The Ground-Water Flow System in Northern Missouri with Emphasis on the Cambrian-Ordovician Aquifer

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By JEFFREY L. IMES

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METRIC CONVERSION FACTORS

The inch-pound system of units is used in this report. For readers who prefer the International System of Units (SI), the conversion factors for the terms used in this report are listed below:

Multiply inch-pound units	By	To obtain SI units
foot	3.048×10^{-5}	meter
mile	1.609	kilometer
gallon per minute	6.308×10^{-5}	cubic meter per second
cubic foot per second	2.832×10^{-2}	cubic meter per second
square mile	2.589	square kilometer
foot per mile	1.894×10^{-1}	meter per kilometer
foot per second	3.048×10^{-1}	meter per second
foot per year	3.048×1^{-1}	meter per year

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 mean sea level. NGVD of 1929 is referred to as sea level in this report.

THE GROUND-WATER FLOW SYSTEM IN NORTHERN MISSOURI WITH EMPHASIS ON THE CAMBRIAN-ORDOVICIAN AQUIFER

By JEFFREY L. IMES

ABSTRACT

The hydrologically important aquifers in northern Missouri are (1) alluvial valley deposits, (2) surficial deposits of glacial drift, (3) the Mississippian aquifer, and (4) the Cambrian-Ordovician aquifer. The Cambrian-Ordovician aquifer was studied in detail.

The construction of detailed potentiometric maps and the results of modeling studies of the Cambrian-Ordovician aquifer show that an eight-county region immediately north of the Missouri River has a local freshwater flow system independent of the regional saline-water flow system. Potentiometric divides prevent saline water from entering this freshwater area. Part of the saline water discharges in Chariton and southern Howard Counties. The remainder flows eastward into Illinois. In the freshwater region, water enters the Cambrian-Ordovician aquifer by vertical leakage from the overlying Mississippian limestone formations and infiltration of precipitation where the aquifer crops out atop the Lincoln fold. The freshwater discharges along the Missouri and Mississippi Rivers.

A two-dimensional model of the Cambrian-Ordovician aquifer in northeastern Missouri was calibrated to prepumping steady-state conditions and to 1965 and May 1979 transient potentiometric surfaces. The model was used to predict effects of future water withdrawals at two potential rates: (1) continued withdrawal at 1980 pumping rates, and (2) accelerated withdrawal, increasing by one percent per year more than 1980 pumping rates. Under both conditions the potentiometric surface approaches steady state by 1990. The ground-water divides are slowly migrating southward due to present (1983) pumping stresses on the freshwater part of the aquifer and will continue in the future. This will allow saline water to move into former freshwater areas at a rate estimated to be 5 to 15 feet per year by 1990.

INTRODUCTION

Four major ground-water sources exist in northern Missouri: (1) alluvial valley deposits, (2) surficial deposits of glacial drift, (3) limestone formations of Mississippian age, and (4) dolomite and sandstone formations of Cambrian and Ordovician age. Alluvial deposits are the primary source of ground water along the major river systems (Emmett and Jeffery, 1968, 1969a, 1969b, and 1970), most notably in the Missouri, Mississippi, and Grand River valleys. The total volume of water withdrawn from this aquifer is more than that of the other major aquifers combined. Glacial-drift deposits and Mississippian rocks (mainly those of the Osagean Series) commonly are sources of water for domestic and nonirrigation farm use. The intervening Pennsylvanian shale and sandstone formations, however, produce insufficient quantities of suitable quality water to consider them reliable sources on a regional basis. The large, complex aquifer composed of formations of the Cambrian and Ordovician Systems (the Cambrian-Ordovician aquifer) is the only one of these four aquifers that underlies all of northern Missouri. The excessive salinity of water from this aquifer throughout much of the region limits its use to the southeastern one-quarter of the study area. During recent years, increasing population and industry and a rapid increase in the number of irrigation wells have placed greater demand on the freshwater part of this aquifer.

Farmers desiring to expand crop acreage and yields have developed ground-water sources to supplement surface-water impoundments. From 1978 to 1981, the number of deep irrigation wells increased from none to 28, primarily in or near Audrain County. No new deep wells, municipal or irrigation, have been constructed north of Audrain County because of the salinity of water in that part of the aquifer.

PURPOSE

This study of the hydrology of northern Missouri is a part of a broader investigation of the major aquifers underlying the north-central United States, the Northern Midwest Regional Aquifer-System Analysis (Steinhilber and Young, 1979). Northern Missouri comprises the southwestern part of this larger study area. The objective of this study is to describe the ground-water flow system in northern Missouri and its relationship to the regional ground-water flow system. The study emphasizes the Cambrian-Ordovician aquifer, the primary nonalluvial source of freshwater in northern Missouri, delineates this aquifer's recharge and discharge areas, and provides an estimate of the aquifer's transmissivity and storability. In addition, the possible effect of future withdrawals of water from the aquifer and the degree of saltwater encroachment into the present freshwater area were determined. A brief summary of the geology is presented to aid in understanding the regional hydrology.

Because of the recent increase in the use of ground water as a source for irrigation in Audrain County, a more comprehensive investigation of water supplies in that county was undertaken concurrently with this study (Emmett and Imes, 1983).

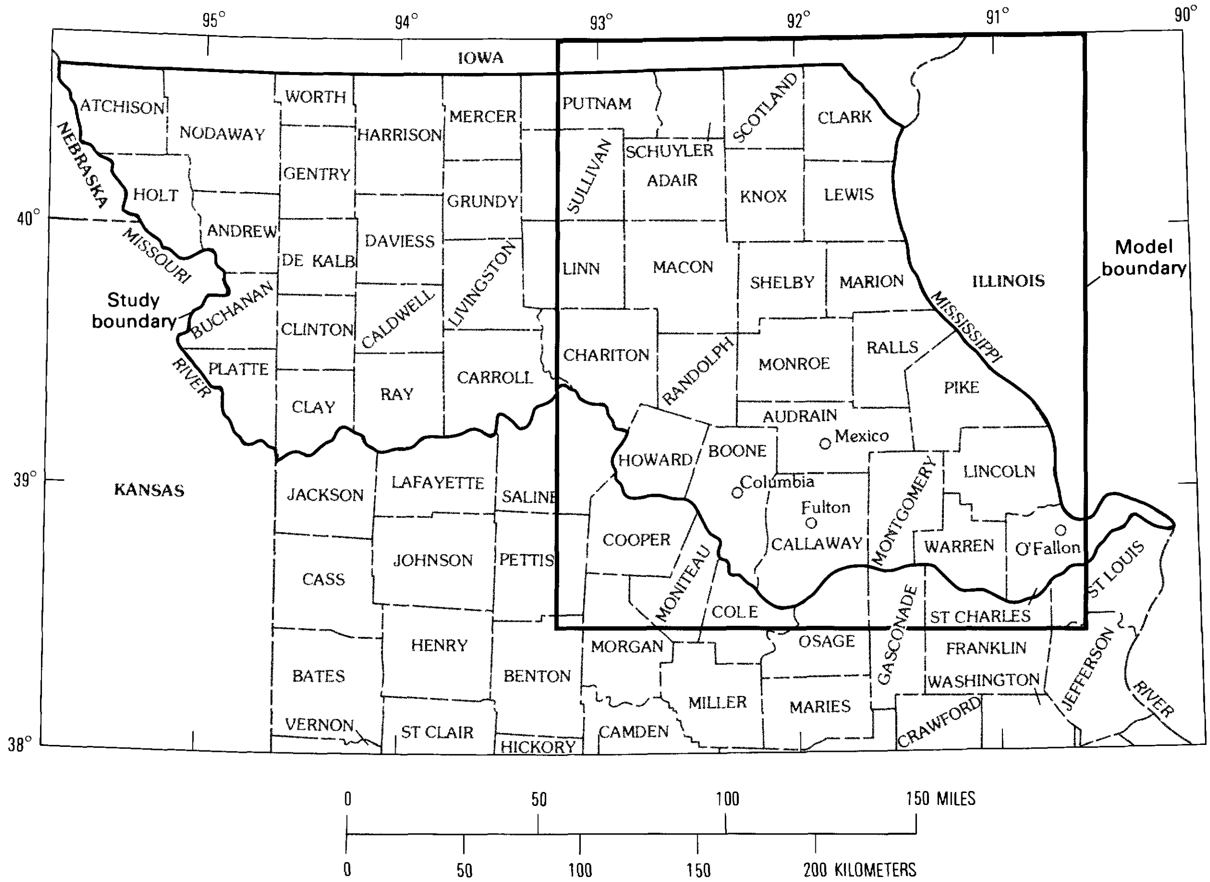


FIGURE 1.—Location of the study area and model boundaries.

SCOPE

This report contains a general description of geology and ground-water hydrology in Missouri north of the Missouri River (fig. 1), and a comprehensive description of the Cambrian-Ordovician aquifer in northeastern Missouri. A two-dimensional ground-water model was developed for the northeastern one-quarter of the state, but does not extend into the northwest because available ground-water and subsurface-structural information are extremely sparse throughout this region. Data that are pertinent to the construction of the model are presented for those areas that lie outside the study area, but inside the model area.

The area modeled contains 22,700 square miles, extending from just south of the Missouri River northward to Iowa and from approximately 91 degrees 20 minutes longitude eastward to Illinois, exclusive of the eastern one-half of St. Charles County, Mo. The model has a uniform 3.2-mile spacing in the more intensively pumped freshwater region with larger node spacings in the northern saline-water area. The model boundary is shown in figure 1.

ACKNOWLEDGMENTS

Persons who were of assistance during this study include Tom Miller and his staff of the U.S. Geological Survey, who converted contour-map data to digital format, and Ken Boyco of the U.S. Geological Survey, who helped to modify the Digital Cartographic Software System (DCASS) for application to this study. Construction of the geologic and hydrologic maps could not have been accomplished without the use of geologic-sample log files at the Missouri Department of Natural Resources, Division of Geology and Land Survey, Rolla, Mo.

GEOHYDROLOGY OF NORTHERN MISSOURI

REGIONAL GEOLOGY

A brief summary of the geologic structure and stratigraphy of northern Missouri is presented to aid in understanding their effect on ground-water flow. The relationship among the geologic units underlying this area is shown in a generalized stratigraphic column (table 1). The dominant lithologies are limestone and dolomite, limestone being more prevalent in post-Ordovician rocks. Several geologic sections have been prepared to clarify the structural features and stratigraphic relationships of the various geologic formations. The location of these geologic sections is shown in figure 2, a geologic map of northern Missouri.

The regional geology of northern Missouri is controlled by the Ozark uplift, which reaches its greatest height where Precambrian rocks are exposed in southeastern Missouri. The Precambrian surface of northern Missouri, modified from Kisvarsanyi (1975), is shown in figure 3. The surface dips slightly to the northwest at about 15 feet per mile toward the Forest City basin. The Precambrian is buried to a depth of more than 3,000 feet below seal level in the basin. Geologic Section *A-A'*, a west-to-east traverse, and geologic section *B-B'*, a south-to-north traverse, both shown in plate 1, are approximately parallel to the regional dip and strike.

Geologic section *A-A'* and paleogeologic maps (McCracken and McCracken, 1965) of the Lower Ordovician indicate the Forest City basin did not develop before Ordovician time. Instead, the area was uplifted as a part of the then northwest-trending Ozark uplift. Erosion of the structural high removed much of the Lower Ordovician (see pl. 1). Basin development began during Middle Ordovician time and continued until Pennsylvanian time.

In the eastern one-half of the study area, especially along the Missouri-Illinois border, the more northerly dip is interrupted by the Lincoln fold, a northwest-trending anticline terminated at its southern extremity by the Cap au Gres fault (Koenig, Martin, and Collinson, 1961, p. 86). The smaller Browns Station anticline lies to the southwest of and parallel to the Lincoln fold. Immediately south of the Cap au Gres fault the Precambrian surface dips into the St. Louis depression. This deep syncline probably opens to the east into the Illinois basin.

Middle and Upper Ordovician formations are exposed along the southern axis of the Lincoln fold (see fig. 2). They dip to the north and are buried to a depth of about 1,000 feet below land surface along the eastern part of the Missouri-Iowa border. In the northwest they dip toward the Forest City basin.

Geologic section *C-C'*, a southwest-to northeast traverse through the Lincoln fold, shows that sediments deposited during earliest Cambrian time had effectively covered the rugged Precambrian topography before later Cambrian and Ordovician sediments were deposited (pl. 1). Because Ordovician sediments are not significantly thinner atop the Lincoln fold, the deposition of these strata occurred before the uplift that produced the anticline. Geologic section *D-D'* (pl. 1), a south-to-north traverse through Lincoln County, contains a distinct portrayal of the Lincoln fold and the large Cap au Gres fault. The altitude of Ordovician formations differ by more than 500 feet across this fault.

Mississippian strata are the primary bedrock formations along a wide band bordering the Mississippi River (see fig. 2) and they are missing atop the Lincoln fold in part of Ralls, Pike, and Lincoln Counties. Mississippian rocks also have been eroded from a narrow strip along the Missouri River from Boone County east to St. Charles County. The younger Pennsylvanian rocks lie unconformably on the older rocks and do not dip significantly to the northwest. They attain a thickness of more than 1,800 feet in the Forest City basin.

Geologic structure maps of several Ordovician and Cambrian formations are available as open-file reports from the Missouri Division of Geology and Land Survey, and other maps have been published in McCracken and McCracken (1965). Descriptions of smaller, locally important geologic structures can be found in McCracken (1971), and information on the stratigraphy of Missouri can be found in Koenig (1961) and references therein.

HYDROLOGY

ALLUVIAL VALLEY DEPOSITS

Alluvial fill in the river valleys and outwash deposits in buried bedrock valleys are the primary sources of freshwater in northern Missouri. The deposits consist of clay, sand, and gravel, and generally grade from fine to course grained with increasing depth. The generally permeable deposits can yield as much as 3,000 gallons per minute along reaches of the Missouri River (Skelton, Harvey, and Miller, 1982). Water levels in the Mississippi and Missouri River alluvium respond to fluctuations in river stage, thus the aquifer both discharges into and is recharged by the river systems (U.S. Geological Survey and Missouri Division of Geology and Land Survey, 1967, p. 304). Water from alluvial wells in northern Missouri is a calcium bicarbonate type with a large dissolved-iron concentration. Dissolved-solids concentrations normally are less than 1,000 milligrams per liter (Gann and others, 1971; and Gann and others, 1973).

A complete study of the alluvial aquifer in northern Missouri is beyond the scope of this report. Several reports on the Missouri River alluvium have been published (Emmett and Jeffery, 1968, 1969a, 1969b, and 1970; and previously referenced reports). The reader is referred to these publications for more detailed information about this aquifer.

GLACIAL-DRIFT DEPOSITS

Glacial-drift deposits, consisting of clay, silt, sand, and gravel, are a source of water for domestic and non-irrigation farm use throughout much of the northern and western parts of the study area. During the Pleistocene Nebraskan and Kansan glaciations, ice covered much of the northern part of Missouri (Koenig, 1961, p. 130). The advance and retreat of these glaciers buried existing river valleys under thick deposits of glacial debris. As the topography was

TABLE 1.—*Generalized stratigraphic column of northern Missouri with descriptions of hydrologic characteristics*

System	Series	Geologic Unit	Lithology	Thickness, in Feet	Water-Bearing Properties	Hydrologic Unit
QUATERNARY	Holocene	Alluvium	Clay, silt, sand, and gravel	0-150	Yields increase with percent increase of gravel and sand in deposits. Large yields along Missouri and Mississippi Rivers. Tributaries supply sufficient water for domestic and farm use 10-3000 gallons per minute.	
	Pleistocene	Glacial Drift	Clay, silt, sand, and gravel	0-400+	Sufficient quantities for domestic and farm use, primarily from buried river valleys. 0-10 gallons per minute.	
PENNSYLVANIAN	Virgilian	Wabaunsee Group Shawnee Group Douglas Group	Shale, sandstone, shaly limestone, and coal	0-1800	Production available for domestic use from sandstone formations. Water excessively mineralized 0-10 gallons per minute	
	Missourian	Pedee Group Lansing Group Kansas City Group Pleasanton Formation[1]	Shale, sandstone, shaly limestone, and coal			
	Desmoinesian	Marmaton Group Cherokee Shale[1]	Shale, sandstone, and coal			
MISSISSIPPIAN	Meramecian	Ste Genevieve Limestone St Louis Limestone Salem Limestone Warsaw Limestone	Limestone, dolomite, and shale	0-350		
	Osagean	Keokuk Limestone Burlington Limestone Fern Glen Limestone	Limestone	0-310	Adequate water for domestic and farm supplies 5-15 gallons per minute	Mississippian aquifer
	Kinderhookian	Sedalia Limestone Chouteau Limestone[1]	Limestone, dolomite, and shale			
		Hannibal Shale "Kinderhook shale"[2]	Shale	0-260	Confining layer throughout much of northern Missouri, thinning to the south.	Upper confining bed
DEVONIAN	Upper	Louisiana Limestone Grassy Creek Shale Snyder Creek Formation	Shale and limestone			

DEVONIAN	Middle / Lower	Undifferentiated	Limestone	0-530	Unimportant as an aquifer	Upper confining bed
SILURIAN		Undifferentiated	Limestone and dolomite			
ORDOVICIAN	Upper	Maquoketa Shale	Shale	0-150	Confining layer in extreme east along Mississippi River	
	Middle	Kimmswick Limestone	Dolomite and limestone	0-1300	Yields generally sufficient for domestic supplies. 5-10 gallons per minute	Cambrian-Ordovician aquifer
		Decorah Formation Plattin Limestone Joachim Dolomite	Dolomite, limestone, and shale		Limited source of water. Locally may be confining layers	
		St. Peter Sandstone Everton Formation	Sandstone and dolomite		Good production for domestic, farm, and small industry. Excessively mineralized in the north. 25-75 gallons per minute	
	Lower	Powell Dolomite Cotter Dolomite Jefferson City Dolomite	Dolomite		Unimportant as an aquifer, but may produce sufficient water locally for domestic and farm use. 0-25 gallons per minute	
		Roubidoux Formation	Sandstone and dolomite		Good producer. Commonly sufficient for municipal, industrial, and irrigation water supplies. 50-500 gallons per minute	
		Gasconade Dolomite Gunter Sandstone Member	Dolomite and sandstone			
CAMBRIAN	Upper	Eminence Dolomite Potosi Dolomite	Dolomite		Excellent producer. Capable of large yields for large cities, industry, and irrigation. 440-1,100 gallons per minute	
		Derby-Doe Run Dolomites	Shale and dolomite	20-300	Limited source of water	
		Davis Formation			Confining layer in northern Missouri	
		Bonneterre Dolomite Lamotte Sandstone	Sandstone and dolomite	0-700	Little information available. Probably some production from the Lamotte sandstone	
PRECAMBRIAN			Igneous rocks		Unimportant as a source of water	

[1]Designated Pleasanton, Cherokee, and Chouteau Groups by the Missouri Geological Survey.
[2]Subsurface equivalent of the Hannibal Shale in northwest Missouri

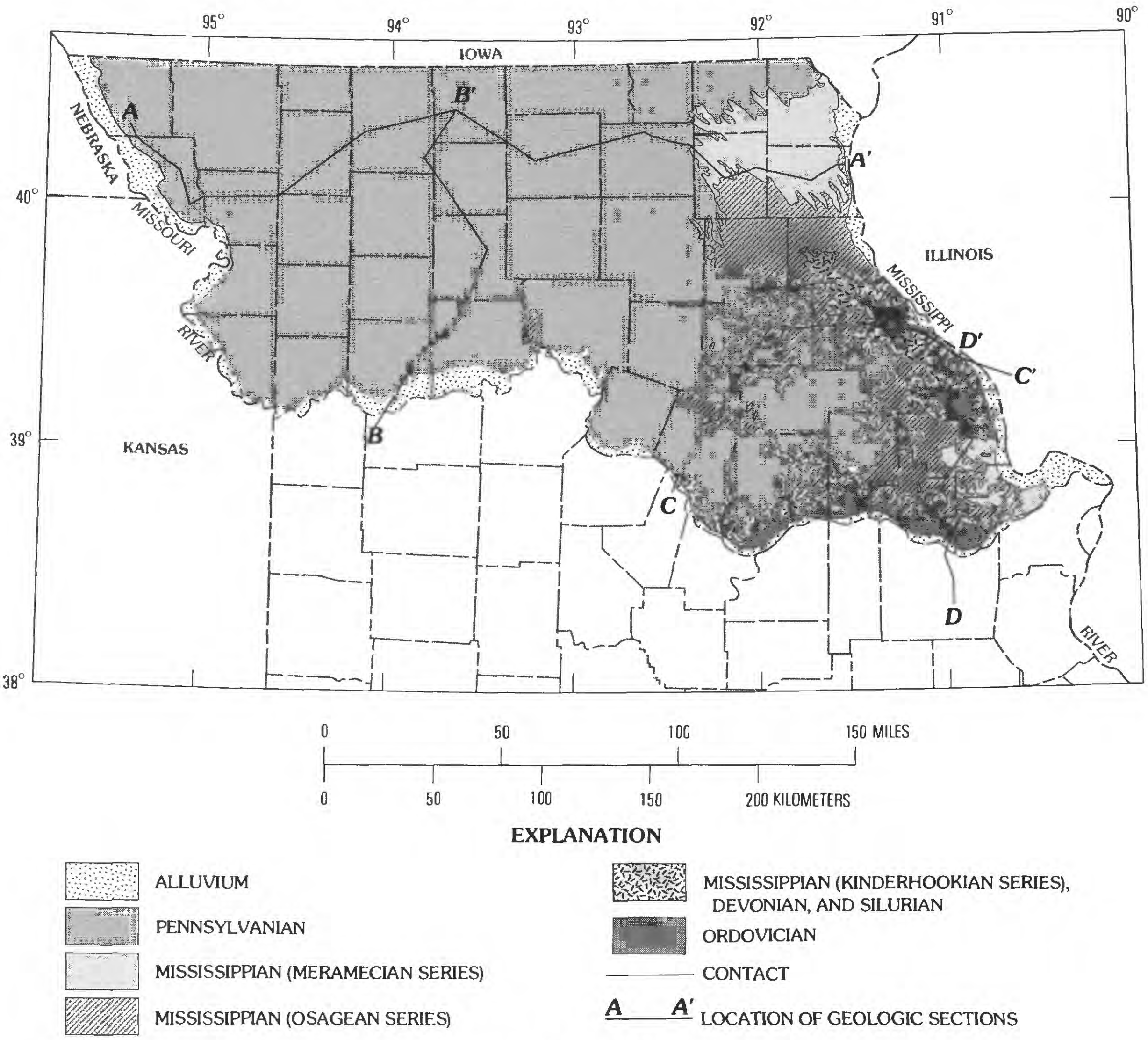
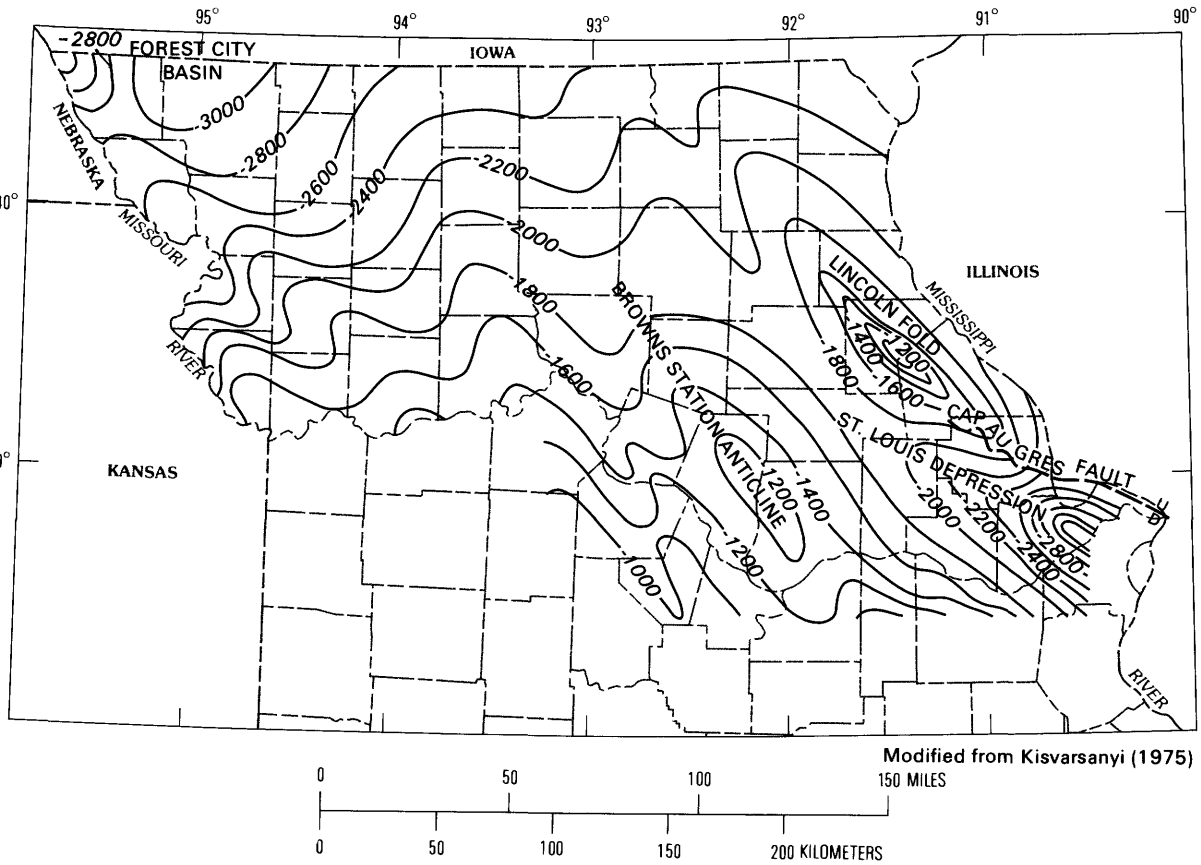


FIGURE 2.—Geology of northern Missouri and location of geologic sections.

modified, new drainage patterns evolved to create the present-day river system (Heim and Howe, 1963). Throughout the western two-thirds of the study area, drainage is southward into the Missouri River; and in the eastern one-third, streamflow is to the south and southeast into the Missouri and Mississippi Rivers. Glacial deposits range in thickness from zero in the extreme southeast, where erosion has removed the original deposits, to as much as 400 feet in the northwest. They reach their maximum thickness were preglacial valleys are filled with glacial debris (Gann and others, 1973).

