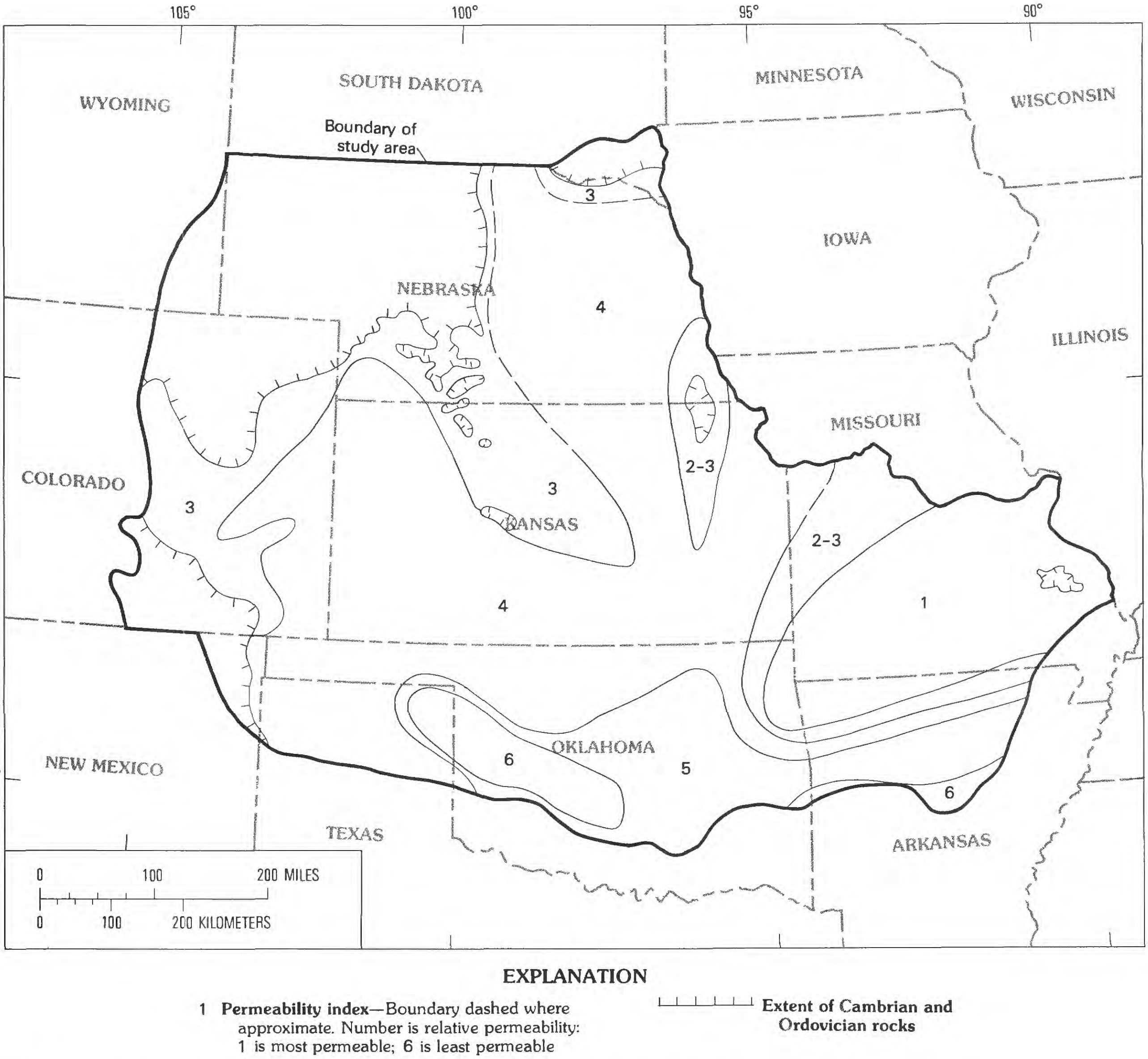


Figure D26. Relative permeability of Cambrian and Ordovician rocks in the study area, Central United States.