Yields from wells in the glacial drift usually are small (less than 10 gallons per minute) due to the presence of large quantities of relatively impermeable silt and clay. However, in areas containing well-sorted sand bodies, yields may be sufficient to supply small towns and industries (30–500 gallons per minute). These cleaner, coarser sands normally occur at the base of the glacial drift in the preglacial valleys. Glacial-drift water is a mixed calcium bicarbonate sodium sulfate type with large iron concentration. The dissolved-solids concentration may exceed 1,000 milligrams per liter. A median dissolved-solids concentration of 620 milligrams per liter was determined using chemical analyses of water samples from 128 glacial-drift wells in northwestern Missouri (Gann and others, 1973).

The potentiometric surface in this aquifer, which can be either water table or artesian, is affected by the regional topography (fig. 4). Although the potentiometric-head distribution shown in figure 4 primarily is based on water levels in wells open only in the glacial drift, water levels in shallow bedrock or alluvial wells were used where glacial-drift deposits are thin or absent. In areas where little or no data are available, the regional topographic relief has been



EXPLANATION

—-2200— STRUCTURE CONTOUR—Shows altitude of top of Precambrian basement rocks. Contour interval 200 feet. National Geodetic Vertical Datum of 1929

U/D FAULT—Dashed where approximately located. U upthrown side; D, downthrown side

FIGURE 3.—Altitude of the top of Precambrian basement rocks.

used as a guide to contouring the water table. The glacial drift is recharged by direct precipitation and discharges into the major river systems of northern Missouri.

The transmissivity of glacial drift varies considerably, depending on the quantity of silt and clay present (Skelton, Harvey, and Miller, 1982). Transmissivity is largest in the glacial outwash deposits of the buried river valleys.

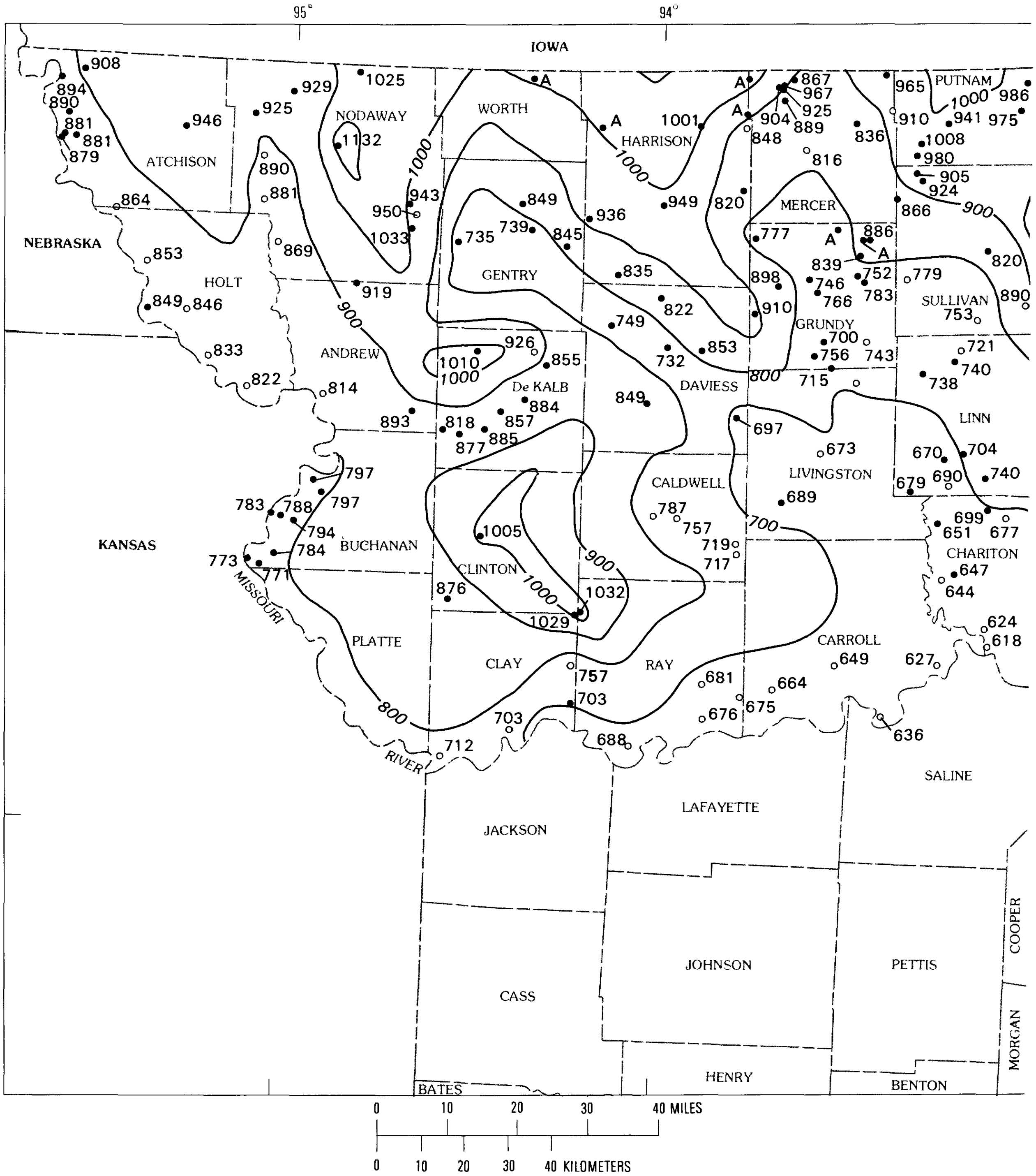
PENNSYLVANIAN ROCKS

Rocks of Pennsylvanian age form the predominant bedrock material underlying the glacial drift. The Pennsylvanian rocks are composed primarily of shale and sandstone interbedded with shaly limestone and coal. A thickness map of Pennsylvanian deposits (fig. 5) shows that these rocks thicken toward the west and attain a maximum thickness of more than 1,800 feet in the Forest City basin. The Pennsylvanian rocks are absent along the eastern edge of the study area due to erosion of the Lincoln fold anticline.

The large shale content of most Pennsylvanian rocks greatly impedes the flow of ground water; thus the Pennsylvanian probably is a confining bed atop the relatively permeable Mississippian aquifer. Few wells are completed in Pennsylvanian sediments due to small yields and inferior quality water. Thus, there is insufficient water-level data to construct a map of the potentiometric surface of water in Pennsylvanian rocks.

MISSISSIPPIAN AQUIFER

The Mississippian aquifer includes formations of the Osagean Series and the underlying limestone formations of the upper part of the Kinderhookian Series. The overlying Meramecian Series in northern Missouri generally contains sufficient interbedded shale to make the series incapable of yielding water in large quantities. The base of the aquifer rests on the Hannibal Shale (or "Kinderhook shale," of informal subsurface usage in northwest Missouri) throughout most of the study area (see table 1). Water enters the Mississippian aquifer by direct recharge from precipitation in the east and southeast and by leakage from overlying Pennsylvanian and Mississippian strata where it is confined.



EXPLANATION

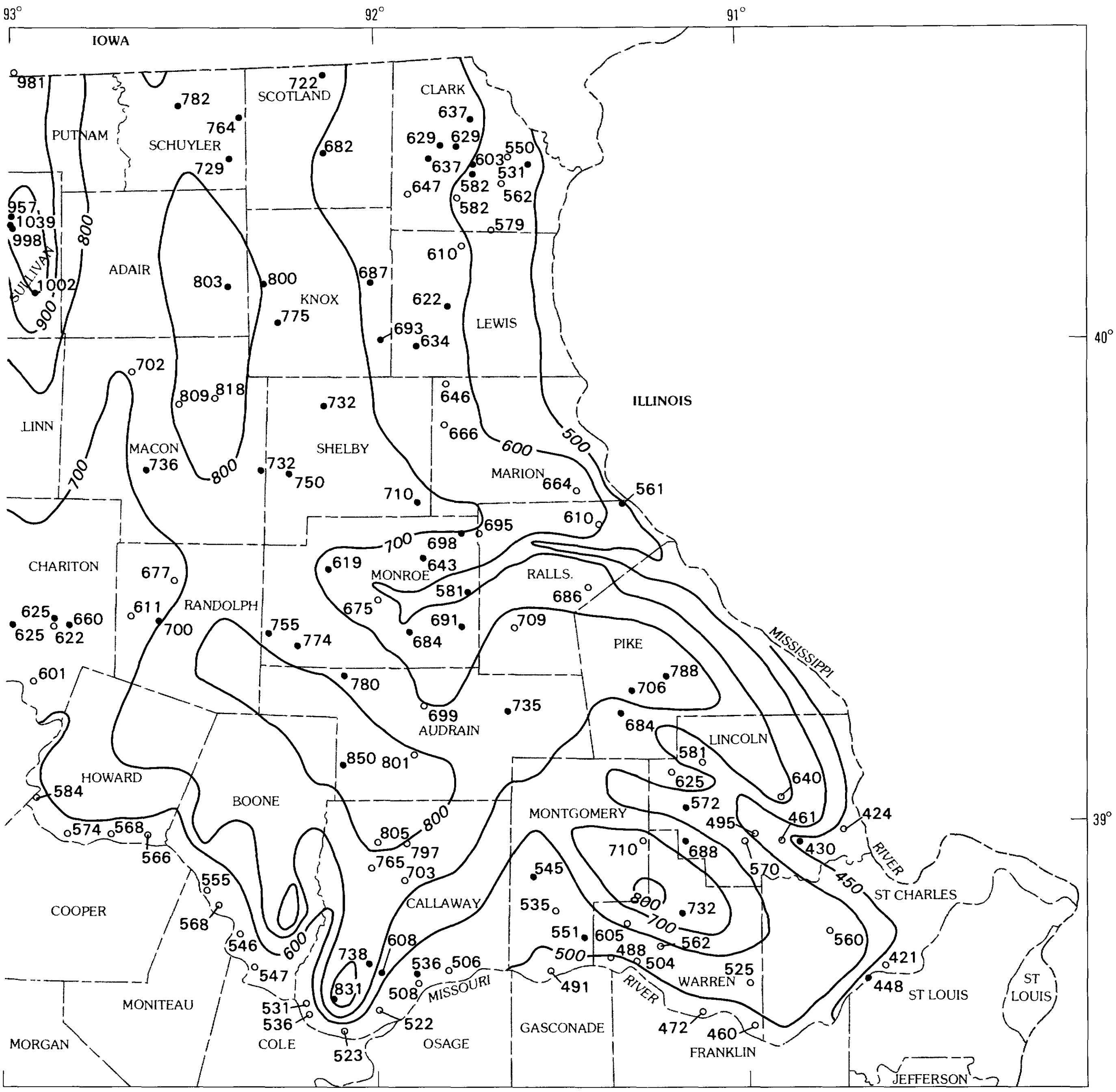
— *600* — POTENTIOMETRIC CONTOUR—Shows altitude of potentiometric head. Contour interval 100 feet. National Geodetic Vertical Datum of 1929

•950 GLACIAL-DRIFT WELL—Number is altitude of potentiometric head

o673 SHALLOW BEDROCK OR ALLUVIAL WELL—Number is altitude of potentiometric head

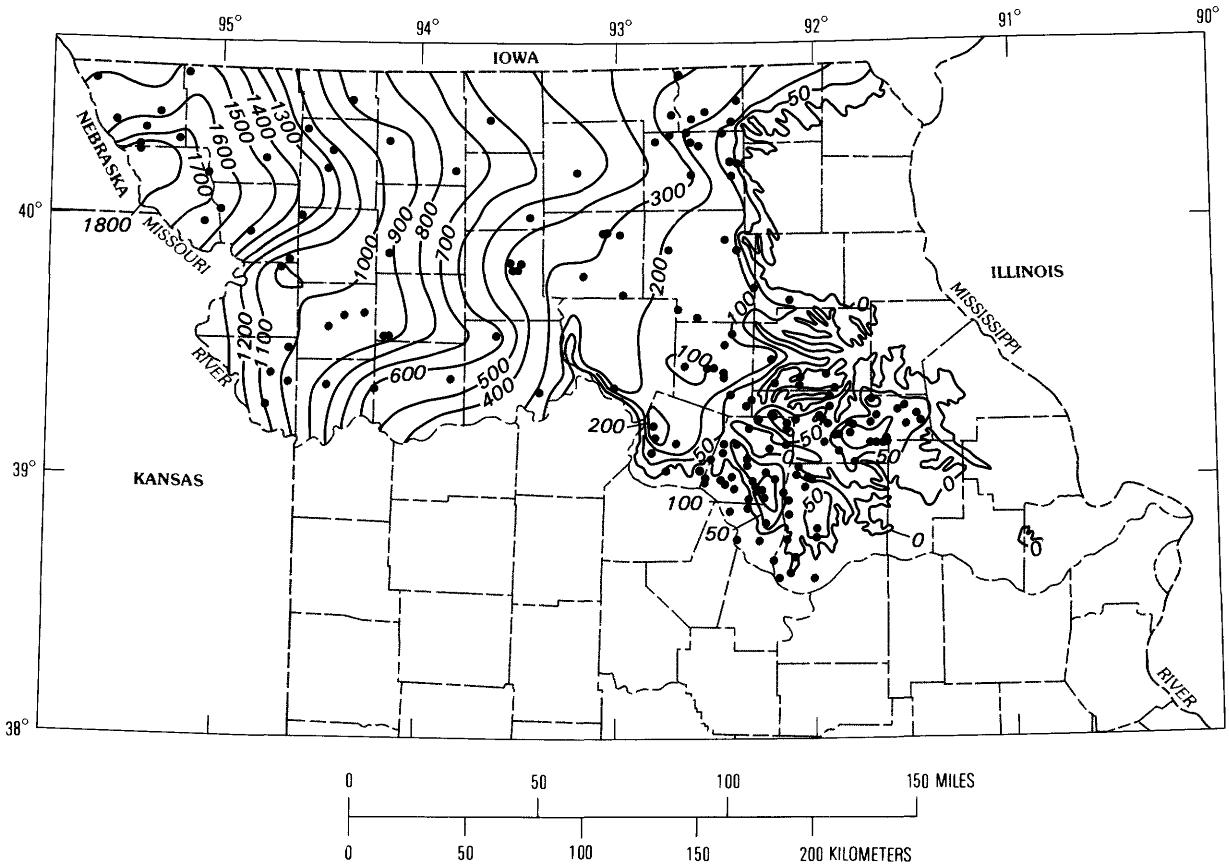
•A FLOWING ARTESIAN WELL

FIGURE 4.—Potentiometric-head distribution in glacial drift or surface deposits.



The Burlington and Keokuk Limestones, generally treated as one geologic unit due to the difficulty in distinguishing their contact, are the principal water-yielding rocks in this aquifer (table 1). Both normally are composed of coarsely crystalline limestone containing varying quantities of chert nodules. Well-developed solution channels are common and provide a source for domestic and farmwater supplies in the eastern part of the study area. The combined Burlington-Keokuk Limestones attain a thickness of 200 feet in the study area and dip slightly from the Ozark uplift and Lincoln fold toward the northwest (fig. 6).

A map of the prepumping potentiometric surface of the Mississippian aquifer in northeastern Missouri is shown in figure 7. Insufficient data are available to map the entire study area. Most data used to prepare this map are for wells that penetrate the Burlington and Keokuk Limestones. The



EXPLANATION

—100— LINE OF EQUAL THICKNESS OF PENNSYLVANIAN ROCKS— Interval 50 and 100 feet

• WELL OR TEST HOLE FOR WHICH A GEOLOGIC LOG IS AVAILABLE

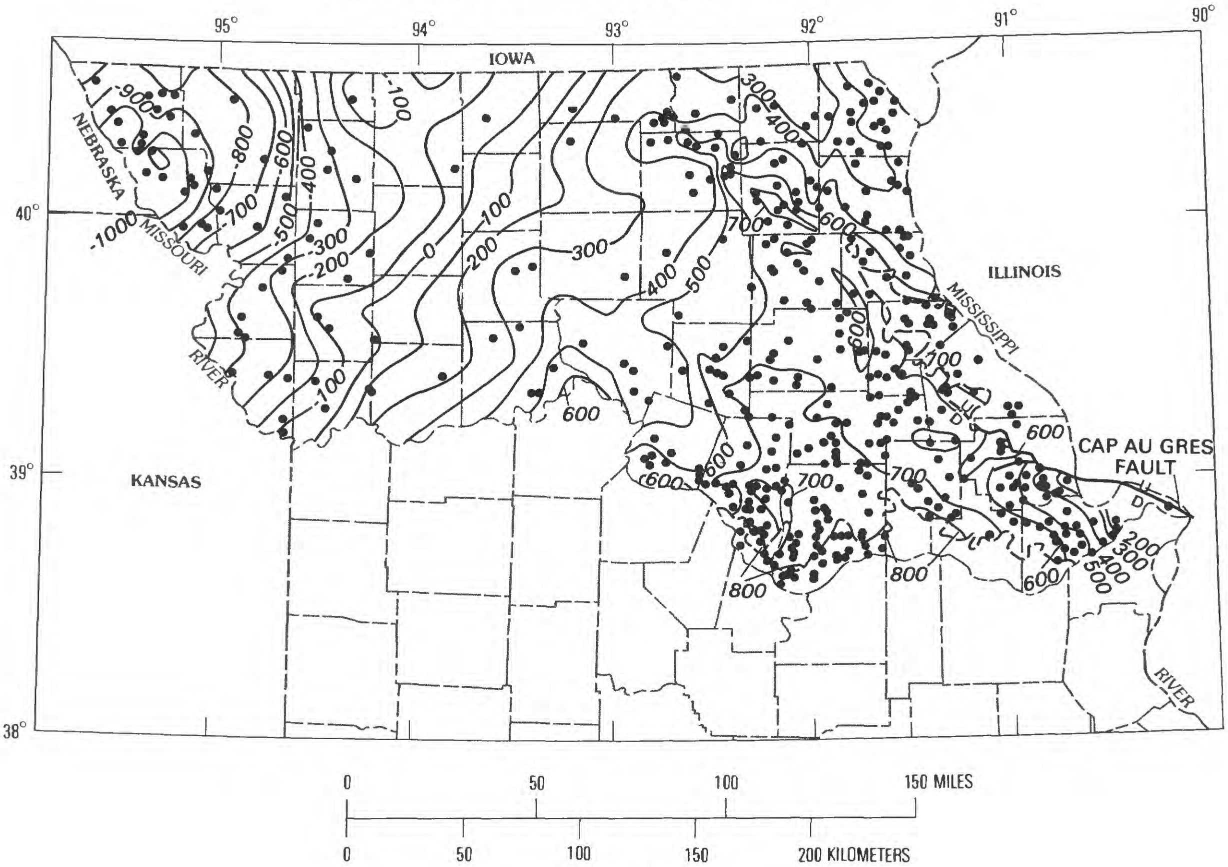
FIGURE 5.—Thickness of combined Pennsylvanian rocks.

earliest recorded water level for each well was used to construct the map if the regional potentiometric surface at the well site was not significantly affected by previous pumping of nearby wells.

In the northern half of the model area, the ground-water flow divides; part flows eastward to discharge into the Mississippi River, and the remainder flows southwest and discharges into the Chariton and Missouri Rivers. In the south and southeast the potentiometric surface is affected more by topography as the aquifer changes from confined to unconfined conditions. The effect produces two large mounds in the potentiometric surface at southwestern Audrain County and northwestern Warren County. Ground water flows radially outward from these mounds and discharges into the major rivers.

UPPER CONFINING BED

The upper confining bed is not a single unit, but a sequence of several Lower Mississippian, Devonian, Silurian, and Upper Ordovician shale and limestone formations (see pl. 1). The Hannibal Shale of Mississippian age (fig. 8) is the uppermost formation of this sequence of rocks that separates the Mississippian aquifer from the underlying Cambrian-Ordovician aquifer. The data from northwestern Missouri used to construct this map is the top of the "Kinderhook shale." Historically, the relationship between the "Kinderhook shale" and other Lower Mississippian and Upper Devonian shales has not been clearly understood (Koenig, 1961, p. 41–49), but this shale is now believed to be a subsurface equivalent of the Hannibal Shale of northeastern Missouri



EXPLANATION

—300— STRUCTURE CONTOUR—Shows altitude of top of Burlington and Keokuk Limestones. Contour interval 100 feet. National Geodetic Vertical Datum of 1929

• WELL OR TEST HOLE FOR WHICH A GEOLOGIC LOG IS AVAILABLE

– – – – – AREAL EXTENT OF BURLINGTON AND KEOKUK LIMESTONES

U/D FAULT—Dashed where appoximately located. U, upthrown side; D, downthrown side

FIGURE 6.—Altitude of the top of Burlington and Keokuk Limestones.

(T.J. Thompson, Missouri Division of Geology and Land Survey, oral commun., 1982). The Hannibal Shale attains a thickness of 130 feet in the northeast, but due to abrupt thinning is not present south of Monroe County (fig. 8).

Throughout most of northeastern Missouri, the Cambrian-Ordovician aquifer is confined by Upper Devonian and Kinderhookian shale and limestone formations (fig. 9). The least conductive formations are the relatively impermeable Hannibal Shale, Grassy Creek Shale, and Snyder Creek Formation (table 1). The intervening Louisiana Limestone, a thin Upper Devonian limestone, contributes little to the confining nature of this group of formations. In the north and east, the dominant confining beds are the Hannibal Shale and Grassy Creek Shale. These two formations attain their maximum thickness (310 feet) in the extreme northeast, thin toward the southwest, and are absent along much of the southern boundary of the study area. The formations have been eroded from the southern part of the Lincoln fold. Within Callaway County, the Snyder Creek Formation becomes the predominant confining bed, merging into the Hannibal–Louisiana–Grassy Creek sequence along the northern edge of the county. The Snyder Creek forms a roughly circular confining layer in central Callaway County, reaching a thickness of about 35 feet at the center of the lens-shaped shale bed.

The Maquoketa Shale, which overlies and confines the Cambrian-Ordovician aquifer throughout much of northern Illinois, also is an effective confining bed in the extreme eastern part of the study area. The Maquoketa attains a thickness of 100 feet along the Lincoln fold in Pike County (fig. 10), and is exposed in a wide band atop the Lincoln fold in Ralls, Pike, and Lincoln Counties.

EXPLANATION

— 800 — POTENTIOMETRIC CONTOUR — Shows altitude at which water levels would have stood in tightly cased wells. Contour interval 25, 50, and 100 feet. National Geodetic Vertical Datum of 1929

•699 WELL FOR WHICH WATER LEVEL DATA ARE AVAILABLE—Number is altitude of water level, in feet above National Geodetic Vertical Datum of 1929

AREAL EXTENT OF MISSISSIPPIAN AQUIFER

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

Note: Contours representing the potentiometric surface in Illinois are approximate. They were compiled by lowering the average regional topographic surface by about 1000 feet. The Mississippi aquifer is exposed throughout most of this area

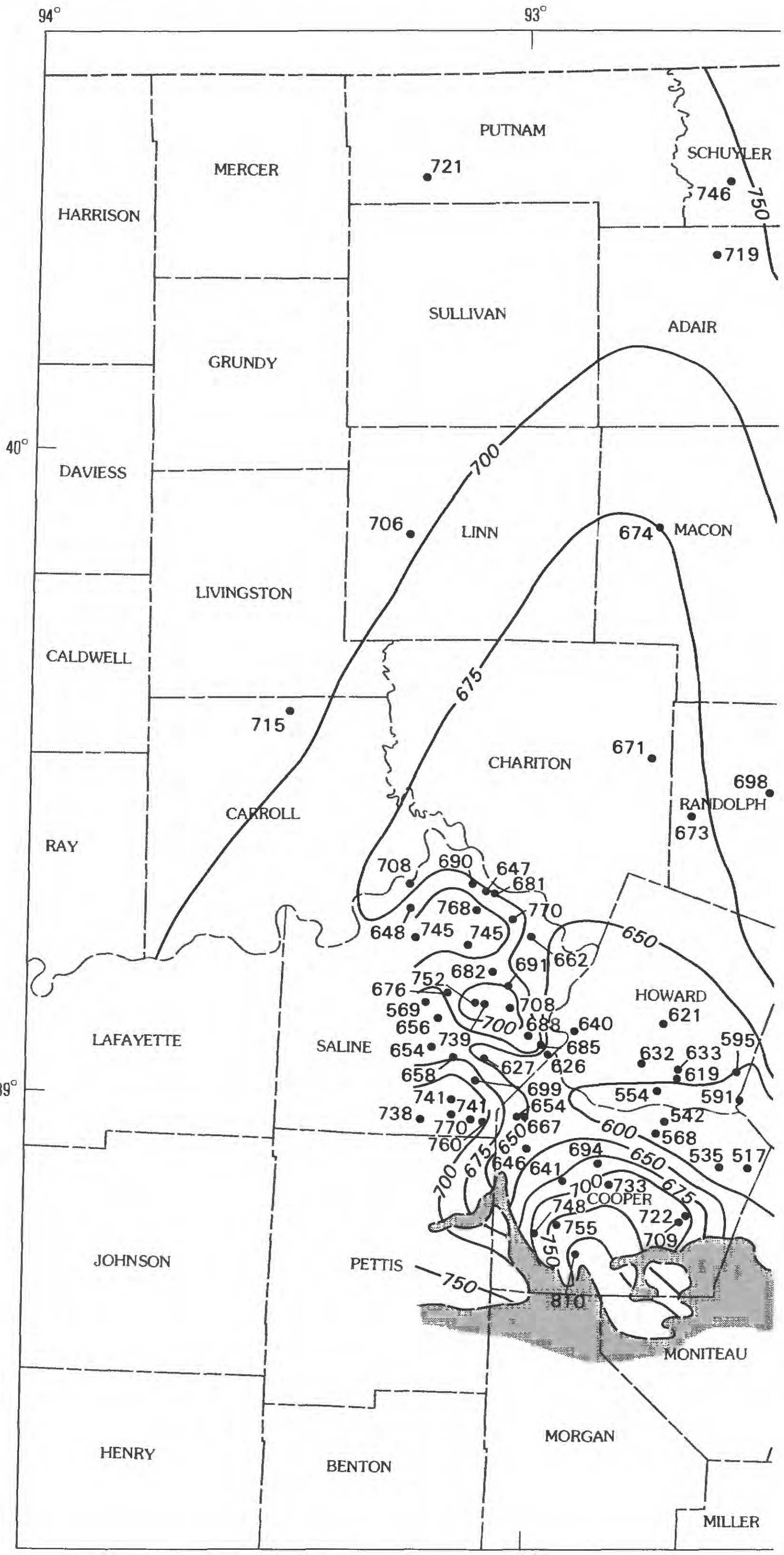
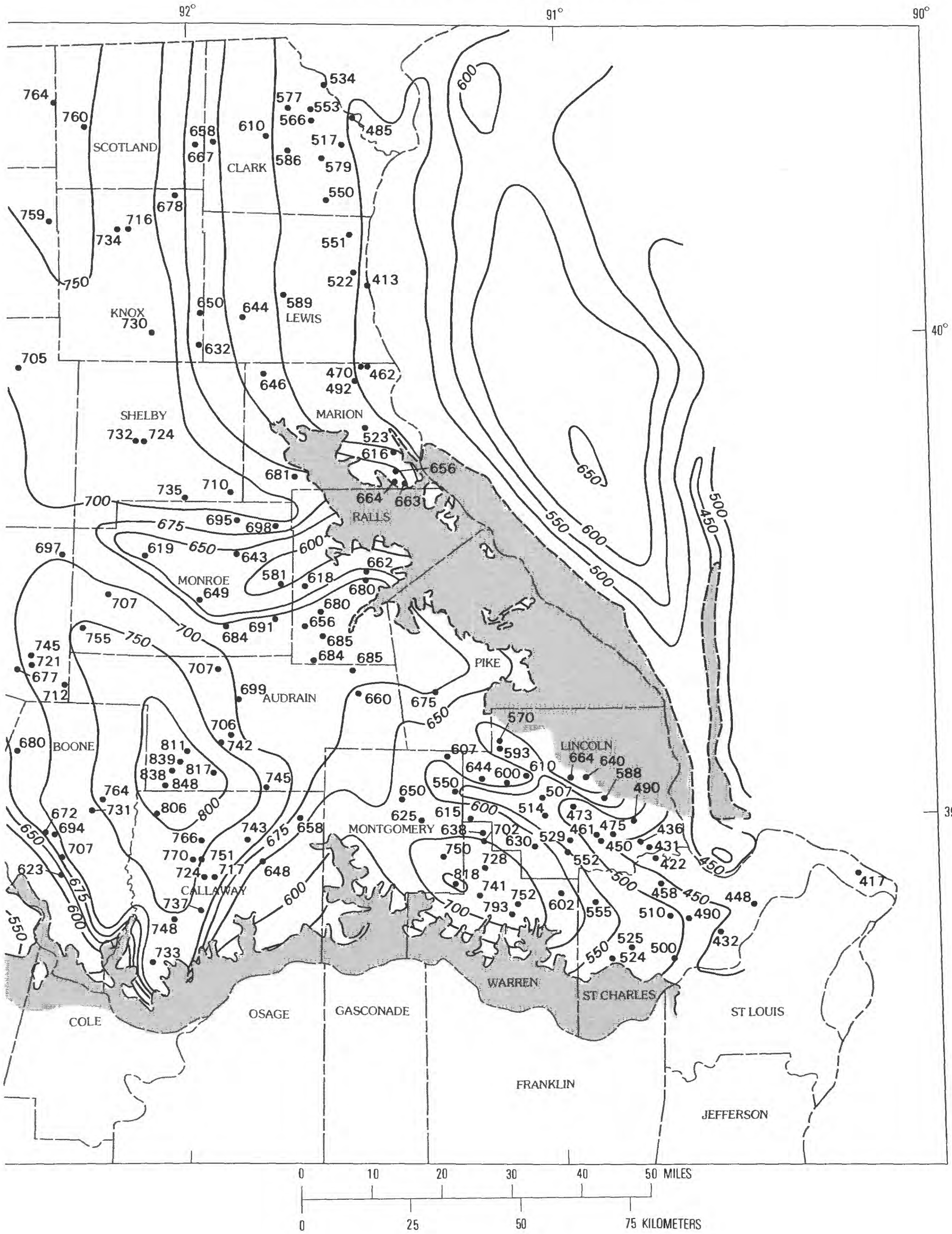


FIGURE 7.—Altitude of the prepumping potentiometric surface of the Mississippian aquifer.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90°
40°
39°
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BOONE
LINCOLN
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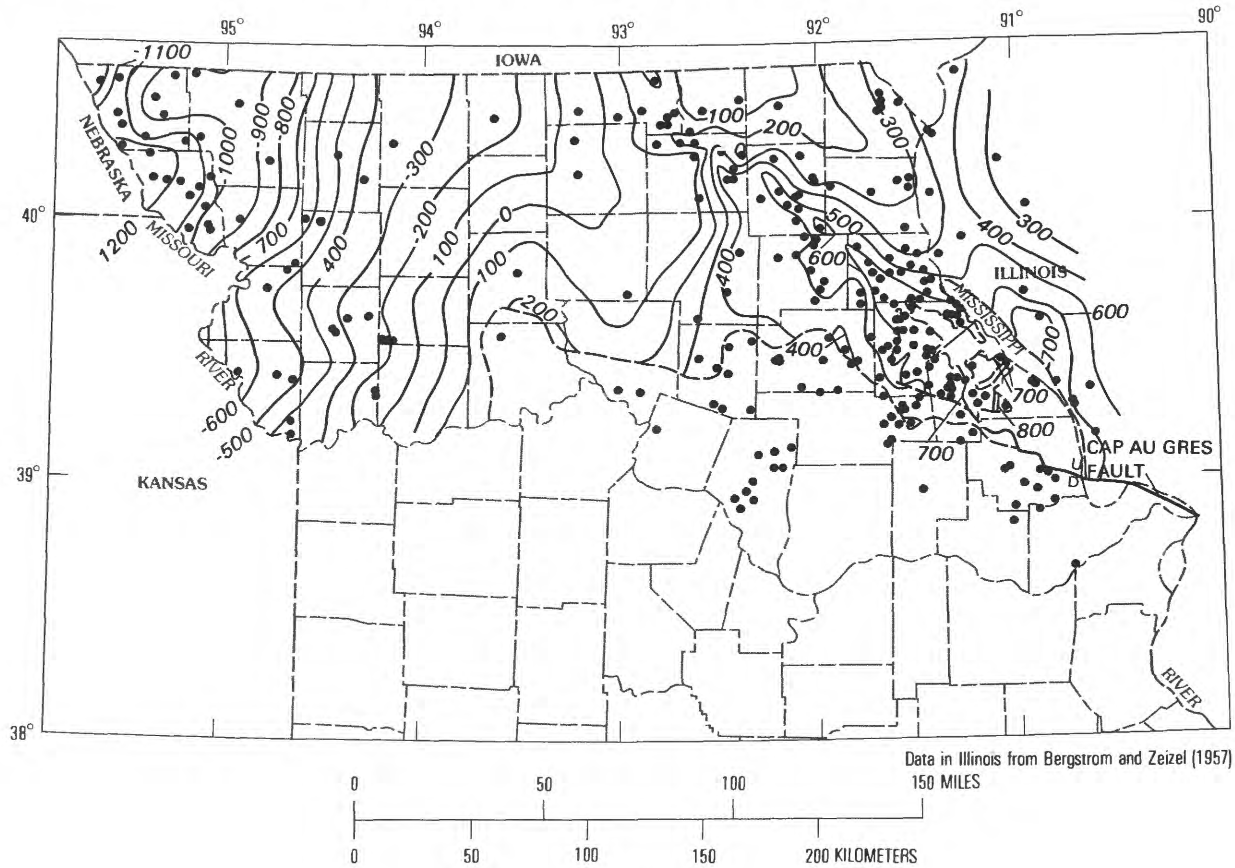


EXPLANATION

—-200— STRUCTURE CONTOUR—Shows altitude of top of Hannibal Shale or equivalent "Kinderhook shale." Contour interval 100 feet. National Geodetic Vertical Datum of 1929

• WELL OR TEST HOLE FOR WHICH A GEOLOGIC LOG IS AVAILABLE

– – – – – AREAL EXTENT OF HANNIBAL SHALE OR EQUIVALENT "KINDERHOOK SHALE"

U/D FAULT—Dashed where approximately located. U, upthrown side; D, downthrown side

FIGURE 8.—Altitude of the top of the Hannibal Shale or equivalent "Kinderhook shale."

Although these shale formations are not present in Montgomery and southeastern Audrain Counties, potentiometric data and the calibration of the model (see subsequent section "Digital model") indicate that some low permeability zones separate the Mississippian and Cambrian-Ordovician aquifers in at least part of this area. Middle and Lower Devonian limestones, which are of little significance as confining beds in areas overlain by the major shale units, may become the primary confining unit where the shale formations are absent. Whether this is due to a large horizontal to vertical hydraulic conductivity ratio or to a relatively impermeable limestone and dolomite formation is uncertain. There is evidence from wells north of this area that the Middle and Lower Devonian limestones are leaky confining beds. Hydrogeologic section *E-E'* (pl. 1) extends from Adair to Lewis County. During the drilling of wells used to construct this section, drillers observed zones that yielded significant quantities of water at depths as indicated by a small letter "w" on the section. None of these zones are located immediately below the massive shale confining beds, but those stratigraphically lower all occur near the base of the Devonian. Therefore, Middle and Lower Devonian formations have been treated as a leaky confining bed throughout the model area. The Middle and Lower Devonian formations (including some small local deposits of Silurian age) are thicker in the northwest, and are thin or absent on the Lincoln fold and along the southern edge of the model area (fig. 11).

It also is possible that the Decorah Formation, Plattin Limestone, and Joachim Dolomite (table 1) obstruct the vertical movement of water, and therefore are leaky confining beds in the Montgomery County area. Each of these formations contains dolomite interbedded with varying amounts of shale throughout this part of the model area. The presence of the shale may cause the upper part of the Cambrian-

Ordovician aquifer to have a large horizontal to vertical hydraulic conductivity ratio, thus impeding the vertical flow of ground water.

CAMBRIAN-ORDOVICIAN AQUIFER

Other than the Missouri River alluvium, the most important aquifer in northern Missouri, based on volume of water withdrawn, is the Cambrian-Ordovician aquifer. As defined in this report, the aquifer includes the stratigraphic sequence between the top of the Davis Formation and the base of the Maquoketa Shale (see table 1). Use of the aquifer is limited largely to the southeastern one-quarter of the study area, because elsewhere the water in the Cambrian-Ordovician aquifer is too saline for domestic use.

The Cambrian-Ordovician aquifer is composed of a complex layering of permeable and semipermeable rock units. The stratigraphic column (table 1) shows the lithologic and hydrologic characteristics of the major formations in the aquifer. The top of the aquifer is characterized in northeastern Missouri by a northwest dip broken by the Lincoln fold anticline (fig. 12). The aquifer crops out along the Missouri River where rocks of Mississippian age have been removed by erosion. (See shaded area in figure 12.) The aquifer has a relatively uniform thickness of about 1,200 feet in the northern and western part of the model area, but becomes thicker to the southeast, especially south of the Cap au Gres fault (fig. 13). The thickness data presented in this figure were computer generated using data derived from maps of the top (fig. 12) and base of the aquifer. The following comments about the hydrologic properties of the aquifer apply principally to the eastern one-half of the study area.

The deepest formations that are hydrologically important are the Eminence and Potosi Dolomites; both formations can yield large quantities of water. This is principally a result of the increased permeability and porosity in the coarse-grained vuggy and drusy dolomite of these formations. Well-developed solution channels also commonly are present. Wells penetrating the Eminence and Potosi Dolomites can produce 400 to 1,100 gallons per minute.

The overlying Gasconade Dolomite and Roubidoux Formation contain permeable sandstone bodies and also can yield significant quantities of water. The Gunter Sandstone Member of the Gasconade Dolomite stores sufficient quantities of water to make it a valuable source for municipalities and industry. Wells penetrating the Gunter Sandstone Member at Columbia have produced more than 1,000 gallons per minute, but typical yields range from 50 to 500 gallons per minute.

The most shallow hydrologically important formation is the St. Peter Sandstone. This medium-to-coarse grained sandstone can produce 25 to 75 gallons per minute throughout much of the freshwater part of the aquifer. The St. Peter Sandstone crops out in two small areas atop the Lincoln fold and thins to the south, existing only as small local deposits in southern Callaway and Boone Counties.

Historical water-level data for the Cambrian-Ordovician aquifer are limited in northern Missouri. A few wells were drilled at the turn of the century near the cities of Mexico, Columbia, and Centralia. Because of the presence of adequate surface-water supplies and the lack of industry, few deep wells were drilled until the middle of this century, except for several oil-test wells in the northeastern counties. The range of geologic formations to which the wells are open causes complications in determining water levels in the aquifer. Many wells in this area are open to both Ordovician and Mississippian strata. Even those open only to Cambrian and Ordovician formations rarely are open to the entire aquifer, but instead to specific groups of formations within the aquifer. Thus the water levels reflect vertical as well as horizontal variations in the potentiometric surface. The criteria for selecting prepumping water-level data were the same as those for the Mississppian aquifer; that is, only if it was reasonable to expect that the potentiometric surface at the well site was unaffected by drawdown from wells previously drilled in the area. The water levels used are for various dates during the first half of this century.

The prepumping potentiometric surface for the Cambrian-Ordovician aquifer in northeastern Missouri is shown in figure 14. Because the accuracy of some of the data is questionable, the data were visually smoothed in the process of contouring. It is believed that the potentiometric map properly depicts the general features of the historical ground-water levels. Regional saline water enters Missouri from the northwest (Horick and Steinhilber, 1978). In the vicinity of Linn, Chariton, and Macon Counties this water divides; part flows eastward and passes under the Mississippi River into Illinois, and part flows southward to discharge into the Missouri River in southern Chariton and Howard Counties.

The Cambrian-Ordovician aquifer in an area of approximately eight counties in the southeastern corner of the study area has a local freshwater flow system, which is nearly independent of the regional saline-water flow system. Ground-water divides prevent the regional saline water from entering the freshwater area. Water enters this local flow system by leakage from the overlying Mississippian aquifer, primarily in southwestern Audrain County and northern Warren County (fig. 7), and by infiltration where the aquifer crops out along the Missouri River and atop the southern end of the Lincoln fold (shaded area in fig. 14). The small unnamed faults located south of the major Cap au Gres fault system (fig. 12) do not significantly affect ground-water flow in the aquifer, but the Cap au Gres fault impedes the movement of ground water.

The withdrawal of water from the freshwater part of the Cambrian-Ordovician aquifer has steadily increased during this century. An exception to this is at Columbia, which began to supplement water from deep wells with water from wells drilled into the Missouri River alluvial deposits during

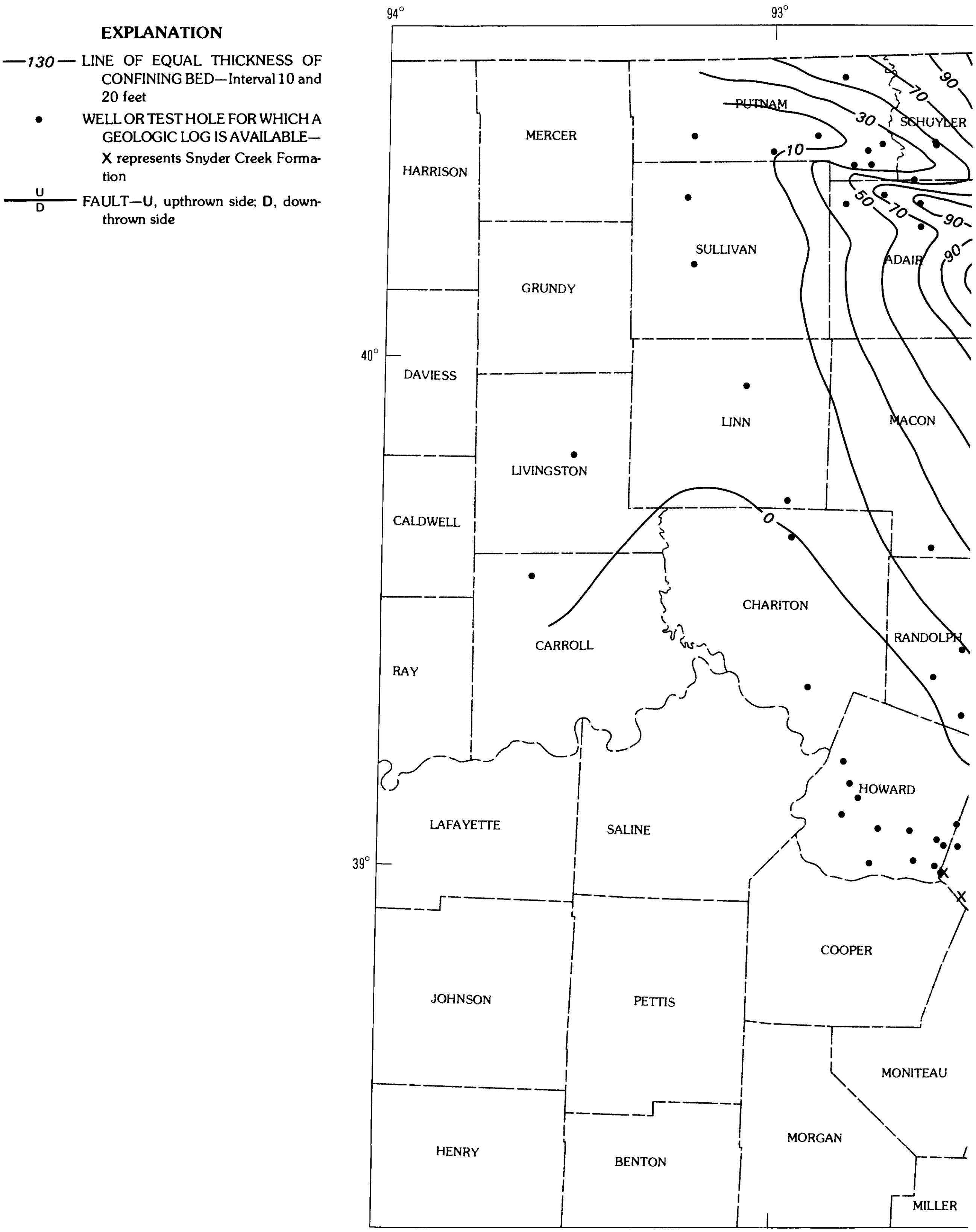
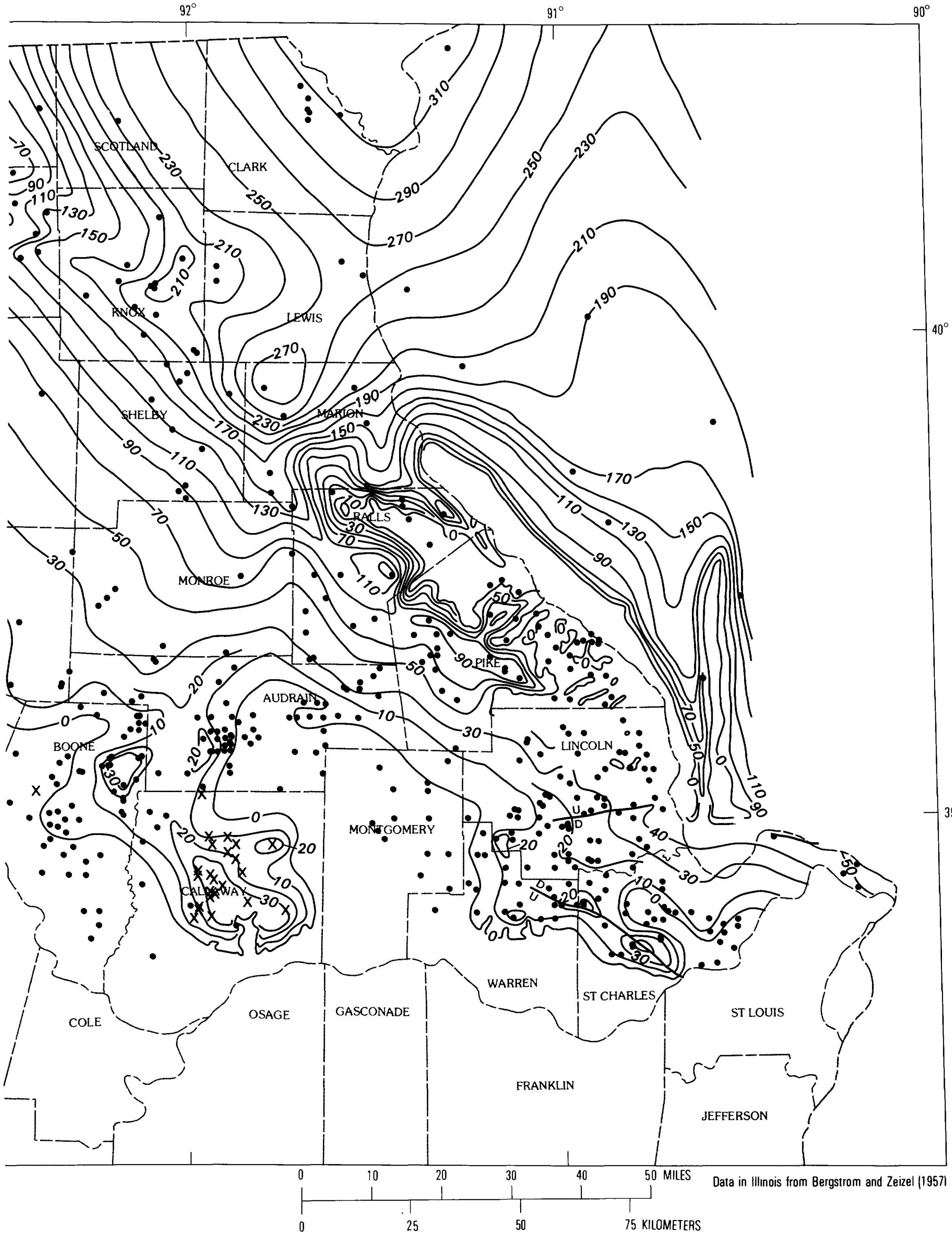


FIGURE 9.—Thickness of the combined Kinderhookian and Upper Devonian confining formations.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Data in Illinois from Bergstrom and Zeizel (1957)

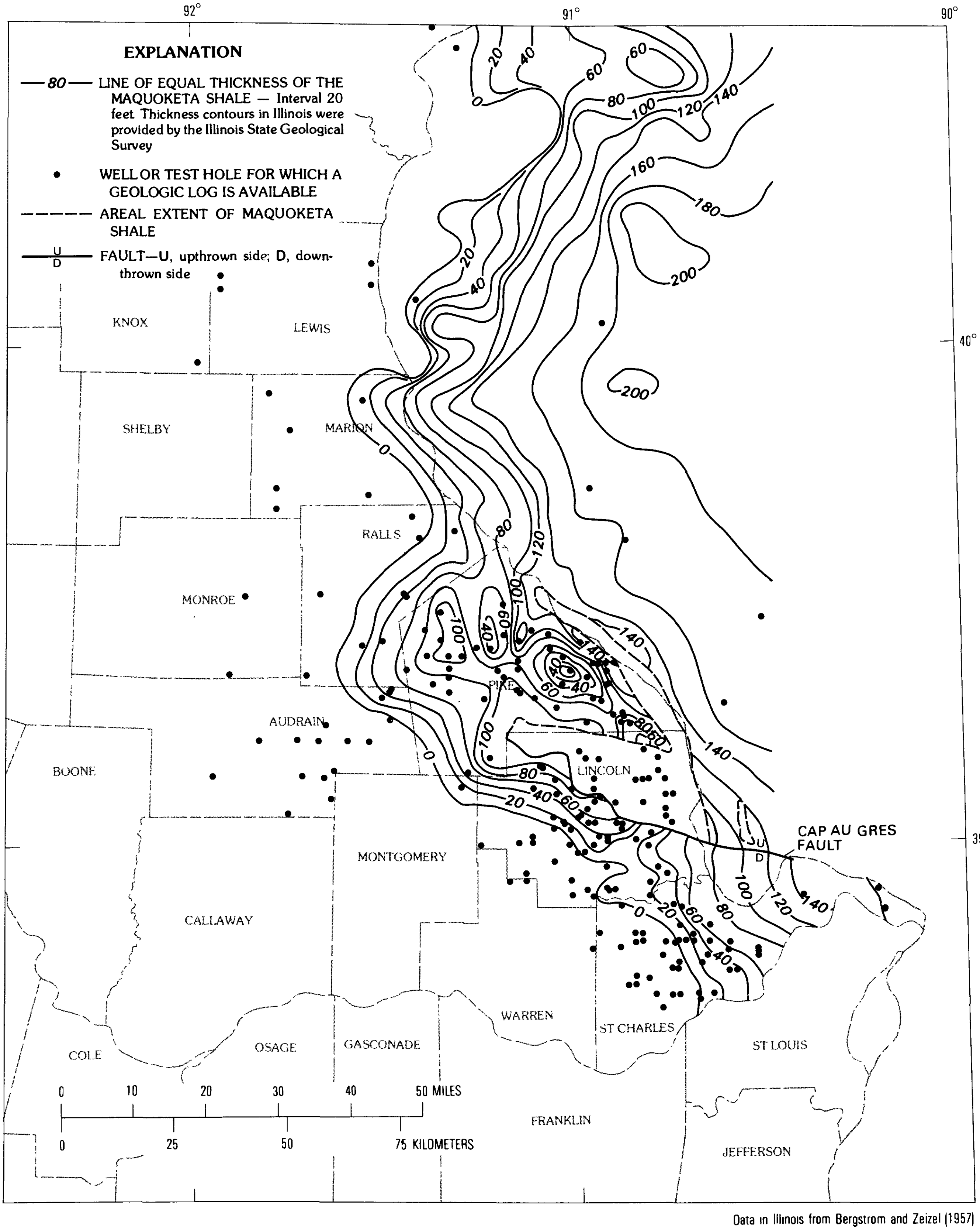


FIGURE 10.—Thickness of the Maquoketa Shale.

the late 1960's. The contours in figure 15 represent a potentiometric surface based on data collected primarily during the 1960's (referred to as the "1965" potentiometric surface). A well-developed drawdown cone existed around Columbia by this time. Much smaller areas of drawdown are evident near Mexico, Fulton, and O'Fallon. During the 1970's, the population of central St. Charles County increased rapidly and Audrain County experienced a rapid growth in crop irrigation and an increase in the population of Mexico. By May 1979, the increased rate of ground-water withdrawal had altered the potentiometric surface to that shown in figure 16. The increasing stresses resulted in a substantial drawdown cone around O'Fallon, and in the joining of the Mexico and Columbia drawdown cones. Water levels measured during May 1979 are predominantly from Audrain, Boone, and Callaway Counties.