in Colorado to the Missouri and Mississippi Rivers in eastern Nebraska and Missouri and from the Siouxana arch in southeastern South Dakota to the Ouachita, Arbuckle, Wichita, and Amarillo uplifts of Arkansas, Oklahoma, and Texas. This area forms a reasonably distinct hydrologic study area suitable for subcontinental paleohydrologic analysis. The present-day geohydrologic system is influenced by topography, geologic structures, climate, and hydraulic properties of the rocks. Diagenesis resulting from past conditions, in general, has determined the hydraulic characteristics of the present-day aquifers.

From the end of the Precambrian to the Late Cambrian, the study area was above sea level and an uneven erosional surface developed. Crystalline bedrock was fractured by the stresses resulting from large compressive forces, and northwest-southeast and northeast-southwest lineaments formed. This condition continued, with some deviation, throughout Paleozoic time.

From the Late Cambrian through the Middle Ordovician, a generally transgressive, but cyclic, sea covered the area. The earliest deposits were mostly permeable sand followed by slightly permeable calcareous mud of aragonite and algal lime. During periods when rocks were above sea level because of uplift or recession of the sea, uplift diagenesis, which, in general, greatly increases porosity and permeability, occurred. Uplift diagenesis typically includes erosion and chemical weathering of exposed rocks and results in extensional fracturing, dissolution of minerals in rocks along fractures, and dolomitization of limestone near shorelines where fresh ground water and saline water mix.

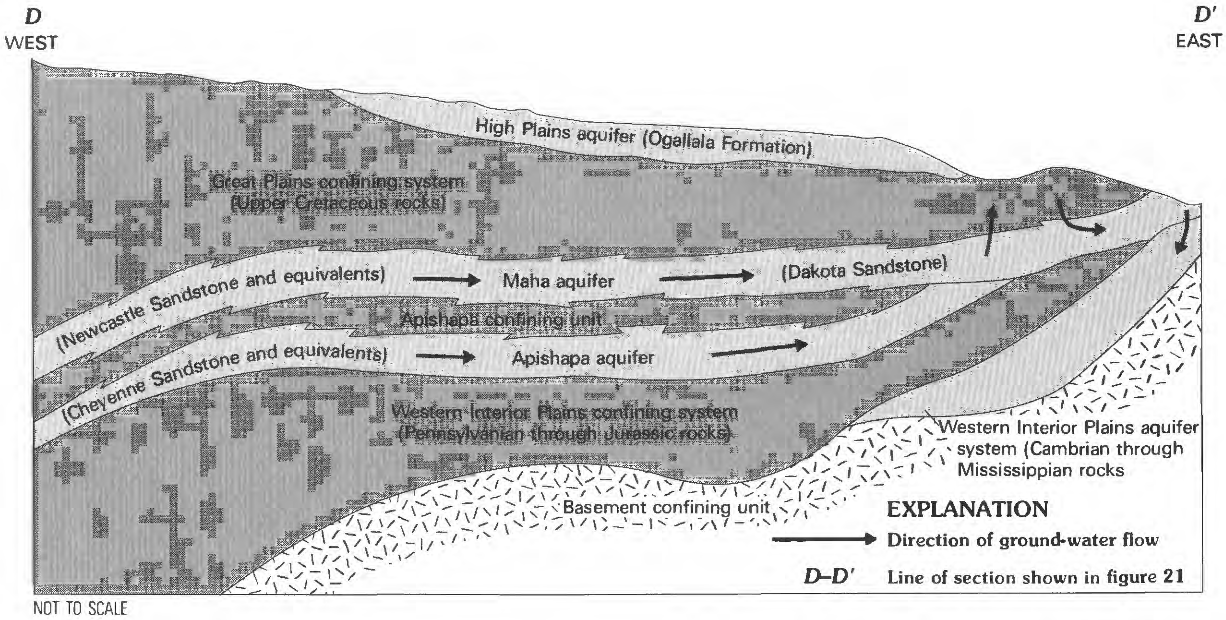


Figure D27. The Maha and Apishapa aquifers of the Great Plains aquifer system, Central United States