WATER QUALITY

Water containing more than 1,000 milligrams per liter of dissolved solids is considered saline by the U.S. Geological Survey (Hem, 1970, p. 219). Saline water is classified as slightly saline (1,000–3,000 milligrams per liter), moderately saline (3,000–10,000 milligrams per liter), very saline (10,000–35,000 milligrams per liter), and briny (more than 35,000 milligrams per liter). Water from the localized freshwater area of the Cambrian-Ordovician aquifer has dissolved-solids concentrations ranging from about 350 to 750 milligrams per liter (fig. 17). A transition from saline to freshwater, as defined by the line representing a concentration of 1,000 milligrams per liter of dissolved-solids, occurs along an approximate east-west line passing through northern Audrain and central Pike Counties and along the western border of Boone County. The transition also occurs in St. Charles County and eastern Lincoln County.

Water in the Cambrian-Ordovician aquifer is saline in the regional-flow system to the north and west of Audrain County (fig. 17). The greatest salinity occurs along the southwest edge of the study area and in northeastern Ralls County where water in the aquifer can have greater than 10,000 milligrams per liter dissolved-solids concentration (fig. 17). As the saline water flows eastward from Missouri into Illinois, it flows around the northern edge of the Lincoln fold and flows south through eastern St. Charles County. Thus the water in this part of St. Charles County also is saline. Because of its salinity, no municipal and few domestic wells are completed in the aquifer outside the freshwater region in the southeast part of the study area. A more detailed study of water quality in the Cambrian-Ordovician aquifer is presented in Emmett and Imes (1983).

VERTICAL GROUND-WATER MOVEMENT

Those regions where the Cambrian-Ordovician aquifer was recharged by or discharged into the Mississippian aquifer, before stresses were applied to the flow system, are delineated by the shaded areas in figure 17. Three primary recharge centers in the local freshwater zone are clearly outlined by the transition line between recharge and discharge areas. Recharge to two of these centers is by leakage from the Mississippian aquifer (see potentiometric surface mounds in southwest Audrain County and northeast Warren County in figure 7) and to the third center atop the Lincoln fold by precipitation (see shaded area in figure 14). The discharge areas parallel the major rivers of northeastern Missouri. The distribution of water discharging from the aquifer as shown by this map is consistent with information obtained from drillers' logs. This is evident by comparing the location of those data points in figure 14 depicting increasing potentiometric head with depth and flowing artesian wells with the discharge areas shown in figure 17. The conceptual vertical flow pattern is supported by dissolved-solids concentration data from wells open to the Mississippian aquifer (fig. 18). In the vicinity of Chariton and southern Howard Counties, where the overlying confining bed is leaky, the Mississippian aquifer contains more saline water due to upward movement of saline water from the Cambrian-Ordovician aquifer. This degradation does not occur in the large discharge area along the Mississippi River in the northeast where the confining bed that overlies the Cambrian-Ordovician aquifer contains as much as 200 feet of shale. The hydrogeologic cross section *E-E'* (pl. 1) depicts this shale and the relative positions of the potentiometric surfaces above and below the confining bed. The point at which the Cambrian-Ordovician potentiometric surface rises above the water levels of the shallow aquifers represents the transition to the discharge area.

The thick shale confining bed impedes the upward movement of water and causes the potentiometric surface of the Cambrian-Ordovician aquifer to rise more than 100 feet higher than that of the Mississippian aquifer. Any small quantity of saline water that does move upward through the shale may be subject to a filtering process that can trap dissolved electrolytes while allowing water molecules to pass freely (Hanshaw and Zen, 1965, p. 1379). Therefore, little saline water may actually be moving into the Mississippian aquifer in this area.

LOWER CONFINING BED

The confining bed at the base of the Cambrian-Ordovician aquifer is the Davis Formation. The Davis Formation and the overlying Derby–Doe Run Dolomites comprise the Elvins Group. Although the Derby–Doe Run sequence has been included as part of the aquifer, it probably contributes little water. The Davis is a relatively thick dolomitic formation (ranging in thickness from 100 to 300 feet) underlying the entire study area, except above the Lincoln fold where it is absent. Shale and silt comprise as much as 50 percent of the Davis Formation and impede water movement between the

EXPLANATION

—80— LINE OF EQUAL THICKNESS OF MIDDLE AND LOWER DEVONIAN AND SILURIAN DEPOSITS—Interval 20 feet

• WELL OR TEST HOLE FOR WHICH A GEOLOGIC LOG IS AVAILABLE

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

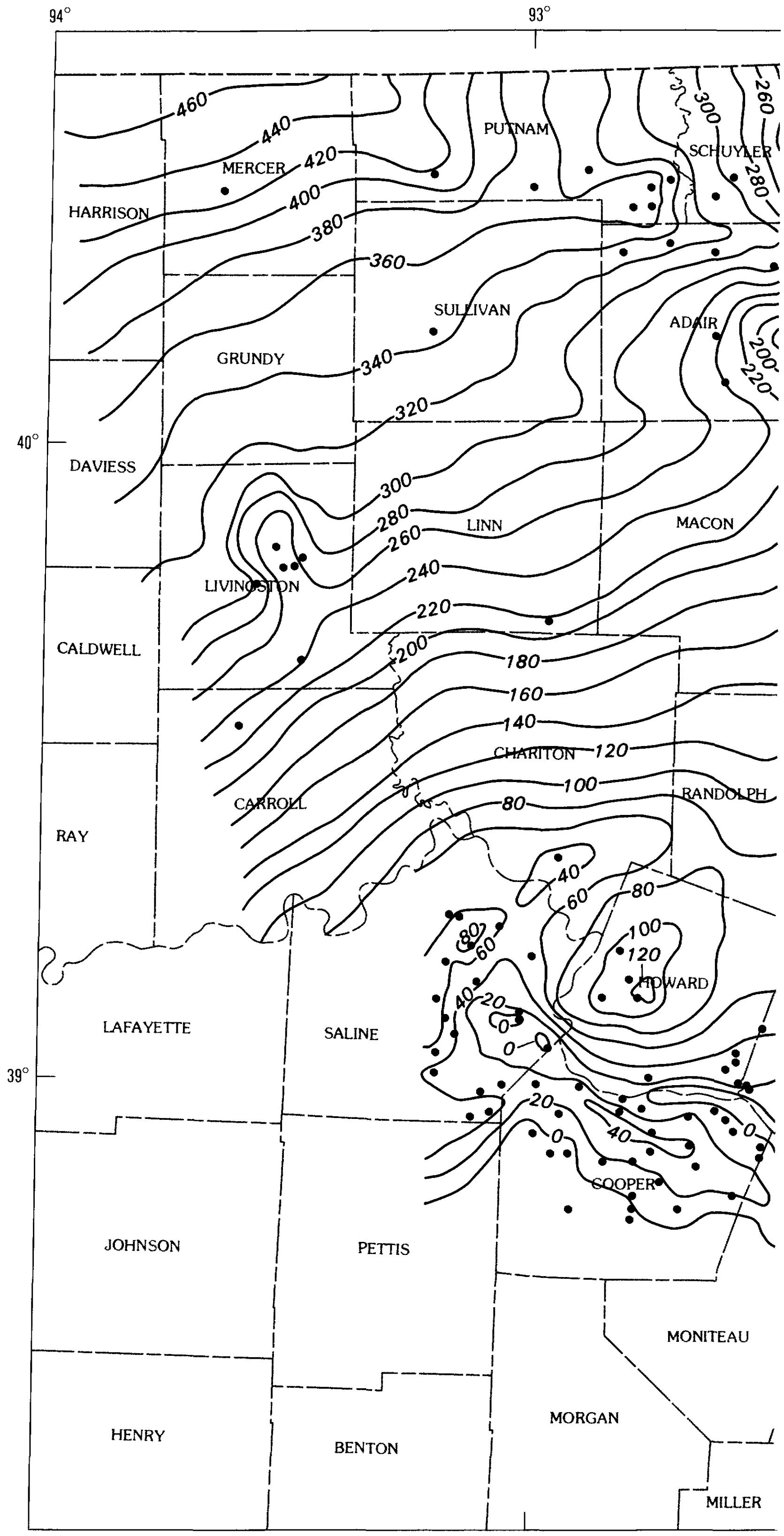
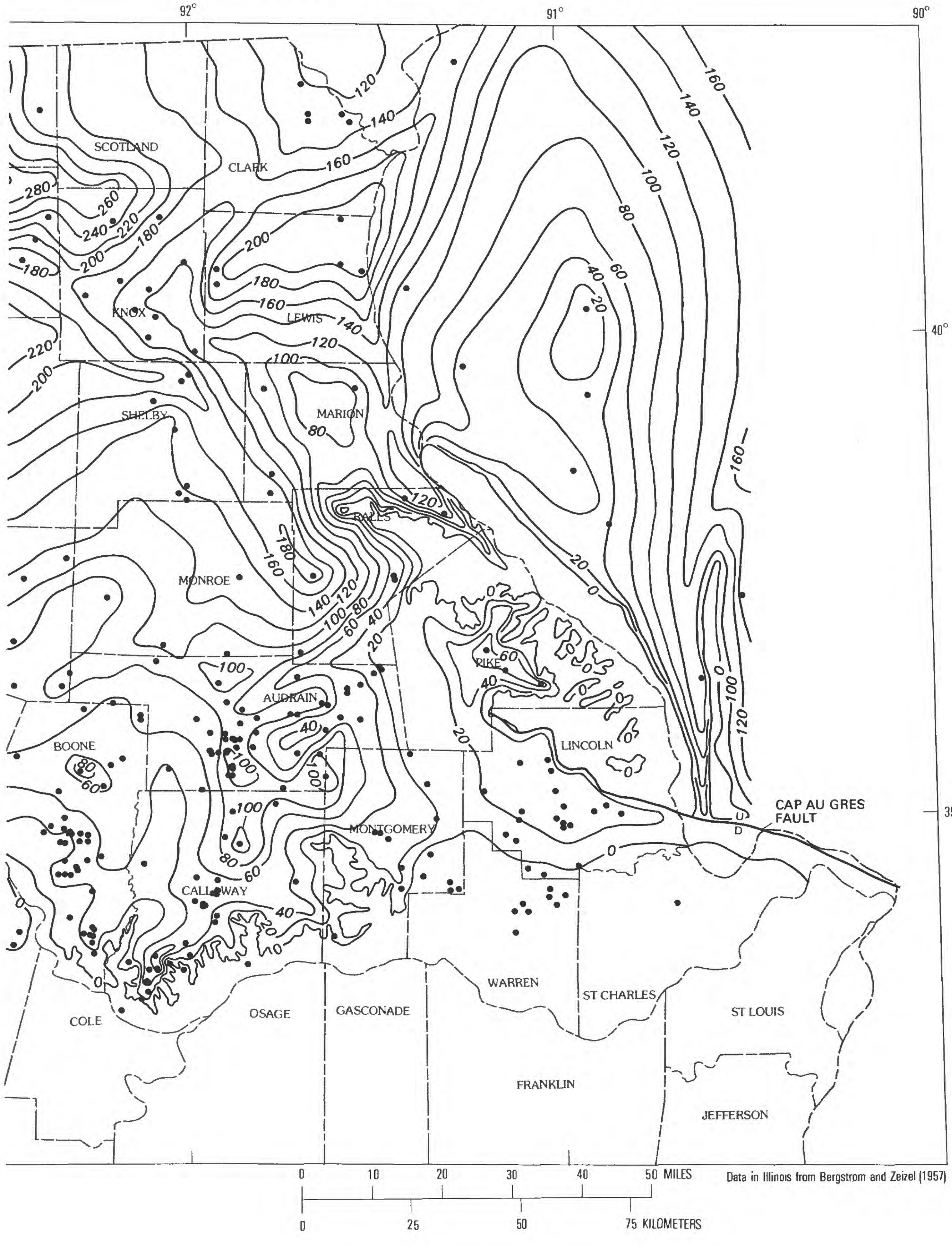


FIGURE 11.—Thickness of the combined Middle and Lower Devonian and Silurian rocks.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ST LOUIS
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JEFFERSON
CAP AU GRES FAULT
U
D
0 10 20 30 40 50 MILES
0 25 50 75 KILOMETERS
Data in Illinois from Bergstrom and Zeizel (1957)

EXPLANATION

—*300*— STRUCTURE CONTOUR—Shows altitude of top of Cambrian-Ordovician aquifer. Contour interval 100 feet. National Geodetic Vertical Datum of 1929

• WELL OR TEST HOLE FOR WHICH A GEOLOGIC LOG IS AVAILABLE

OUTCROP AREA OF THE CAMBRIAN-ORDOVICIAN AQUIFER

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

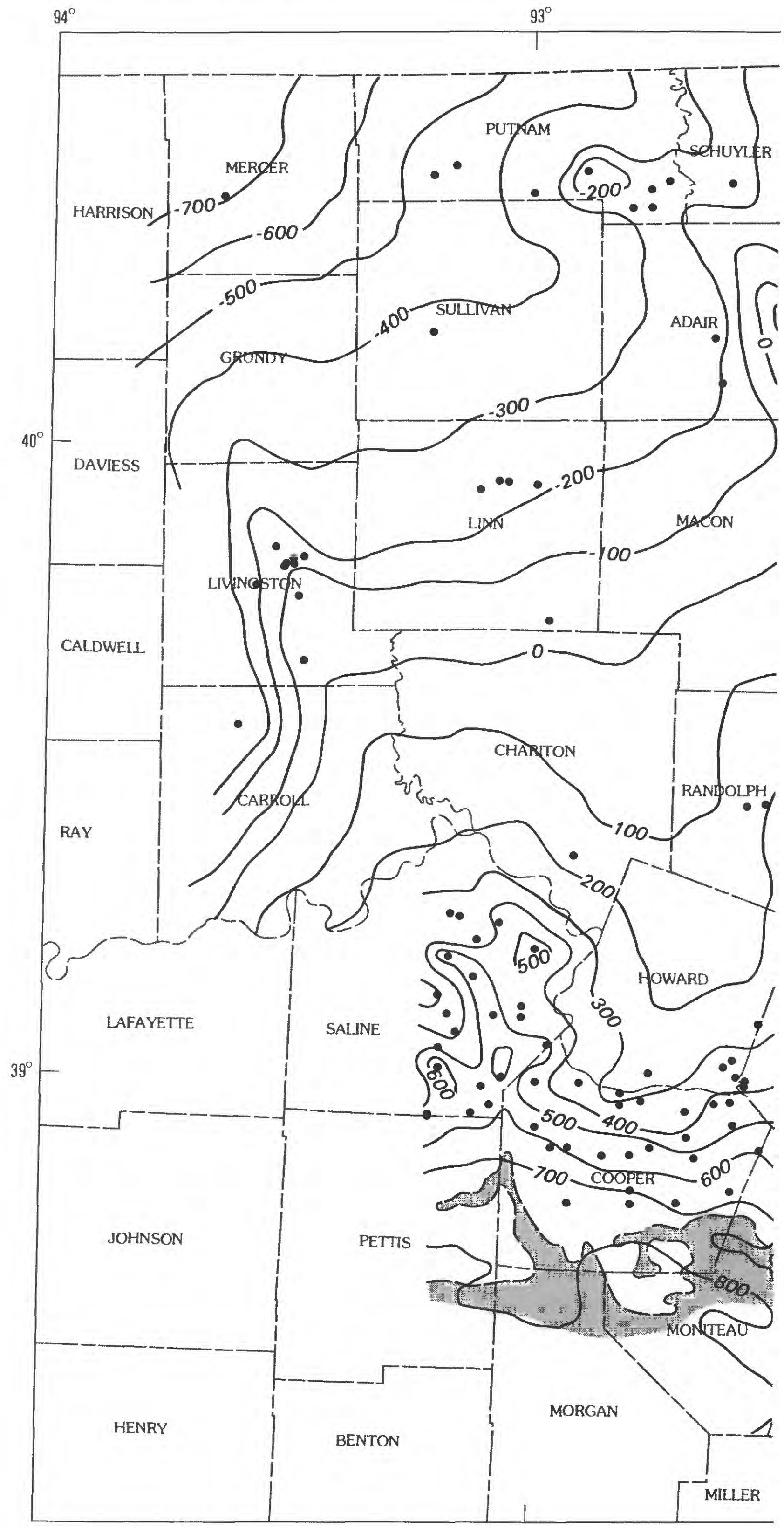
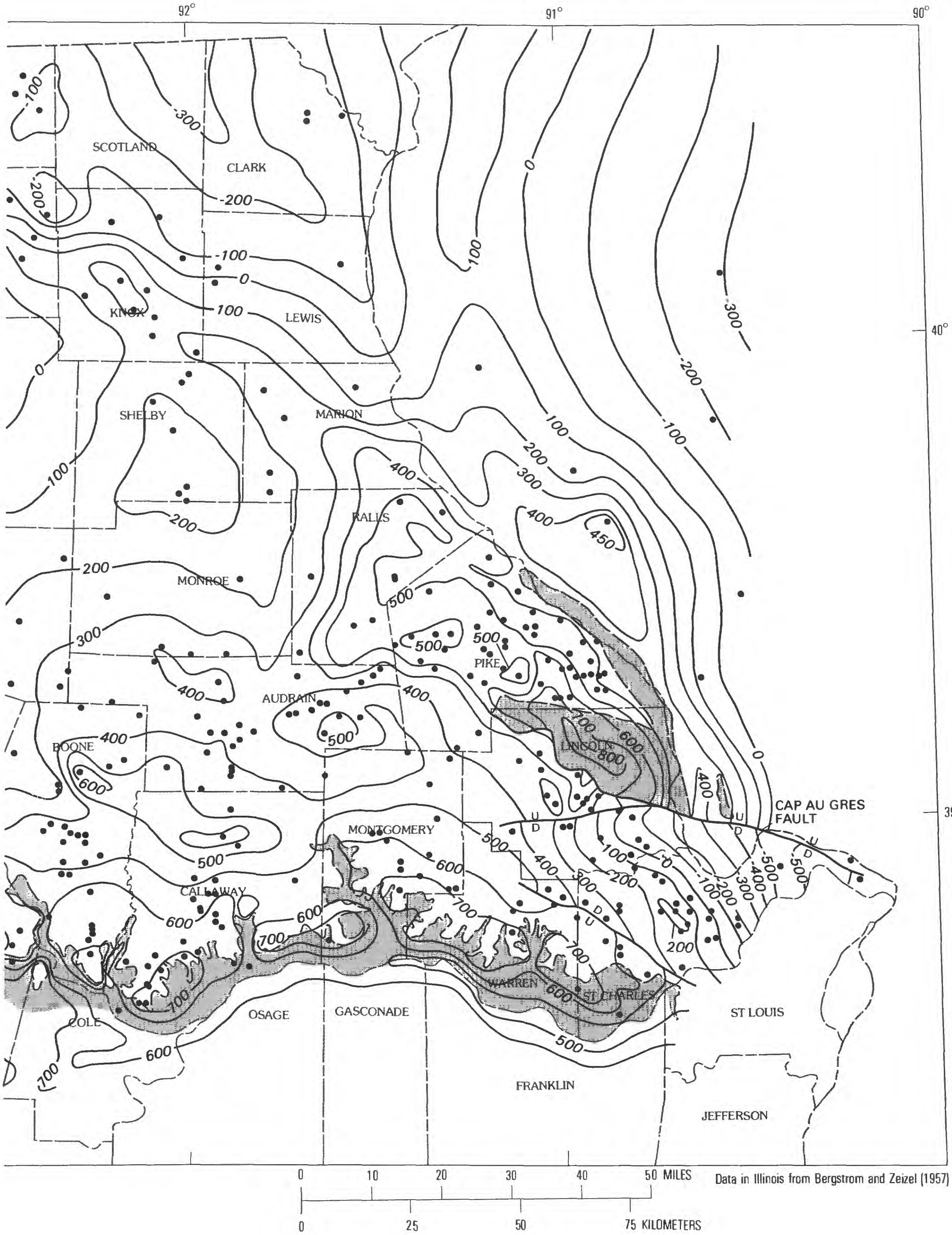


FIGURE 12.—Altitude of the top of the Cambrian-Ordovician aquifer.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0 10 20 30 40 50 MILES
0 25 50 75 KILOMETERS
Data in Illinois from Bergstrom and Zeizel (1957)

EXPLANATION

—*1400*— LINE OF EQUAL THICKNESS OF CAMBRIAN-ORDOVICIAN AQUIFER—Interval 100 feet

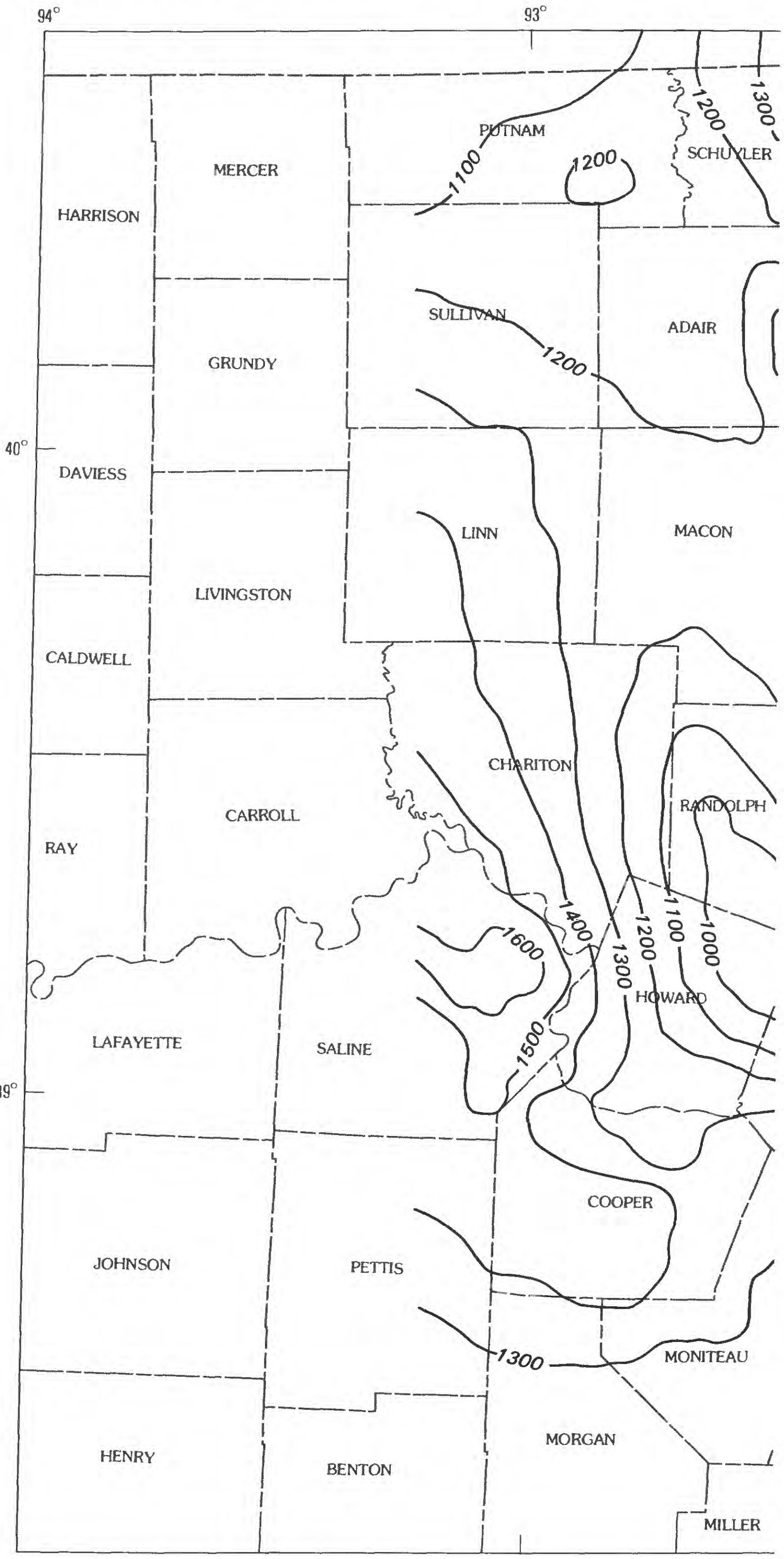
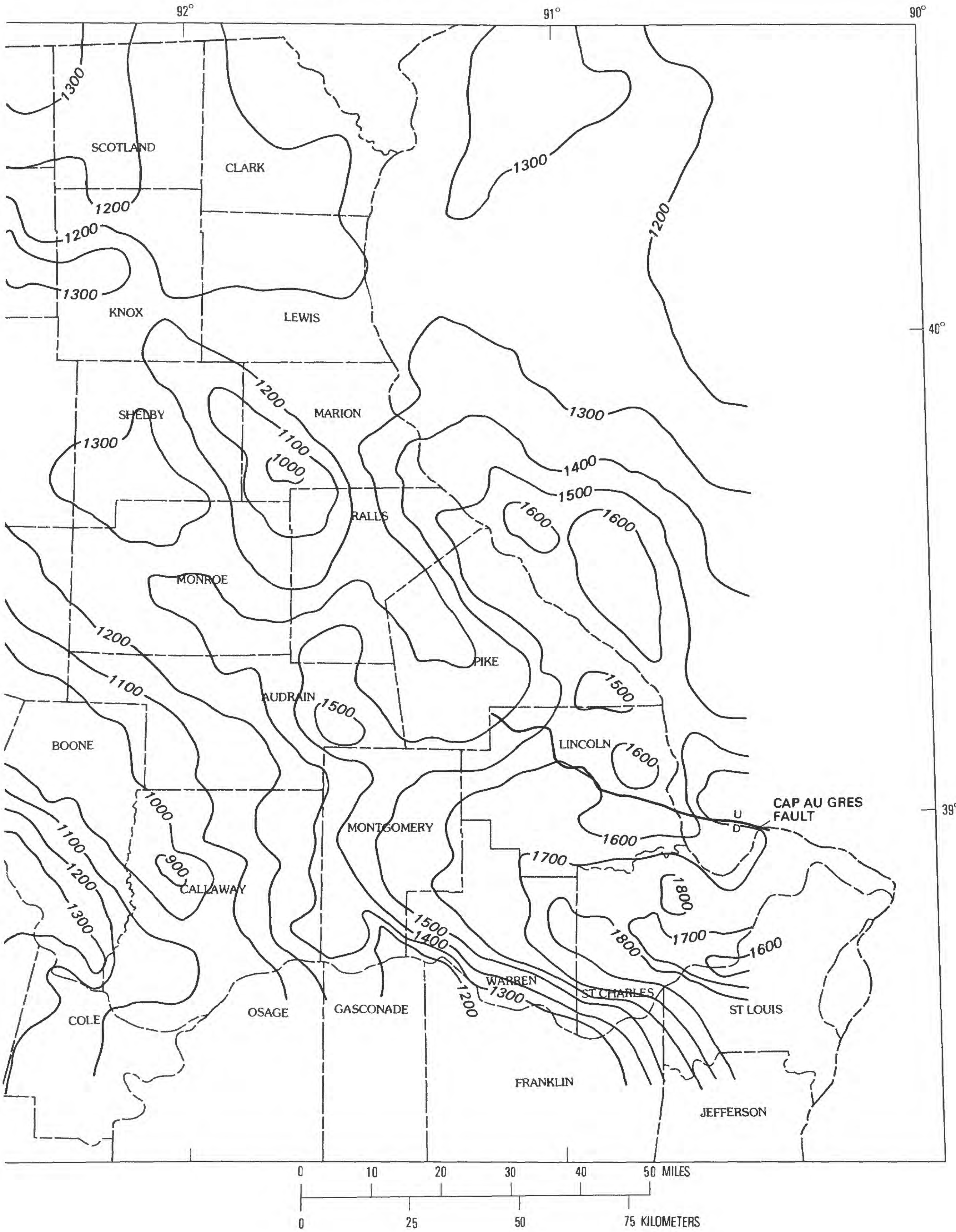


FIGURE 13.—Thickness of the Cambrian-Ordovician aquifer.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0 10 20 30 40 50 MILES
0 25 50 75 KILOMETERS

EXPLANATION

— 650 — POTENTIOMETRIC CONTOUR — Shows altitude of the actual prepumping potentiometric surface of the Cambrian-Ordovician aquifer. Contour interval, in feet, is variable. National Geodetic Vertical Datum of 1929

•670 WELL—Number is altitude of measured potentiometric head, in feet above National Geodetic Vertical Datum of 1929. A indicates flowing artesian well; indicates increasing potentiometric head with depth-discharge based on drillers' records; indicates decreasing potentiometric head with depth-recharge based on drillers' records

OUTCROP AREA OF THE CAMBRIAN-ORDOVICIAN AQUIFER

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

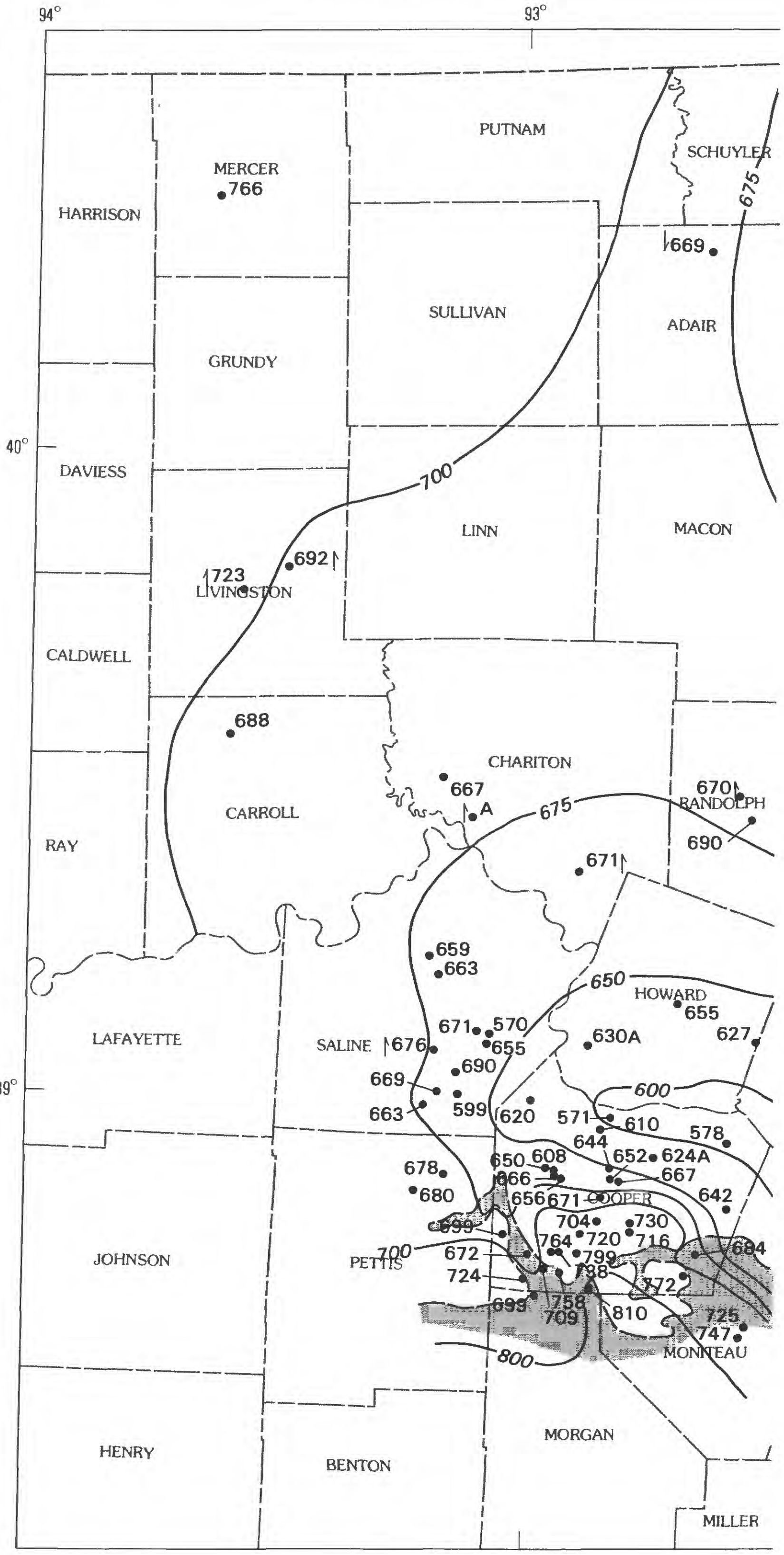
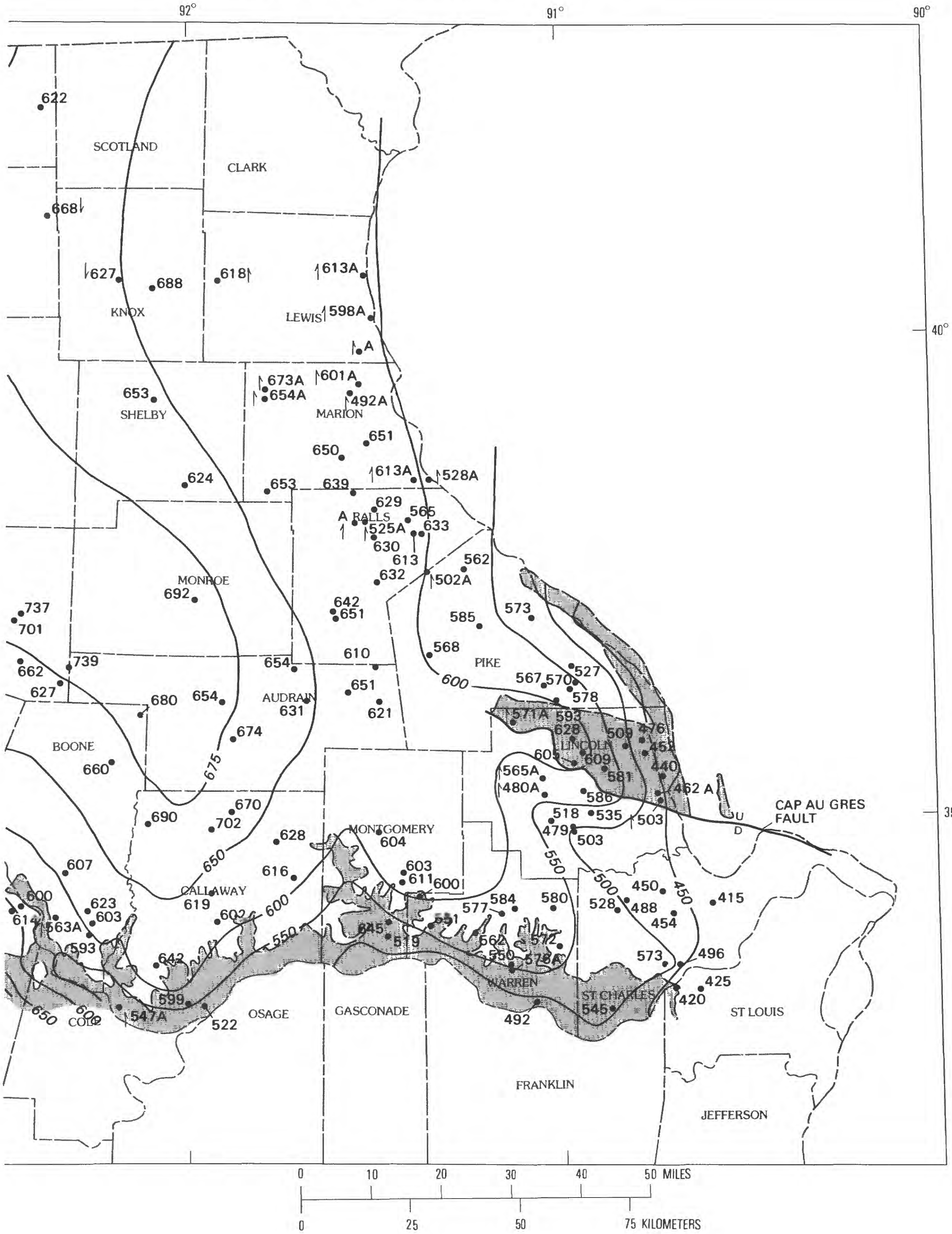


FIGURE 14.—Altitude of the prepumping potentiometric surface of the Cambrian-Ordovician aquifer.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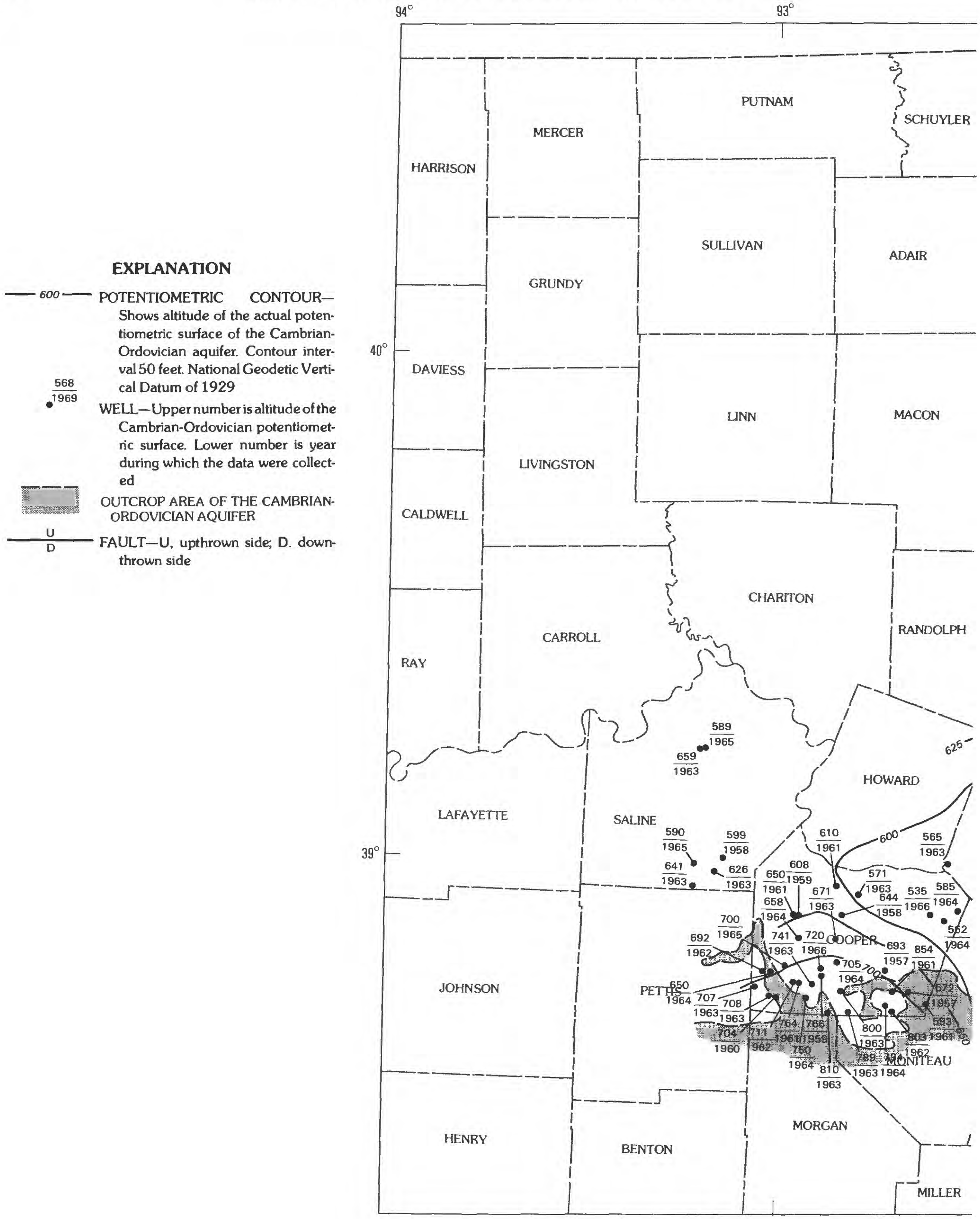
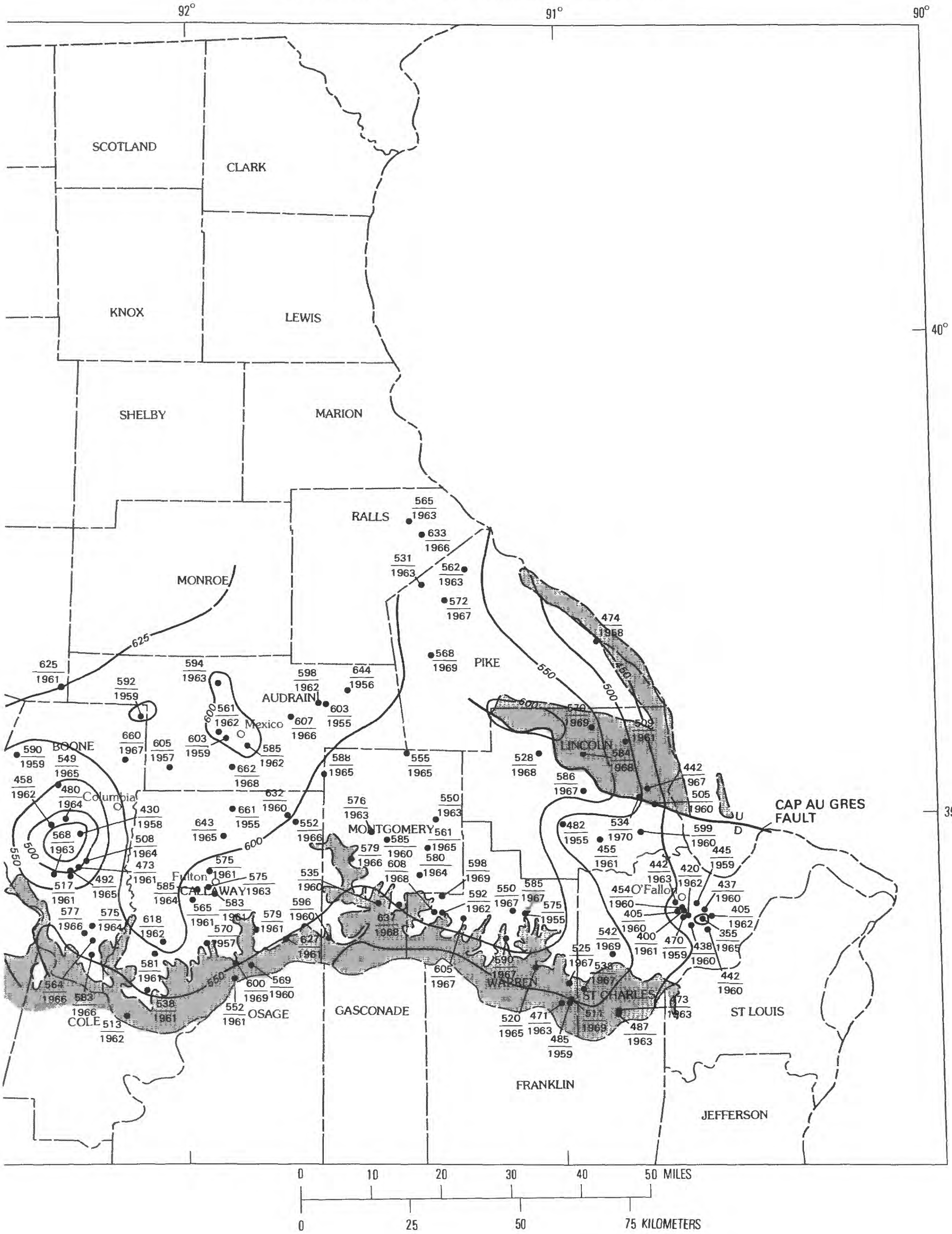


FIGURE 15.—Altitude of the "1965" potentiometric surface of the Cambrian-Ordovician aquifer.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WARREN
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ST LOUIS
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JEFFERSON
CAP AU GRES
FAULT
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625
600
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0 10 20 30 40 50 MILES
0 25 50 75 KILOMETERS

EXPLANATION

—575— POTENTIOMETRIC CONTOUR—Shows altitude of actual potentiometric surface of the Cambrian-Ordovician aquifer. Contour interval, in feet, is variable. National Geodetic Vertical Datum of 1929

593 / •1977 WELL—Upper number is altitude of the Cambrian-Ordovician potentiometric surface, in feet, above National Geodetic Vertical Datum of 1929. Lower number is year during which the data were collected. If no lower number is present, data were collected during May, 1979. P, measurement made while well was being pumped. T, measurement made while nearby well was being pumped

OUTCROP AREA OF THE CAMBRIAN-ORDOVICIAN AQUIFER

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

FIGURE 16.—Altitude of the May 1979 potentiometric surface of the Cambrian-Ordovician aquifer.


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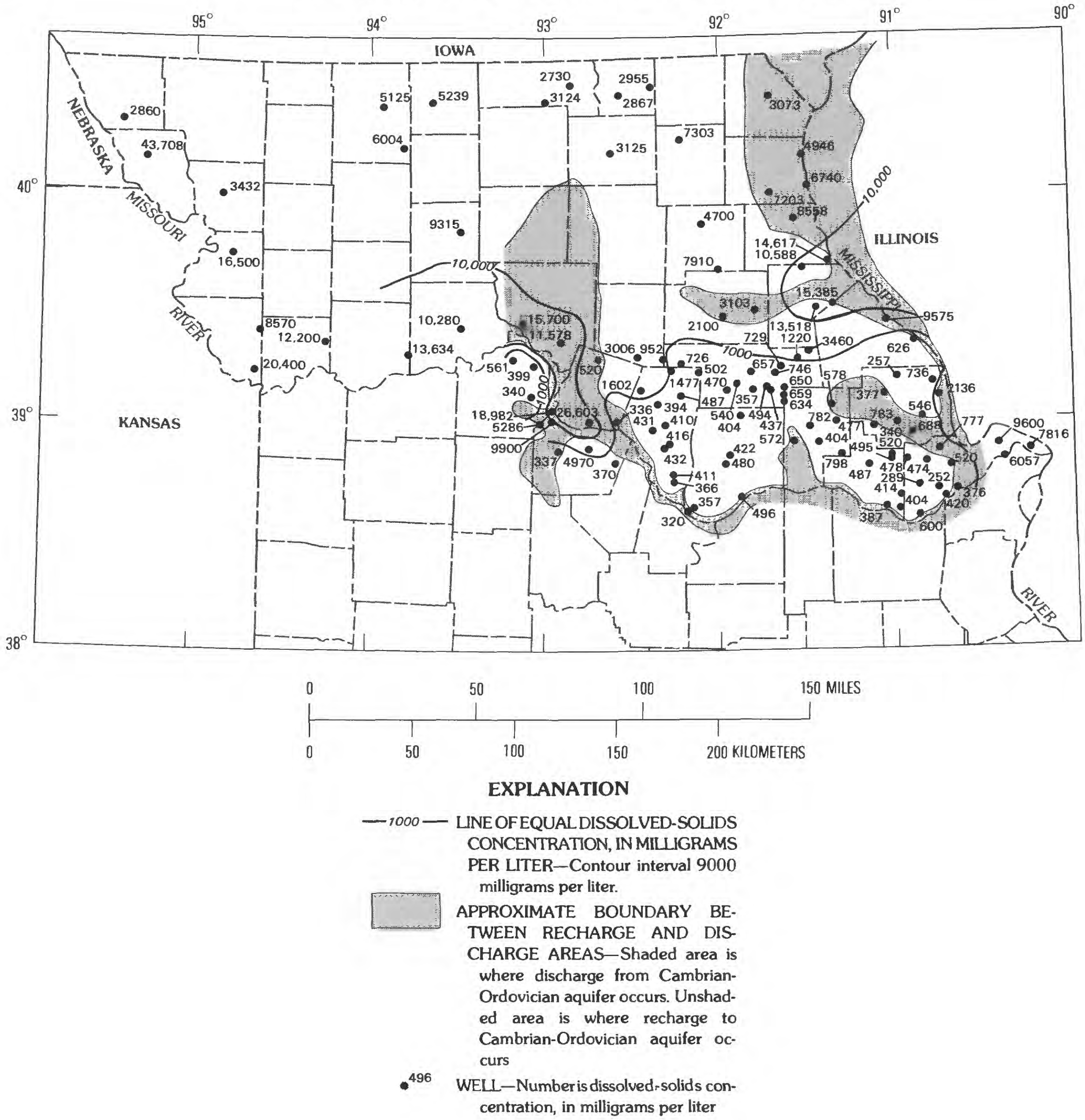


FIGURE 17.—Areas of recharge and discharge and the dissolved-solids concentration in the Cambrian-Ordovician aquifer.

Cambrian-Ordovician aquifer and the underlying Lamotte Sandstone and Bonneterre Dolomite. Data are not sufficient to confirm the confining ability of the Davis Formation in northern Missouri, but the assumption is supported by water-level measurements made south of the model area where water levels above and below the Davis Formation differ by 50 feet, and, therefore, indicate that the Davis Formation is a confining bed.