During most of the Silurian and the Devonian, nearly the entire area was above sea level. Uplift diagenesis greatly increased porosity and permeability of the rocks. At the end of the Devonian and during the Early Mississippian, a transgressive euxinic sea covered most of the area and very slightly permeable clay was deposited, the clay restricting flow to and from the underlying rocks.

Calcareous mud, which was lithified to permeable limestone, was the predominant sediment deposited during most of Mississippian time. Increased tectonic activity formed the Colorado-Wyoming and Nemaha uplifts. Subsiding basins, such as the Arkoma and the Anadarko, received large quantities of sediment that covered the older rocks, causing burial diagenesis, especially thermal alteration of organic material at a slow to moderate rate. (Processes of burial diagenesis typically include compaction, compression, thermal alterations of organic materials and clay, and pressure dissolution at grain contacts and recrystallization in the pores.) In general, burial resulted in a reduction in primary porosity and permeability; however, carbon-dioxide-rich solutions, which are products of thermal alteration of organic material, increased secondary porosity and permeability by selective dissolution of carbonate minerals within the rock section.

Tectonic activity reached its maximum intensity during the Pennsylvanian and decreased through the Permian. The Front Range, Apishapa, Sierra Grande, Amarillo, Wichita, Criner, Arbuckle, Ozark, Nemaha, Cambridge–Central Kansas, and Ouachita uplifts were active. The Arkoma and Anadarko basins continued to subside and received more than 20,000 ft of sediments, which caused rapid thermal alteration of organic material and compaction. Although the predominant sediment was clay, lesser amounts of calcareous mud, sand, and evaporites also were present. During the Permian, the eastern part of the area was tilted upward; the sea receded, and regional ground-water flow from east to west commenced over much of the area. In the Ozark area, a small ground-water flow system was established around the St. Francois Mountains.

During the Triassic and the Jurassic, the eastern part of the study area was above sea level, and uplift diagenetic processes were active. However, during the Early Cretaceous, a generally transgressive, but cyclic, sea deposited permeable sand and clay over the western and central parts of the study area. During the Late Cretaceous, clay having low permeability was deposited in thick layers, and burial diagenesis affected most of the area, including the Denver basin. At the end of the Cretaceous and continuing into the Tertiary, major uplifts, such as the Rocky Mountains, were formed as part of the Laramide orogeny. Uplifting in the west accompanied regional tilting of the study area downward in the east. Regional ground-water flow from west to east throughout most of the study area began in the Lower Cretaceous sandstone of the Great Plains and continues today. Similarly, except in the geopressure zone in the Pennsylvanian rocks in Oklahoma, west-to-east flow began in the Cambrian-Mississippian permeable rocks. The ground-water flow system around the St. Francois Mountains, which was established during the Permian, continued to expand as Pennsylvanian and Permian rocks were removed by erosion.

In the Arkoma basin hydrocarbon accumulations are relatively sparse and no regional geopressure zone is present. The rapid burial by sediments during the Pennsylvanian and Permian Periods in the Arkoma basin could have caused thermal pressuring to such a degree that widespread regional fracturing and microfracturing occurred. In the deepest part of the basin, the fracturing would have allowed upward movement of hot water into the overlying strata. However, along the northern flank of the basin relatively permeable formations existed. These formations could have transmitted hot metal-bearing fluids updip to the axis of the Ozark uplift and adjacent to it. These fluids could be the source of the Mississippi Valley–type mineral deposits along, and south of, the axis of the Ozark uplift.

In the Anadarko basin thermal pressuring also occurred, but not fracturing and microfracturing. Thus, the geopressure zone and large accumulations of hydrocarbons still exist.

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