THE DIGITAL MODEL

GENERAL FEATURES AND DATA PREPARATION

A two-dimensional digital model of the Cambrian-Ordovician aquifer in northeastern Missouri was prepared using the Trescott, Pinder, and Larson (1976) ground-water model. Finite-difference techniques are used to solve the basic flow

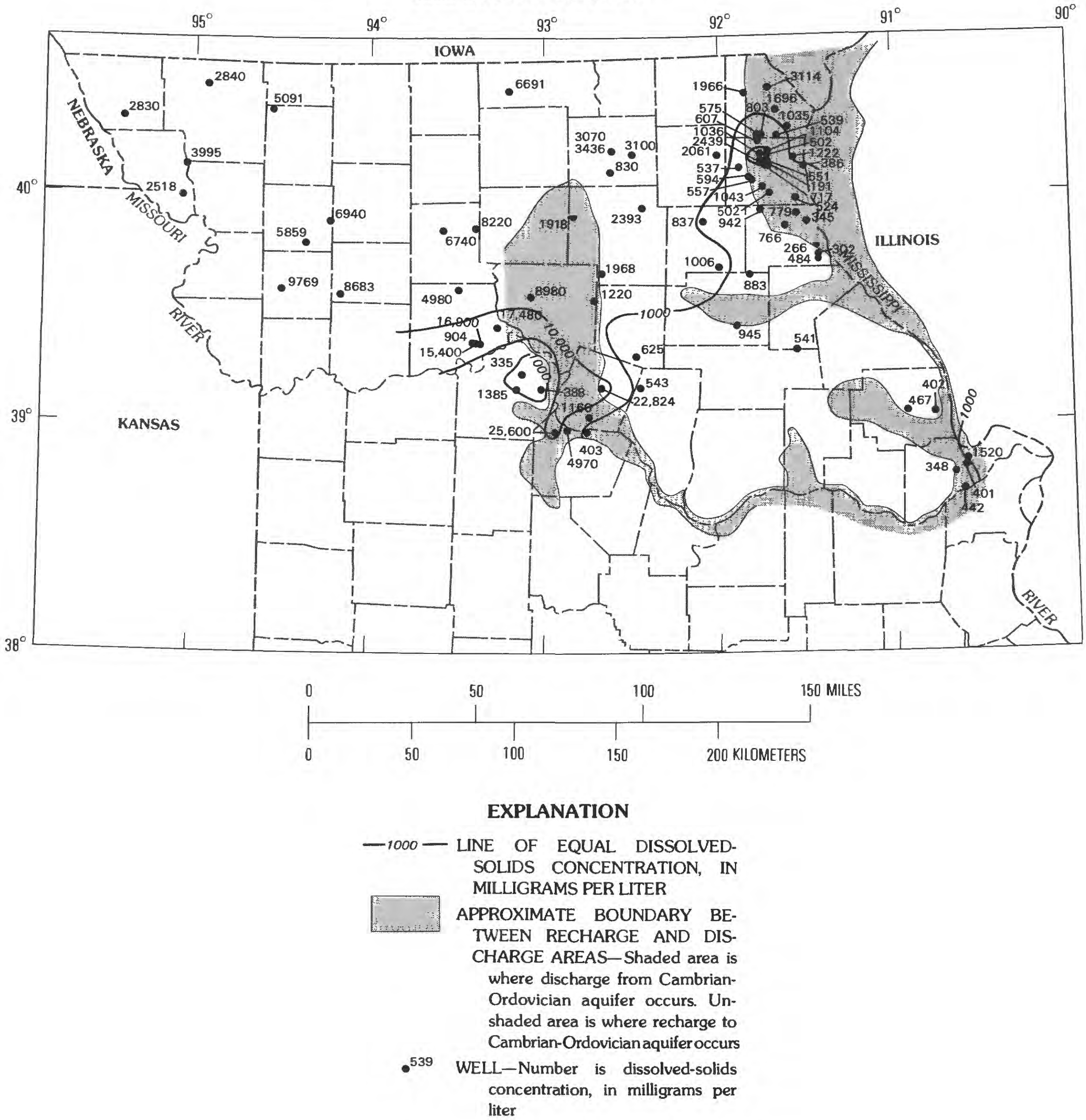


FIGURE 18.—Dissolved-solids concentration in the Mississippian aquifer.

equation in this model. The model provides conversion from confined to unconfined conditions as potentiometric levels decline below the top of the aquifer. The form of the ground-water flow equation applicable to this aquifer model is:

$$\frac{\partial}{\partial x}\left(K_{xx} b \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy} b \frac{\partial h}{\partial y}\right) = S \frac{\partial h}{\partial t} + W(x,y,t), \quad (1)$$

where K_{xx} and K_{yy} are the principal components of hydraulic conductivity and are assumed to be collinear with the Cartesian coordinate axes (LT^{-1}); b is the saturated thickness of the aquifer (L); S is the storage coefficient when the aquifer is confined and converts to the specific yield (Sy) if the aquifer becomes unconfined (dimensionless); and W(x,y,t) is a function that describes the recharge flux into, or discharge flux out of, the aquifer (LT^{-1}). W(x,y,t) generally is a composite of several terms. In this model these terms are well discharge, leakage through confining beds, streambed leakage, and recharge at outcrop locations. The flow equation is solved by the strongly implicit procedure (SIP), an efficient modification of the Gaussian elimination method of numerical solution.

The modeled area is divided into 1,886 rectangular elements by a grid of 41 horizontal rows and 46 vertical columns (fig. 19). The horizontal node spacing is constant at 3.2 miles, but the vertical node spacing ranges from 6.4 miles in the northern one-third to 3.2 miles in the southern two-thirds of the model area. The geologic and hydrologic data assigned to each node were determined by interpolating contour-map data. The transformation from contour-map format to digital-point format for this model was accomplished using a computer program developed by the U.S. Geological Survey.

TWO-DIMENSIONAL MODEL MODIFICATIONS

During the transient calibration, two small "single node" drawdown cones were noticed at locations where no pumping wells existed. An investigation showed that the model incorrectly withdraws water from the transition zone between the confined and unconfined (outcrop) regions of the aquifer under certain conditions. This error occurs due to the relative values of water levels and the aquifer top, and only when the option to convert from artesian to water-table conditions is used. It is quite possible for this error condition to go undetected if the withdrawal rate is not large.

The Trescott, Pinder, and Larson (1976) two-dimensional model treats leakage through an overlying confining bed as proportional to the difference between the potentiometric surface of the aquifer above the confining bed (River) and the current potentiometric surface of the aquifer being modeled (PHI), divided by the confining-bed thickness (M),

$$L \alpha (River - PHI)/M.$$

If the aquifer becomes unconfined as its potentiometric surface is lowered, the leakage is limited by not allowing the gradient across the aquifer to become greater than (River – Top)/M, where "Top" is the top of the aquifer. When this condition (Top > PHI) is reached, the aquifer is assigned a specific yield (Sy) to replace the storage coefficient (S) associated with the aquifer under confined conditions.

In the development of this model, the array River was assigned values of the prepumping potentiometric surface of the Mississippian aquifer, except in outcrop areas where the surface was smoothly merged into the prepumping potentiometric surface of the Cambrian-Ordovician aquifer. During transient calibration the array PHI (or STRT) was first assigned the simulated Cambrian-Ordovician potentiometric surface from the steady-state calibration. The array Top was assigned the altitude of the top of the Cambrian-Ordovician aquifer. The relative positions of these surfaces are shown in figure 20. With these definitions it is possible for the top of the aquifer to be higher than both River and PHI in the transition zone where the confining bed crops out. At nodes within this transition zone, the model "limits" the leakage (because Top > PHI) and sets the leakage proportional to (River - Top)/M, which is negative. Therefore, water is improperly withdrawn from the aquifer at these nodes.

A similar situation in which the confining bed thins out before reaching the surface is shown in figure 21. The model may fail to assign proper storage variables to the aquifer in part of the transition zone (zone 3). This will occur when the current aquifer water level and the level from a prior iteration are greater than the top of the aquifer, but no confining bed is present. This difficulty occurs when the aquifer becomes unconfined in a small region along the edge of an outcrop area. The problem is more fundamental that just indicated because it involves the definition of the aquifer. Hydrologically, there is only one aquifer in zone 3, but the zone is being treated as if it contained two distinct hydrologic units. No attempt has been made to adjust the transmissivity in this zone because the error in this model will be quite small.

Brief summaries of the manner in which the model treats each situation before and after modifications are shown in figures 20 and 21. The Fortran code changes that have been made in the model are listed in the "Additional Data" section at the end of this report. The changes represent an alternative method for treating these situations, the other being to adjust the confining-bed thickness array and the potentiometric surface above the confining bed on a node-by-node basis to generate the proper leakage in the transition zones. With the changes presented here, these arrays can be taken directly from formation-thickness and hydrologic maps. These changes are necessary due to the limitations inherent in applying a two-dimensional model to a three-dimensional problem.

BOUNDARY CONDITIONS

Boundary conditions for this model were determined as accurately as possible from available data. Because effects of boundary conditions generally can be observed in the interior of a model, accurate boundary conditions or the placing of boundaries well away from the area of interest is necessary. All zero-flux model boundaries (fig. 19) need to be placed at a sufficient distance from the area of interest so that they do not cause excessive drawdown by limiting the quantity of water available to flow toward pumping wells. The northern boundary is treated as a zero-flux or no-flow boundary. Because ground-water flow virtually parallels this boundary, as indicated by the map showing the prepumping potentiometric surface of the Cambrian-Ordovician aquifer (fig. 14), and there are no deep wells in use in the northern, saline-water part of the aquifer, it is a good representation of actual conditions.

The eastern and western boundaries (fig. 19) are simulated as constant-flux or constant-flow boundaries based on application of Darcy's Law at the appropriate nodes:

$$Q = Kb\,\Delta y\,\frac{\Delta h}{\Delta x}, \qquad (2)$$

where b(△y) is the aquifer cross-sectional area across which flow occurs (L^{2}), K is the hydraulic conductivity (LT^{-1}), and $\frac{\Delta h}{\Delta x}$ is the hydraulic gradient at the boundary of the model (dimensionless). The boundary fluxes applied during the steady-state model calibration were derived using hydraulic gradients estimated from the prepumping potentiometric map. Due to the proximity of pumping wells to the extreme southeastern corner of the model (St. Charles County), it is necessary to modify nearby boundary fluxes with time when transient conditions are simulated. This cannot be done directly because there are not enough data to determine the actual hydraulic gradient as a function of time. Therefore, the adjustment of boundary fluxes was made by observing the shape of the drawdown cone around the city of O'Fallon in central St. Charles County during each pumping period of the model. When the drawdown cone reaches the boundary, it distorts from the shape it would maintain if the boundary were not present. The boundary fluxes are then adjusted to increase the flow of water toward the drawdown cone, thus restoring its previous shape. Because there are no wells pumping significant volumes of water from the aquifer just outside the model boundary, this method of treating the boundary is valid. The time-varying boundary condition does not begin until the 1965–1970 pumping period.

The Cambrian-Ordovician aquifer is exposed immediately north of, and is deeply eroded by, the Missouri River from Howard County east to St. Charles County. Potentiometric data along the river indicate the aquifer water levels are approximately equal to those of the river, but there is some evidence from deep wells that indicates water moves vertically upward into the river. Thus streambed leakage is simulated in nodes along the southern edge of the model (see figs. 14 and 19). The leakage rate is defined as:

$$L = K'_{st}\left(\frac{A_s}{A}\right)\frac{\Delta h}{1}, \qquad (3)$$

where K'_{st} is the effective vertical hydraulic conductivity of the streambed (LT^{-1}),

$\frac{A_s}{A}$ is the ratio of streambed (alluvium) area within the grid cells to the entire cell area (dimensionless), and

$\frac{\Delta h}{1}$ is the hydraulic gradient across a uniform 1-unit thick streambed (dimensionless). A similar situation occurs adjacent to the Lincoln fold where Ordovician rocks crop out and have been eroded by the Mississippi River.

CALIBRATION OF THE MODEL

STEADY-STATE CALIBRATION

The model was first calibrated by adjusting hydrologic variables until the simulated predevelopment potentiometric surface under steady-state conditions matched the historic predevelopment potentiometric surface. Assuming proper boundary conditions, the transmissivity of the aquifer and vertical leakage across the confining beds control the hydrologic flow system. The Cambrian-Ordovician aquifer crops out along the Missouri and Mississippi River. In the outcrop areas precipitation recharges the aquifer at the higher elevations and ground-water discharges from the aquifer along the river valleys. Recharge was introduced at outcrop nodes located within the recharge area shown in figure 17. The average quantity of recharge required to calibrate these nodes was 6.0×10^{-10} foot per second (0.6 percent of the yearly precipitation). No information is available that will allow a more accurate treatment using actual precipitation and evapotranspiration rates or base-flow measurements.

The initial aquifer transmissivity array used in the model calibration was determined as a product of the aquifer thickness array (constructed from fig. 13) and an estimate of the hydraulic conductivity (1.0×10^{-5} foot per second) obtained from aquifer-test data of southeastern Audrain County:

$$T = Kb, \qquad (4)$$

where K is the aquifer hydraulic conductivity (LT^{-1}), and b is the aquifer thickness (L). In a similar manner, the effective vertical leakage array of the overlying composite confining bed was calculated from the individual confining units (figs. 9, 10, and 11). The confining-bed leakage is proportional to the leakage coefficient:

$$L = \frac{K'}{b'} \qquad (5)$$

where K' is the vertical hydraulic conductivity (LT^{-1}), and b' is the thickness (L). When the confining bed is a composite of two or more layers having different hydraulic properties the leakage coefficient of the composite confining bed is:

$$b'/K' = \Sigma\, b'_i/K'_i, \qquad (6)$$

where K'_i is the vertical hydraulic conductivity of the i^{th} layer (LT^{-1}), and b'_i is the thickness of the i^{th} layer (L). The initial vertical hydraulic conductivity of the individual shale confining units (see Kinderhookian and Upper Devonian confining beds in fig. 9 and Maquoketa confining bed in fig. 10) was 1.0×10^{-10} foot per second, a value estimated by

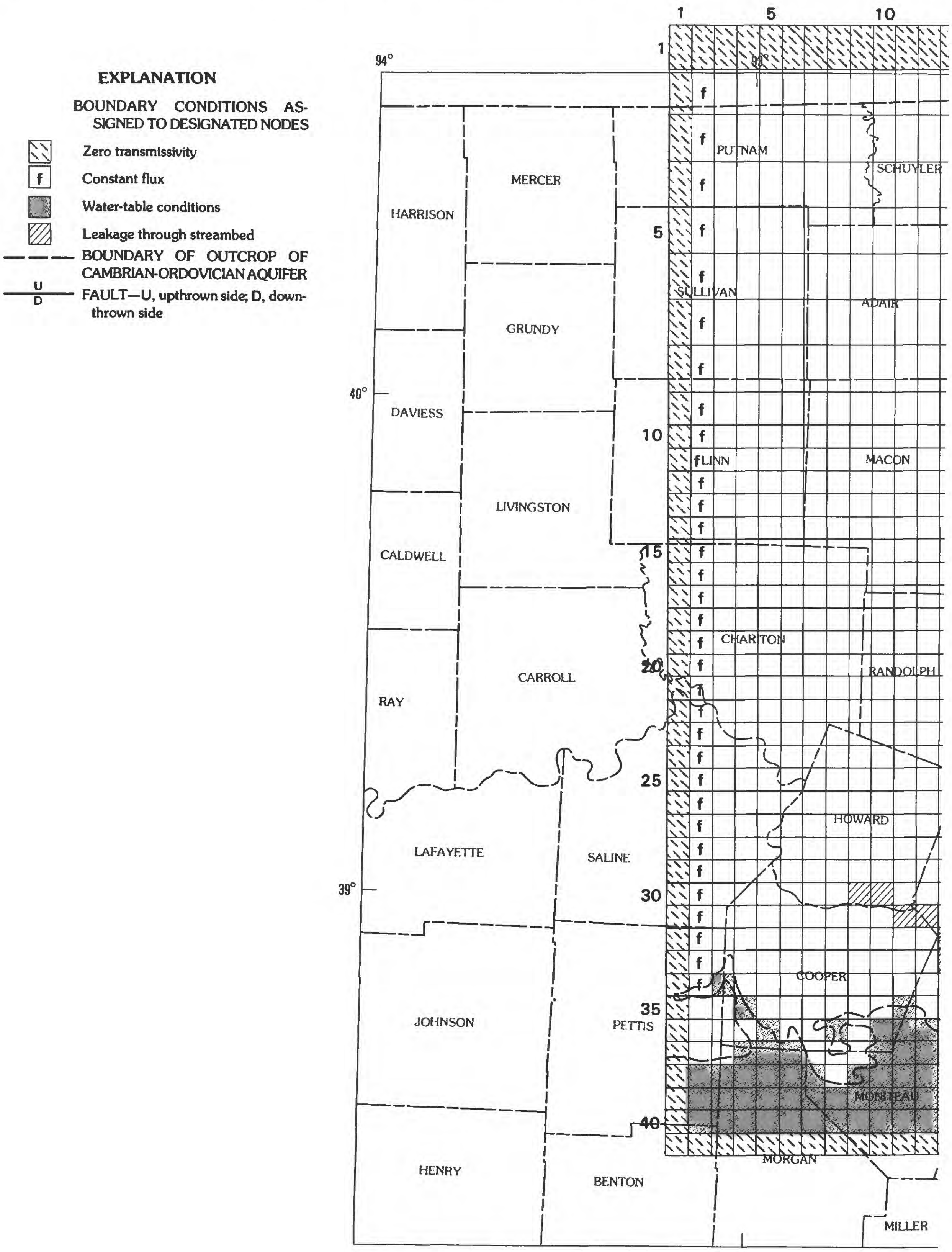
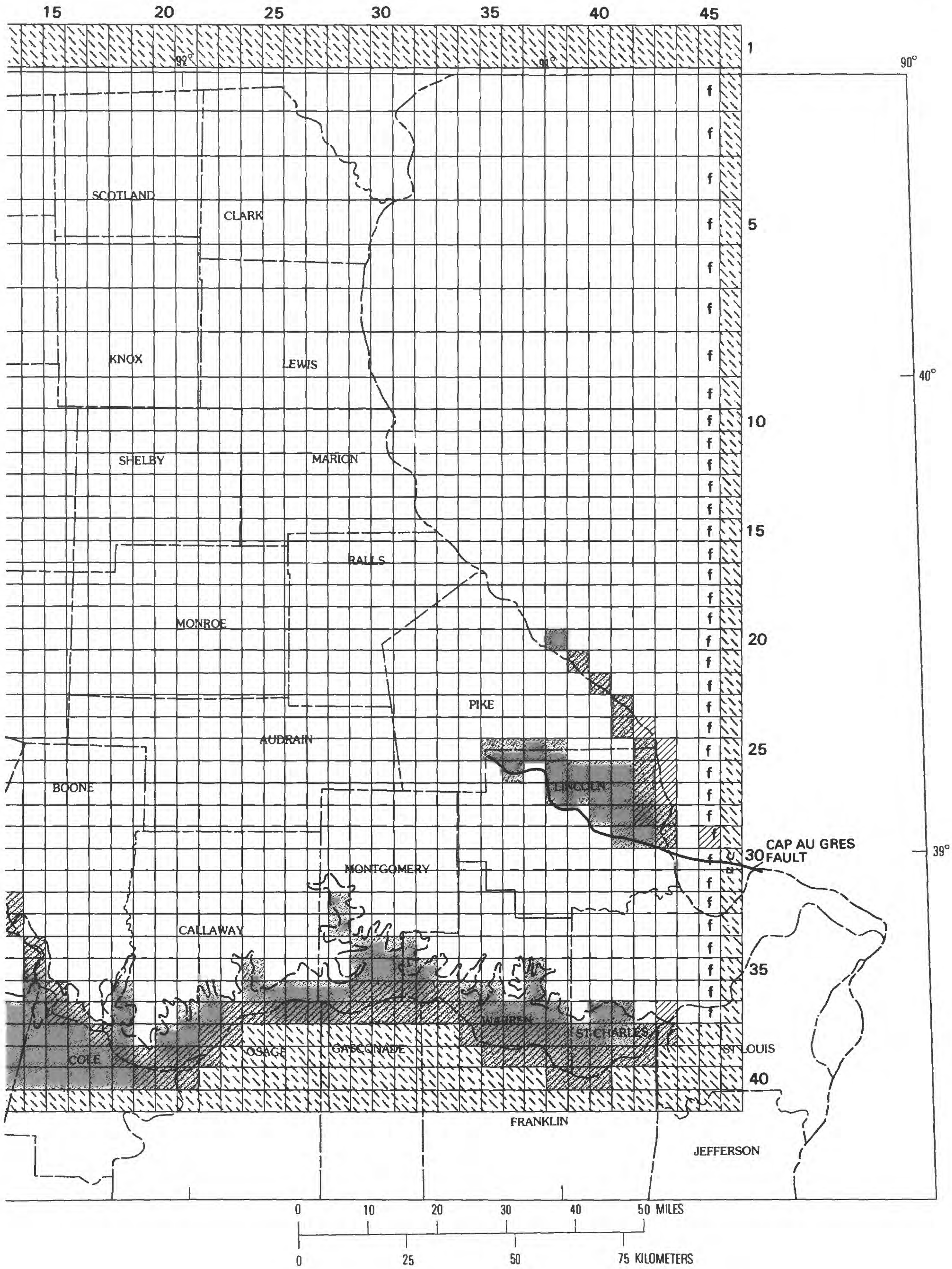


FIGURE 19.—Model grid and boundary conditions.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92°
91°
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40°
39°
SCOTLAND
CLARK
KNOX
LEWIS
SHELBY
MARION
RALLS
MONROE
PIKE
AUDRAIN
BOONE
LINCOLN
CAP AU GRES FAULT
MONTGOMERY
CALLAWAY
WARREN
ST CHARLES
COLE
OSAGE
GASCONADE
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0
25
50
75 KILOMETERS

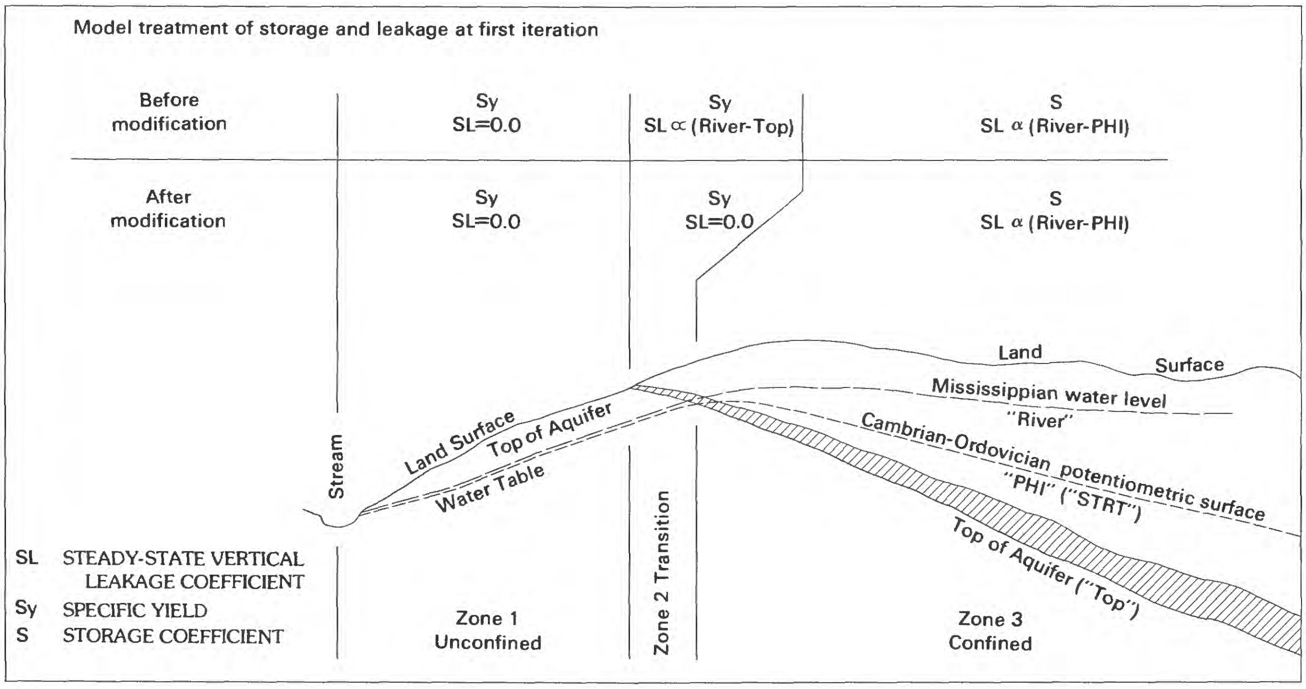


FIGURE 20.—Two-dimensional model treatment of transition zone (case A).

Walton (1960, p. 18) for the Maquoketa Shale in northeastern Illinois. The initial vertical hydraulic conductivity of the limestone confining units (fig. 11) was 1.0×10^{-9} foot per second. Because of the lack of data, leakage through the underlying Davis Formation is not incorporated in the model. The formation is treated as an impermeable barrier.

A preliminary calibration was concluded by varying the aquifer hydraulic conductivity and individual vertical conductivity of the confining units until the simulated predevelopment potentiometric surface approximated the regional features of the historic predevelopment potentiometric surface. Thereafter, only the effective vertical hydraulic conductivity of the composite confining bed and the aquifer hydraulic conductivity were varied to refine the calibration. The calibration was refined by subdividing the model into groups of nodes (zones) in which the hydraulic variables were held constant, but varied from zone to zone. This method of adjusting model variables helps make the calibration process more manageable and minimizes rapid changes in the variables within small distances. The actual calculation of new nodal hydraulic conductivities and insertion of the new data arrays into the model data set are accomplished by computer. In this procedure the hydraulic variables from the best preliminary calibration are used as reference values. Three computer files that define the nodes associated with each zone, the scaling factor to be applied to the reference values in each zone, and the horizontal or vertical hydraulic-conductivity reference values are used as entry data to a program that calculates a revised hydraulic-conductivity array and then replaces the old array with the new in the model data set.

Constant-flux boundary conditions are a function of the aquifer hydraulic conductivity and were adjusted before each calibration trial to be consistent with the hydraulic conductivity of the appropriate boundary node. Water enters the predevelopment, steady-state model across the western boundary at a rate of 7.6×10^{-5} cubic foot per second and exits across the eastern boundary at 6.2×10^{-5} cubic foot per second.

The Cambrian-Ordovician aquifer discharges into parts of the Mississippi and Missouri Rivers, and was first modeled with constant-head nodes based on the average stage of the river within a grid cell. Later, a more detailed treatment was attempted by specifying a streambed leakage proportional to K'_{st}/b', where $b' = 1$ (a unit thick streambed) and K'_{st} is the streambed vertical hydraulic conductivity (LT^{-1}). The simulations show there is significant hydraulic connection between the aquifer and the rivers. Values of K'_{st}/b' between 2×10^{-6} and 2×10^{-9} per second were used to calibrate the model. This large range in streambed leakage produced insignificant changes in the model calibration and varied little from the constant-head method. The smaller of the values indicates an unreasonably small volume of water being discharged along the length of both the Missouri and Mississippi Rivers. Thus the model is so insensitive to this leakage variable it cannot be used to calculate physically meaningful values of discharge to the Missouri and Mississippi Rivers.

The calibration process pointed to the necessity of limiting

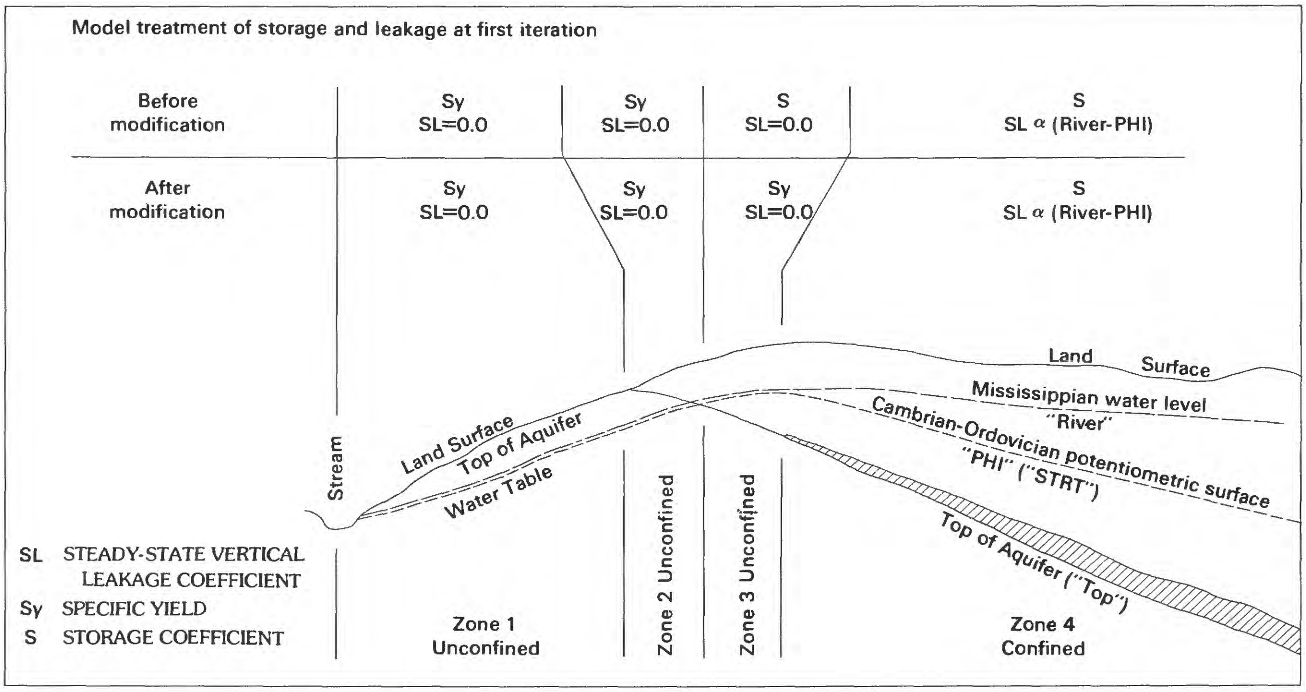


FIGURE 21.—Two-dimensional model treatment of transition zone (case B).

the flow across the Cap au Gres fault in Lincoln County (fig. 14). Therefore, the computer code was modified so that the internodal transmissivity perpendicular to the fault was decreased to approximately 2 to 10 percent of the transmissivities near the fault. Two factors causing the decrease in ground-water flow within the aquifer across the Cap au Gres fault are likely. One possibility is that the fault zone is impervious and restricts the flow of water perpendicular to it, and the other is the probable discharge of water from the Cambrian-Ordovician aquifer north of the fault into the Mississippian aquifer across the face of the fault (pl. 1).

A comparison of the simulated and actual prepumping potentiometric levels are shown in figure 22. Because the simulated and actual levels are quite similar, the maximum difference being about 10 to 15 feet, this calibration was deemed acceptable. The aquifer hydraulic conductivity varies throughout the model from 1.5×10^{-6} foot per second to 7.5×10^{-6} foot per second, the largest values occurring in Audrain County and the smallest values in St. Charles County. These values are less than, but compare favorably with, the initial hydraulic conductivity of 1.0×10^{-5} foot per second estimated from the aquifer test in Audrain County. The transmissivity of the aquifer is greatest along a northwest-trending line passing through Monroe, Audrain, and Montgomery Counties (fig. 23).

The effective vertical hydraulic conductivity of the composite upper confining bed ranges from 6×10^{-2} to 1.9×10^{-10} foot per second. The leakage coefficient of the confining bed is shown in figure 24. The leakage coefficient is smallest in the northeast where the Hannibal Shale and Grassy Creek Shale are thick (pl. 1) and becomes greater in the south and southeast where shale confining beds are thin or absent.

TRANSIENT CALIBRATION

The model was calibrated under transient conditions by matching the simulated and actual potentiometric surfaces of the Cambrian-Ordovician aquifer. No published records of historical pumpage exist before 1962, and those of later years are incomplete. Ten-year census population figures were used to approximate municipal pumpage during the first 60 years of this century, based on estimated per capita use. After 1960, population figures and pumping rates tabulated in annual reports published by the Missouri Division of Environmental Quality (1962–80) were used to estimate average municipal pumpage for 5-year intervals. From 1978 to 1981, the Cambrian-Ordovician aquifer was penetrated by 28 irrigation wells that pumped seasonally. The irrigation wells were first pumped during the summer of 1979. Approximate pumping rates for 25 of these wells were added to the model after May 1979. The remaining three wells, for which no pumping rates are available, were used only intermittently and do not contribute significantly to the total pumpage of irrigation wells. The irrigation data were obtained by direct measurement of well discharge rates and length of time the well was pumped. Estimated pumping rates, in cubic feet per second, for all wells are listed in tables 2 and 3.

The storage properties of an aquifer affect the potentiometric

EXPLANATION

— —680— — POTENTIOMETRIC CONTOUR — Shows simulated altitude of prepumping potentiometric surface of the Cambrian-Ordovician aquifer. Contour interval, in feet, is variable. National Geodetic Vertical Datum of 1929

——650—— POTENTIOMETRIC CONTOUR — Shows altitude of the actual prepumping potentiometric surface of the Cambrian-Ordovician aquifer. Contour interval, in feet, is variable. National Geodetic Vertical Datum of 1929

•647 WELL—Number is altitude of measured potentiometric head, in feet above National Geodetic Vertical Datum of 1929. A indicates flowing artesian well; ↿ indicates increasing potentiometric head with depth-discharge based on drillers' records; ⇂ indicates decreasing potentiometric head with depth-recharge based on drillers' records

OUTCROP AREA OF THE CAMBRIAN-ORDOVICIAN AQUIFER

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

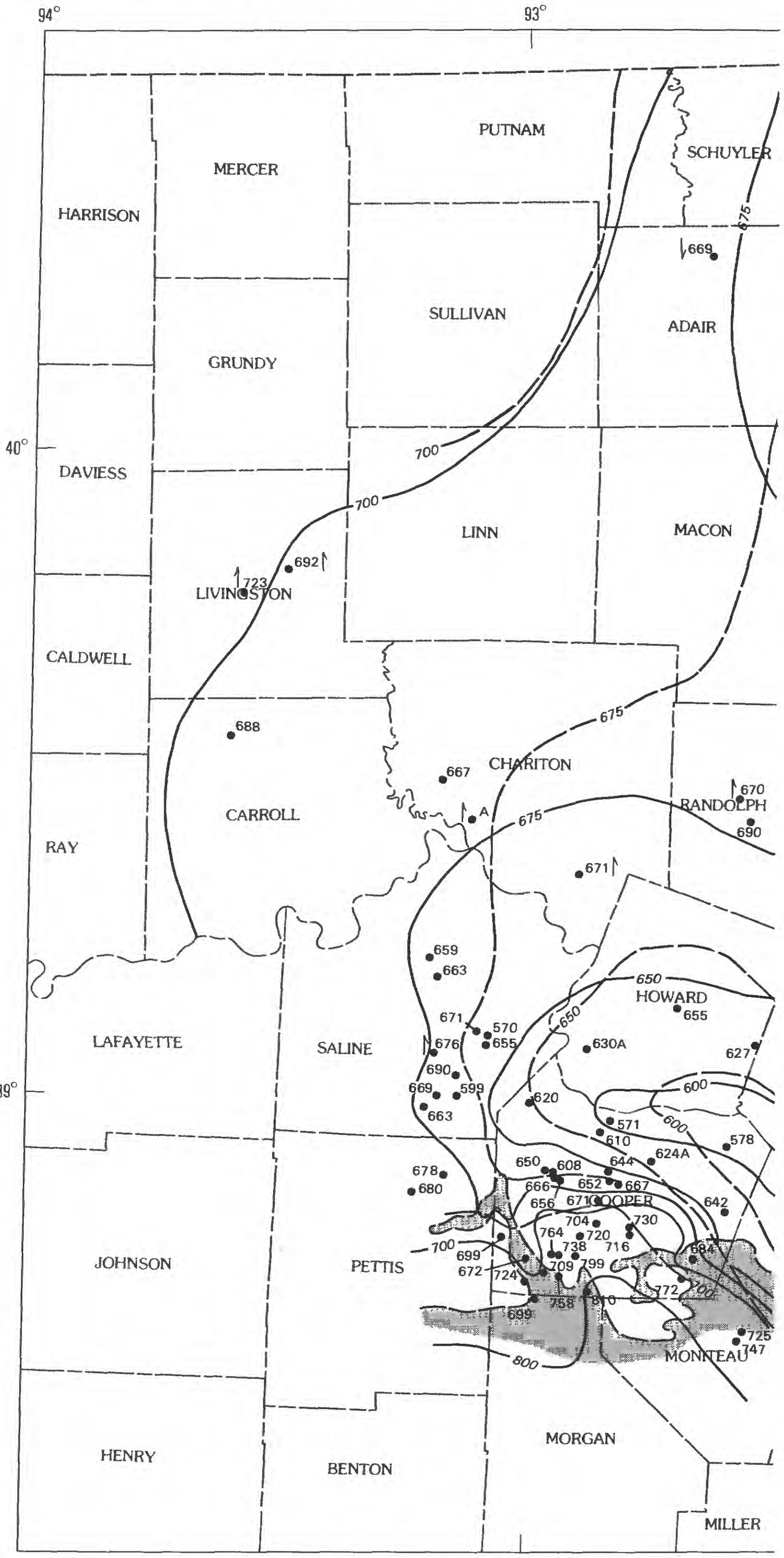
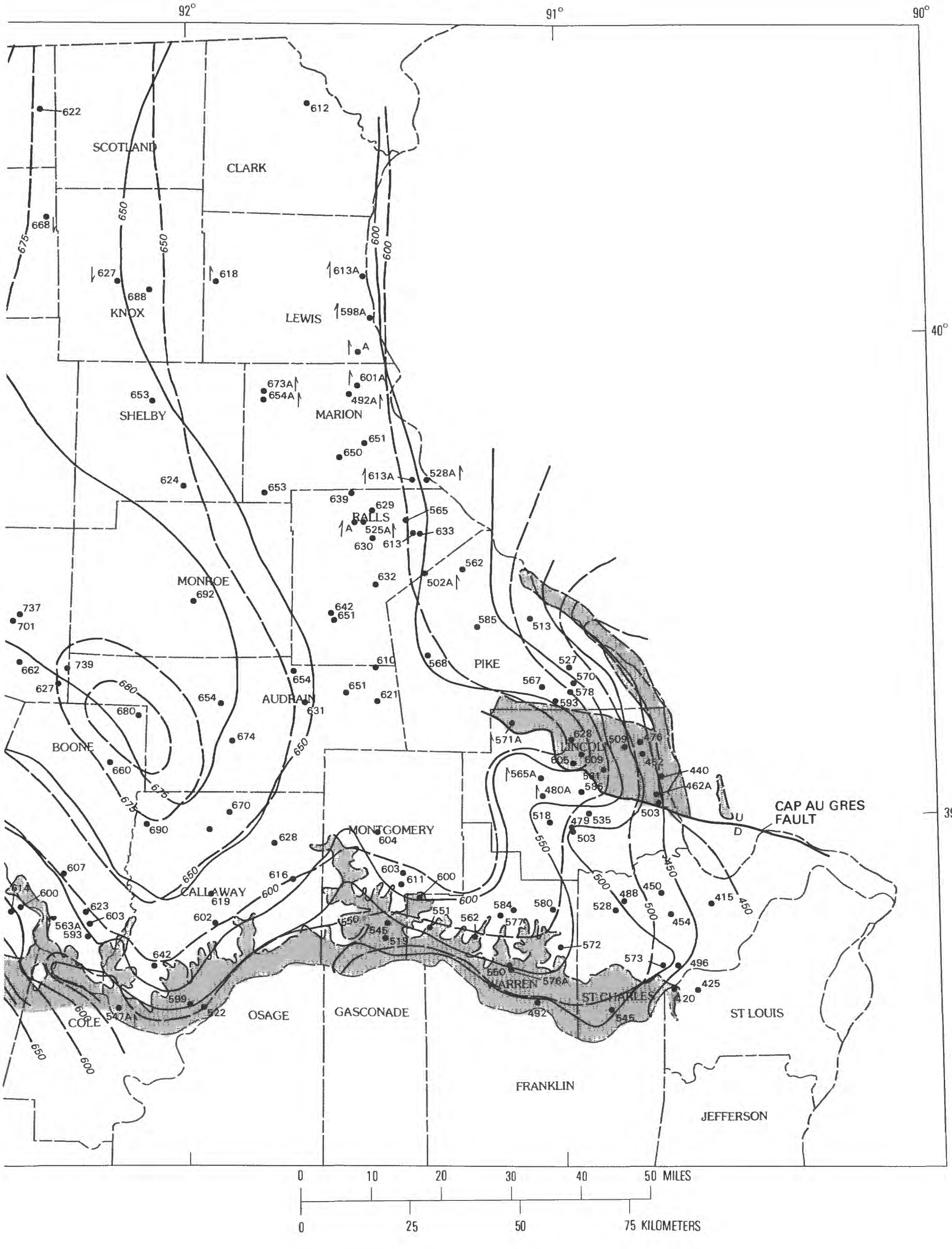


FIGURE 22.—Altitude of the simulated and actual prepumping potentiometric surfaces of the Cambrian-Ordovician aquifer.


SCOTLAND
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KNOX
LEWIS
SHELBY
MARION
RALLS
MONROE
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AUDRAIN
BOONE
LINCOLN
MONTGOMERY
CALLAWAY
COLE
OSAGE
GASCONADE
WARREN
ST CHARLES
ST LOUIS
FRANKLIN
JEFFERSON
CAP AU GRES FAULT
92°
91°
90°
40°
39°
0 10 20 30 40 50 MILES
0 25 50 75 KILOMETERS

EXPLANATION

—0.007— LINE OF EQUAL TRANSMISSIVITY OF THE CAMBRIAN-ORDOVICIAN AQUIFER — Interval 0.001 foot squared per second

OUTCROP AREA OF THE CAMBRIAN-ORDOVICIAN AQUIFER

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

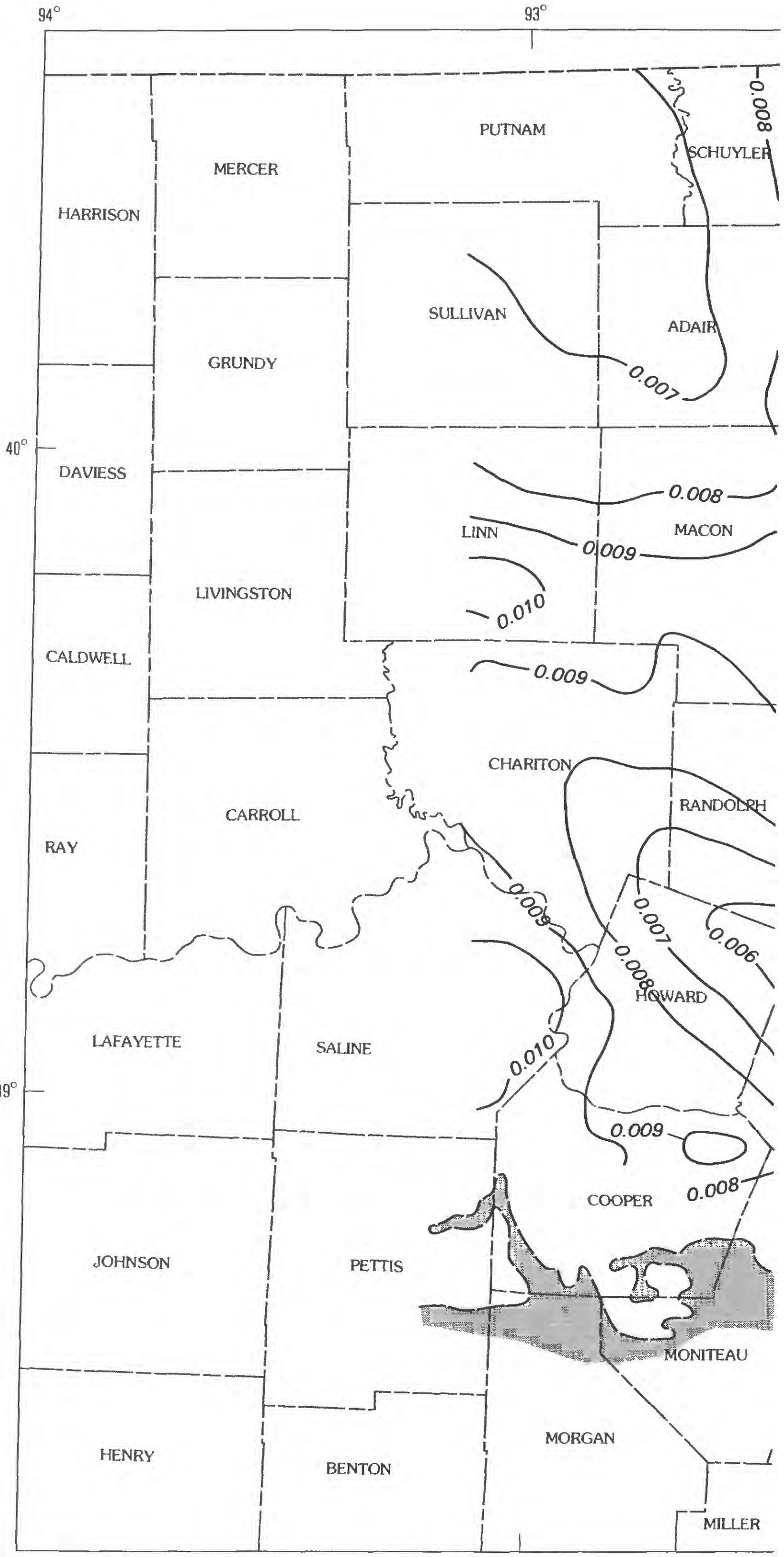
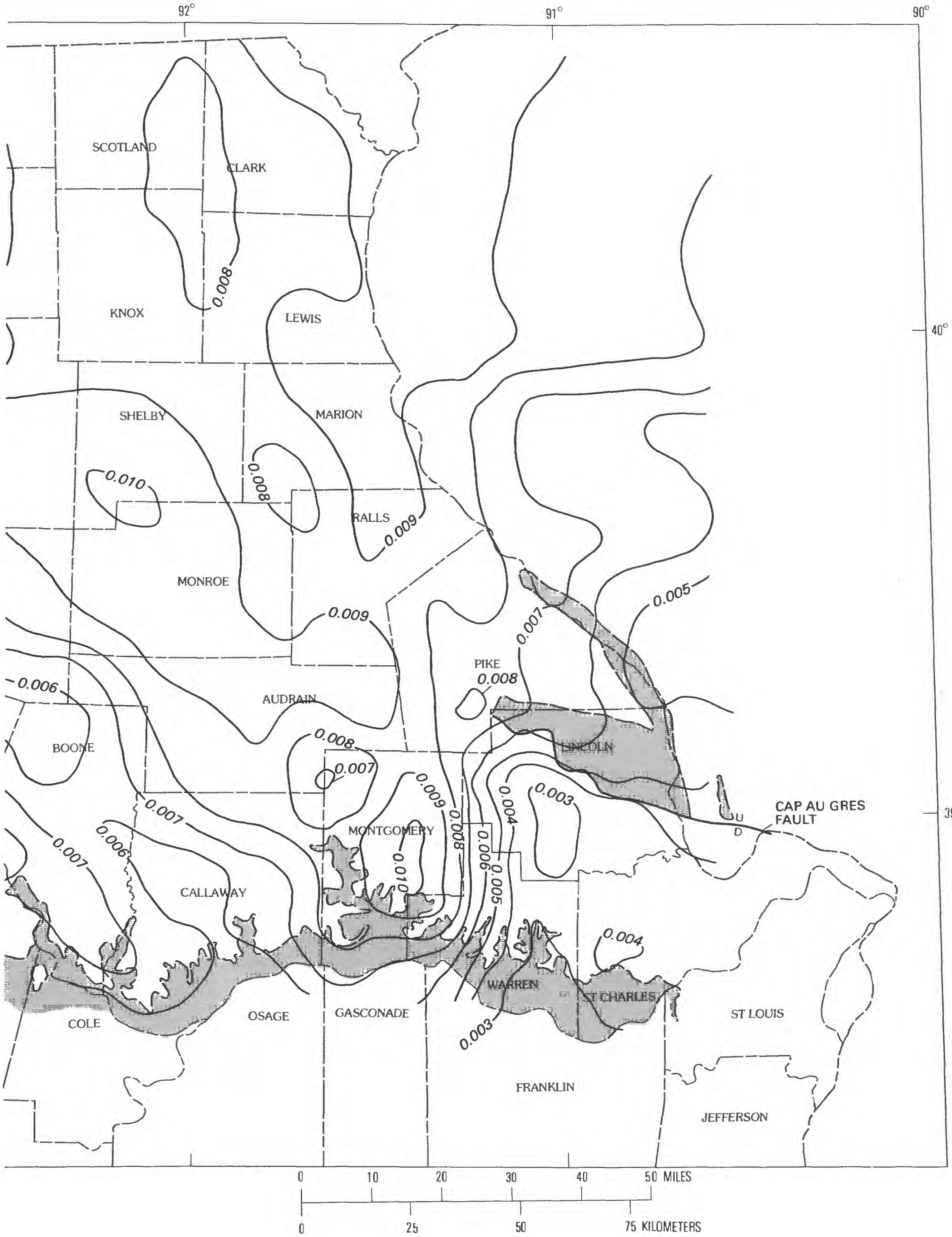


FIGURE 23.—Transmissivity of the Cambrian-Ordovician aquifer.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0 25 50 75 KILOMETERS

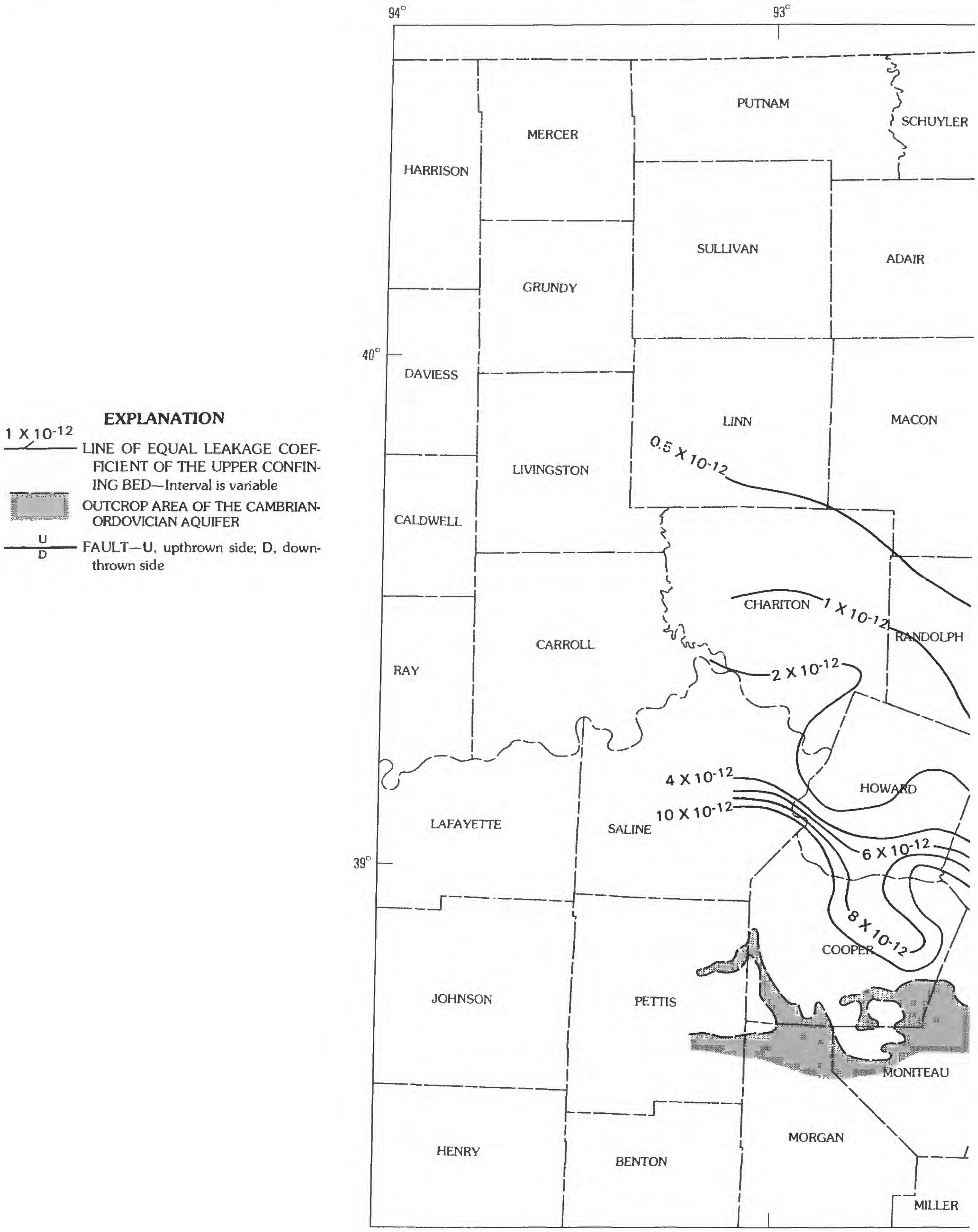
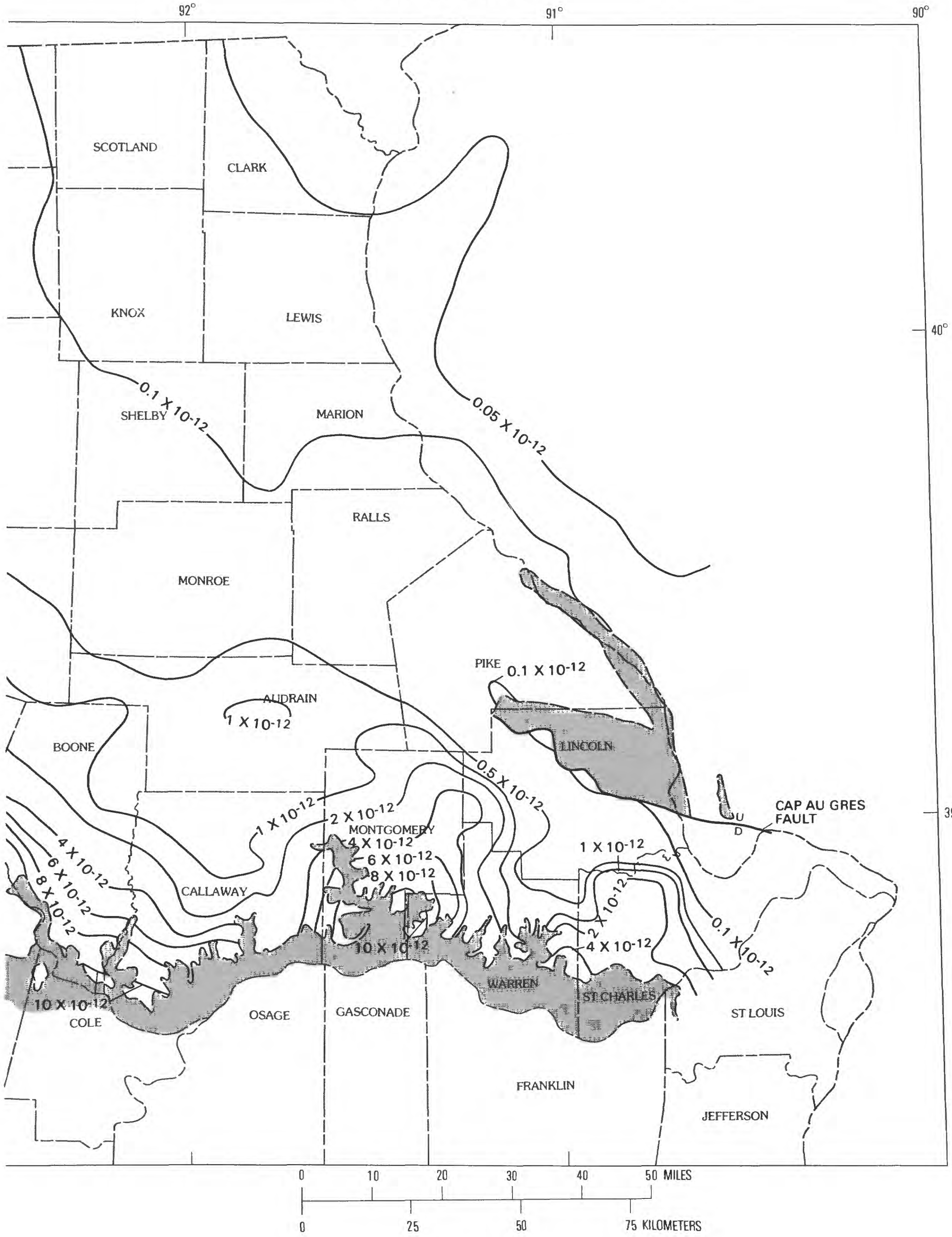


FIGURE 24.—Leakage coefficient of the upper confining bed.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0.1 X 10-12
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8 X 10-12
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8 X 10-12
10 X 10-12
1 X 10-12
2 X 10-12
4 X 10-12
0.1 X 10-12
U
D
CAP AU GRES FAULT
0 10 20 30 40 50 MILES
0 25 50 75 KILOMETERS

TABLE 2.—*Pumping rates for municipal and public-supply wells*

[PWSD. Public Water Supply District]

Municipal or public supply	Location[1]		Node location (i,j)[2]	Average pumpage, in cubic feet per second: 1900 to 1910	1910 to 1920	1920 to 1930	1930 to 1940	1940 to 1950	1950 to 1960	1960 to 1965	1965 to 1970	1970 to 1975	1975 to 1980	1980
Audrain County														
Farber	52-06-21		24,28	— —	— —	— —	— —	— —	0.02	0.03	0.04	0.05	0.05	0.08
Laddonia	52-07-35		25,27	— —	— —	— —	— —	— —	0.02	0.05	0.05	0.10	0.08	0.08
Martinsburg	50-07-24		28,27	— —	— —	— —	— —	— —	— —	— —	0.02	0.03	0.04	0.05
Mexico	51-09-26		26,23	0.19	0.21	0.32	0.44	0.60	0.80	1.32	1.87	2.30	2.94	2.94
Rush Hill	51-07-07		25,26	— —	— —	— —	— —	— —	— —	— —	0.01	0.02	0.02	0.02
		Total		0.19	0.21	0.32	0.44	0.60	0.84	1.40	1.99	2.50	3.13	3.17
Boone County														
Ashland	46-12-10		35,18	— —	— —	— —	— —	— —	0.02	0.04	0.04	0.06	0.13	0.09
Boone County PWSD 1	49-13-25		30,15	— —	— —	— —	— —	— —	— —	— —	0.10	0.15	0.23	0.28
Boone County PWSD 2	49-11-30		30,17	— —	— —	— —	— —	— —	— —	— —	0.05	0.15	0.23	0.29
Boone County PWSD 4	50-11-08		27,17	— —	— —	— —	— —	— —	— —	— —	0.01	0.05	0.07	0.08
Boone County PWSD 4	50-12-14		27,18	— —	— —	— —	— —	— —	— —	— —	0.01	0.05	0.07	0.08
Boone County PWSD 5 North	46-12-16		35,16	— —	— —	— —	— —	— —	— —	— —	0.02	0.02	0.08	0.08
Boone County PWSD 5 South	46-12-22		35,17	— —	— —	— —	— —	— —	— —	— —	0.05	0.05	0.08	0.08
Boone County PWSD 6	47-12-06		33,14	— —	— —	— —	— —	— —	— —	— —	0.02	0.07	0.14	0.20
Boone County PWSD 6	47-12-22		33,17	— —	— —	— —	— —	— —	— —	— —	0.02	0.07	0.14	0.20
Boone County PWSD 7	49-13-02		32,17	— —	— —	— —	— —	— —	— —	— —	0.01	0.02	0.03	0.05
Boone County PWSD 7	50-13-35		29,18	— —	— —	— —	— —	— —	— —	— —	0.01	0.02	0.03	0.05
Boone County PWSD 8	47-13-05		30,13	— —	— —	— —	— —	— —	— —	— —	0.04	0.15	0.15	0.20
Boone County PWSD 9	48-12-23		32,17	— —	— —	— —	— —	— —	— —	— —	0.05	0.08	0.14	0.18
Boone County PWSD 9	49-11-08		29,18	— —	— —	— —	— —	— —	— —	— —	0.05	0.08	0.14	0.18
Centralia	51-11		25,18	— —	0.02	0.03	0.03	0.04	0.02	0.19	0.19	0.14	0.19	0.23
Centralia	51-11		25,19	— —	0.02	0.03	0.03	0.04	0.02	0.19	0.19	0.14	0.19	0.23
Centralia	51-11		26,18	— —	0.02	0.03	0.03	0.04	0.02	0.19	0.19	0.14	0.19	0.23
Centralia	51-11		26,19	— —	0.02	0.03	0.03	0.04	0.02	0.19	0.19	0.14	0.19	0.23
Columbia	48-12		31,16	— —	0.08	0.14	0.20	0.30	0.43	1.47	1.47	0.51	0.60	0.57
Columbia	48-13		31,15	— —	0.22	0.40	0.59	0.87	1.32	4.41	4.41	1.55	1.80	1.75
Hallsville	50-12-13		28,17	— —	— —	— —	— —	— —	0.02	0.04	0.04	0.10	0.08	0.09
Harrisburg	50-14-11		27,13	— —	— —	— —	— —	— —	— —	— —	0.01	0.02	0.02	
		Total		— —	0.38	0.66	0.91	1.33	1.87	6.72	7.17	3.76	4.92	5.47
Callaway County														
Auxvasse	49-09-14		30,23	— —	— —	0.01	0.03	0.06	0.06	0.06	0.06	0.06	0.07	0.14
Callaway County PWSD 1	45-10-07		37,20	— —	— —	— —	— —	— —	— —	— —	— —	0.03	0.05	0.06
Callaway County PWSD 1	45-11-24		38,19	— —	— —	— —	— —	— —	— —	— —	— —	0.05	0.09	0.12
Callaway County PWSD 1	45-11-24		39,19	— —	— —	— —	— —	— —	— —	— —	— —	0.03	0.05	0.06
Callaway County PWSD 2	48-08-32		32,24	— —	— —	— —	— —	— —	— —	— —	— —	— —	0.06	0.07
Callaway County PWSD 2	48-10-28		35,19	— —	— —	— —	— —	— —	— —	— —	— —	— —	0.10	0.12
Cedar City	44-11-16		39,18	— —	— —	— —	— —	— —	— —	0.02	0.05	0.04	0.04	0.08
Fulton	47-09		33,22	— —	— —	— —	— —	0.50	0.71	1.24	1.39	1.55	1.93	3.10
Mokane	45-09-13		37,23	— —	— —	— —	— —	— —	— —	0.02	0.02	0.04	0.04	0.05
New Bloomfield	46-10-31		27,20	— —	— —	— —	— —	— —	— —	0.02	0.03	0.03	0.04	0.06
		Total		— —	— —	0.01	0.03	0.56	0.77	1.36	2.91	1.83	2.47	3.86
Lincoln County														
Hawk Point	49-02-33		31,36	— —	— —	— —	— —	— —	— —	0.02	0.02	0.02	0.03	0.04
Lincoln County PWSD 1	49-1E-04		29,40	— —	— —	— —	— —	— —	— —	— —	— —	0.02	0.02	0.03
Lincoln County PWSD 1	41-1E-04		29,41	— —	— —	— —	— —	— —	— —	— —	— —	0.02	0.02	0.03
Lincoln County PWSD 1	41-1E-04		29,42	— —	— —	— —	— —	— —	— —	— —	— —	0.02	0.02	0.03
Moscow Mills	48-1E-04		31,39	— —	— —	— —	— —	— —	— —	— —	0.02	0.02	0.03	0.07
Silex	50-01-06		27,34	— —	— —	— —	— —	— —	— —	— —	— —	0.01	0.01	0.01
Troy	49-01-26		30,38	— —	— —	0.06	0.08	0.10	0.13	0.13	0.27	0.46	0.58	0.46
		Total		— —	— —	0.06	0.08	0.10	0.13	0.15	0.31	0.57	0.71	0.67

Municipal or public supply	Location[1]	Node location (i,j)[2]	Average pumpage, in cubic feet per second: 1900 to 1910	1910 to 1920	1920 to 1930	1930 to 1940	1940 to 1950	1950 to 1960	1960 to 1965	1965 to 1970	1970 to 1975	1975 to 1980	1980
Monroe County													
Madison	52-13-23	20,17	— —	— —	— —	— —	— —	— —	— —	0.03	0.03	0.05	— —
Total			— —	— —	— —	— —	— —	— —	— —	0.03	0.03	0.05	— —
Montgomery County													
Bellflower	49-04-22	30,32	— —	— —	— —	— —	— —	— —	— —	0.01	0.03	0.06	0.04
High Hill	48-04-32	32,32	— —	— —	— —	— —	— —	— —	— —	0.01	0.02	0.02	0.04
Jonesburg	47-03-07	33,33	— —	— —	— —	— —	— —	— —	0.02	0.04	0.05	0.06	0.06
Middletown	50-05-01	27,31	— —	— —	— —	— —	— —	— —	— —	0.02	0.02	0.02	0.02
Montgomery City	49-05	31,30	0.01	0.04	0.05	0.05	0.06	0.07	0.10	0.12	0.12	0.18	0.15
Montgomery City	49-05	31,31	0.01	0.04	0.05	0.05	0.06	0.07	0.10	0.12	0.12	0.18	0.15
New Florence	48-05-22	32,30	— —	— —	— —	— —	— —	0.01	0.03	0.05	0.06	0.06	0.13
Total			0.02	0.08	0.10	0.10	0.12	0.15	0.25	0.37	0.42	0.58	0.59
Pike County													
Clarksville	53-1E-16	22,39	— —	— —	— —	0.05	0.06	0.06	0.09	0.12	0.08	0.08	0.10
Total			— —	— —	— —	0.05	0.06	0.06	0.09	0.12	0.08	0.08	0.10
Randolph County													
Clark	54-12-14	22,39	— —	— —	— —	— —	— —	— —	— —	0.03	0.03	0.03	0.03
Total			— —	— —	— —	— —	— —	— —	— —	0.03	0.03	0.03	0.03
St. Charles County													
Beauleau Gardens	47-3E-27	34,44	— —	— —	— —	— —	— —	— —	— —	— —	0.01	0.01	0.01
Belleau Lake Estates	47-3E-28	34,43	— —	— —	— —	— —	— —	— —	— —	— —	0.02	0.02	0.02
Forest Hill Subdivision	47-1E-19	34,39	— —	— —	— —	— —	— —	— —	— —	— —	0.01	0.01	0.01
Lake Charles Subdivision	47-2E-13	34,42	— —	— —	— —	— —	— —	— —	— —	— —	0.03	0.04	0.07
Lake St. Louis	47-2E-27	34,42	— —	— —	— —	— —	— —	— —	— —	— —	0.04	0.10	
Mark Twain Trailer Court	47-3E-30	34,43	— —	— —	— —	— —	— —	— —	— —	— —	0.03	0.03	0.02
O'Fallon	47-3E	34,43	— —	— —	— —	— —	0.04	0.06	0.34	0.90	1.23	1.64	1.67
Prairie View Acres	47-1E-27	34,40	— —	— —	— —	— —	— —	— —	— —	— —	0.01	0.10	0.01
St. Charles PWSD 2 SW	44-1E-01	39,39	— —	— —	— —	— —	— —	— —	— —	— —	— —	0.01	0.02
St. Charles PWSD 2 North		35,42	— —	— —	— —	— —	— —	— —	— —	— —	— —	0.59	0.83
St. Peters	47-4E-31	34,44	— —	— —	— —	— —	— —	— —	0.03	0.05	0.12	0.12	— —
Timberlane Trails Subdivision	47-2E-25	34,42	— —	— —	— —	— —	— —	— —	— —	— —	0.02	0.02	0.04
Warsaw Hills Subdivision	47-2E-30	34,41	— —	— —	— —	— —	— —	— —	— —	0.02	0.03	0.04	0.05
Wentzville	47-1E-24	34,41	— —	— —	— —	— —	0.05	0.08	0.16	0.31	0.57	0.60	0.61
Total			— —	— —	— —	— —	0.09	0.14	0.53	1.28	2.12	3.33	3.36
Warren County													
Marthasville	45-01-30	38,37	— —	— —	— —	— —	— —	— —	0.01	0.02	0.02	0.03	0.06
Warrenton	47-02-38	34,36	— —	— —	— —	— —	0.09	0.11	0.23	0.31	0.40	0.46	0.51
Wright City	47-01	34,38	— —	— —	— —	— —	0.03	0.04	0.05	0.05	0.05	0.22	0.28
Total			— —	— —	— —	— —	0.12	0.15	0.29	0.38	0.47	0.71	0.85

[1] Location is given by township, range, and section. All townships are north. Ranges are west except where noted

[2] See figure 24

TABLE 3.—*Pumping rates for irrigation wells*

Location[1]	Node location(i,j)[2]	Average pumping rate in cubic feet per second	
		May 1979 to Sept. 1979[3]	May 1980 to Sept. 1980[3]
49-08-09	29,25	1.24	.79
49-08-11	29,25	.96	.90
50-06-02	27,29	.29	.25
50-07-02	27,27	1.05	.78
50-07-05	27,26	.95	.45
50-07-08	27,26	.40	.25
50-07-09	27,26	1.41	1.00
50-07-12	27,27	.56	.26
50-08-04	27,24	.61	.51
50-09-05	27,22	—	.64
50-09-05	27,22	.51	.75
50-09-17	28,22	.38	.69
50-10-13	28,21	.64	.88
51-06-30	26,27	—	.70
51-06-31	27,27	.85	1.03
51-07-10	25,26	.84	.81
51-07-31	26,26	.80	.65
51-07-36	27,27	.44	.45
51-08-08	25,24	.37	.50
51-12-10	25,17	.10	.22
52-10-34	25,21	.24	.21
52-11-26	24,19	.41	.42
52-11-33	25,19	.24	.41
52-12-26	24,17	.30	87
53-06-33	23,28	.24	.14

[1]Location is given by township, range, and section. All townships are north, all ranges are west

[2]See figure 24

[3]Averaged from a 92-day pumping season (May 31 - Sept. 1)

surface during transient simulation. Specific yield, the ratio of the volume of water a saturated rock will yield by gravity to the total rock volume, measures the release of water from the unconfined part of the aquifer as the water table declines. The storage property of a confined aquifer is defined as the volume of water the aquifer releases or takes into storage per unit surface area per unit change in head. Potentiometric heads in the aquifer were simulated under transient conditions using several values of specific yield and storage coefficient until there was agreement between the historic and simulated potentiometric surfaces. Two comparisons of simulated and actual potentiometric surfaces were made during the transient calibration: the first using the "1965" potentiometric surface (fig. 25), and the second using the May 1979 potentiometric surface (fig. 26). The dashed lines in figures 25 and 26 represent the simulated potentiometric surfaces. The specific yield of the Cambrian-Ordovician aquifer was determined by this calibration procedure to range from 0.001 to 0.006, and the storage coefficient to range from 3×10^{-5} to 8×10^{-5}.

In the immediate vicinity of Columbia, the May 1979 simulated potentiometric heads are as much as 150 feet deeper than the actual heads. There are several possible reasons for this discrepancy. Most of the May 1979 water-level measurements in this area were made in recently pumped wells or while nearby wells were pumping. These water levels may reflect lower heads due to local drawdown, not the regional potentiometric surface. Some water-level data indicate the potentiometric surface of the Mississippian aquifer has declined during recent years. Because the rate of leakage through the confining bed is proportional to the potentiometric-head difference across the confining bed, vertical leakage should decrease as the potentiometric surface of the Mississippian aquifer is lowered. This model, however, assumes the Mississippian water level is static. Thus too much water can enter the aquifer and decrease the extent of the drawdown cone around Columbia.

Another possible cause of the discrepancy is that near Columbia the model converts from confined to water-table conditions too early in the pumping history, thus releasing too much water from storage and slowing the development of the drawdown cone. This could occur if the uppermost formation of the Cambrian-Ordovician aquifer near Columbia is semiconfining. The thickness of this formation (the Cotter Dolomite) is about 200 feet here. To investigate this possibility, the aquifer top was lowered 200 feet around Columbia to delay the onset of conversion. This change decreased the potentiometric heads a maximum of 40 feet during 1965. By May 1979, they had recovered to within 12 feet of the heads before the change. Therefore, the problem does not seem to be caused by the presence of semiconfining strata near the top of the aquifer.

SENSITIVITY ANALYSIS

An estimate of the reliability of the hydraulic variables determined during the model calibration procedure can be obtained by sensitivity analysis. The historical potentiometric surface to which the model is calibrated may be in error as much as ±10 feet, especially in the more intensely used freshwater area. The range of hydraulic conductivity values that produces a ±10 feet change in simulated potentiometric surface is a measure of the uncertainty in the hydraulic conductivity. A 20 percent increase in the hydraulic conductivity of the aquifer decreases the potentiometric heads in the confined areas of Warren and northern Callaway Counties by just less than 10 feet (solid lines in figure 27). Thus the hydraulic conductivity is no more accurate than ±20 percent.

Because the ground-water flow equation used in this model is isotropic, the predevelopment, steady-state flow equation is a function of K/K′, the ratio of the aquifer hydraulic conductivity (K) to the confining bed vertical hydraulic conductivity (K′). Therefore, the vertical hydraulic conductivity of the confining bed also can be no more accurate than ±20 percent. A 20 percent increase in the confining-bed vertical hydraulic conductivity causes the simulated prepumping potentiometric surface to change, as shown by the dashed lines in figure 27.

APPLICATION OF THE MODEL

A calibrated digital model is a useful tool for predicting the effect of future stresses on an aquifer. Two potential rates of withdrawal from the Cambrian-Ordovician aquifer were simulated from 1980 to 1990. In the first approach, withdrawals continued at the 1980 pumping rates until 1990. The irrigation season was treated as a separate pumping period for each of the simulation years. Seasonal fluctuation, due to the periodic summer irrigation pumpage, became approximately stable at 136 to 139 feet. The dashed contours centered on Audrain County in figure 28 represent the maximum simulated drawdown (relative to May 1990) resulting from the summer 1990 irrigation season before the potentiometric surface has begun to recover. Comparison of potentiometric surfaces at the end of May from two successive years show that by 1990 the year-to-year net head decline is about 2 to 3 feet per year. Thus the potentiometric surface recovers almost completely from the prior years' irrigation pumpage. Significant changes in the regional potentiometric surface occur in the 10-year simulation interval. The drawdown cone around Mexico expands as water levels decline by approximately 50 feet (solid lines in figure 28). The potentiometric surface near Fulton also declines almost 50 feet, but in the vicinity of Columbia and O'Fallon the drawdown remains relatively constant throughout this time period.

In the second approach, the rate of pumpage from all wells was increased by one percent per year more than the 1980 values. This was determined to be a practical method of investigating the effects of potential population increase on the aquifer, but results from this approach need to be used with some reservation. Changes in climatic conditions may result in large variations in the actual volume of irrigation pumpage from one year to the next. Recent population shifts have resulted in increased population of some towns and decreased population of others, although on the average the model areas has gained population during the past 10 years, based on census population figures (Johnson, 1981–82, p. 1197) of towns and cities whose well-pumping rates have been included in the model. Excluding the significant population increase of St. Peters, which shifted to alluvial sources by 1980, this increase in population was about 5.4 percent. It is reasonable to assume this rate of population increase will continue, and to apply the rate to future municipal ground-water withdrawals and include an additional quantity to account for possible increase in pumpage due to direct use by new industry. Thus the figure that was chosen (10 percent during 10 years) probably is representative of future increases in ground-water withdrawal from the aquifer. It has been uniformly applied to all wells.

The difference between the May 1990 potentiometric surfaces simulated by the two approaches is not great, ranging from almost zero to 29 feet, with the largest differences near the city of Mexico and the nearby irrigation wells (fig. 29).

Based on the May 1990 potentiometric surface, saline water will move farther south than its historical limit. The historical saltwater-freshwater boundary, depicted by the 1,000-milligram-per-liter dissolved-solids concentration line shown in figure 29, represents the limit of saline-water flow in the absence of aquifer stresses. Due to ground-water withdrawal at Mexico and Columbia, the limit of saline water will shift southward. Similarly, large withdrawals of ground water at O'Fallon will cause the limit of saline water to shift westward in St. Charles County. The approximate position of the limit during May 1990 is shown as a light dashed line in figure 29. In the vicinity of Mexico, Columbia, and O'Fallon it will move about 10 miles into the freshwater area, but to the east of Mexico in Ralls County there will be little change from the historical position.

There is probably no reason to expect immediate saltwater movement into freshwater regions. The rate of ground-water flow is estimated to be 5 to 15 feet per year near the saltwater-freshwater transition zone. At this rate it would take many centuries for saline water to move as far south as the city of Mexico. Perhaps a greater concern is that the saltwater-freshwater transition is not a well-defined plane, but may extend much farther south in more permeable formations with the aquifers. Another concern is the possible vertical upward movement of saline water from the underlying Lamotte Sandstone. No information is currently (1983) available to realistically assess these possibilities.

SUMMARY AND CONCLUSIONS

A description of the stratigraphy of northern Missouri was presented, including several geologic maps and sections. The regional stratigraphy of post-Middle Ordovician deposits consists of northwest-dipping strata that thicken toward the Forest City basin. Older deposits thin toward the northwest, indicating these strata predate basin development. The eastern half of the study area is dominated by a major structural feature, the Lincoln fold, a northwest-alined anticline. This anticline is bounded on the south by the Cap au Gres fault, which apparently is a barrier to ground-water flow.

The hydrologically important aquifers in northern Missouri are (1) alluvial valley deposits; (2) surficial deposits of glacial drift; (3) the Mississippian aquifer, primarily Burlington and Keokuk Limestones; and (4) the Cambrian-Ordovician aquifer. The Cambrian-Ordovician aquifer was studied in detail.

A two-dimensional model of the Cambrian-Ordovician ground-water flow system in northeastern Missouri was

EXPLANATION

—700— (dashed) POTENTIOMETRIC CONTOUR — Shows simulated altitude of potentiometric surface of the Cambrian-Ordovician aquifer. Contour interval 50 feet. National Geodetic Vertical Datum of 1929

—700— POTENTIOMETRIC CONTOUR — Shows altitude of the actual potentiometric surface of the Cambrian-Ordovician aquifer. Contour interval 50 feet. National Geodetic Vertical Datum of 1929

442/1967 WELL—Upper number is altitude of the Cambrian-Ordovician potentiometric surface. Lower number is year during which the data were collected.

OUTCROP AREA OF THE CAMBRIAN-ORDOVICIAN AQUIFER

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

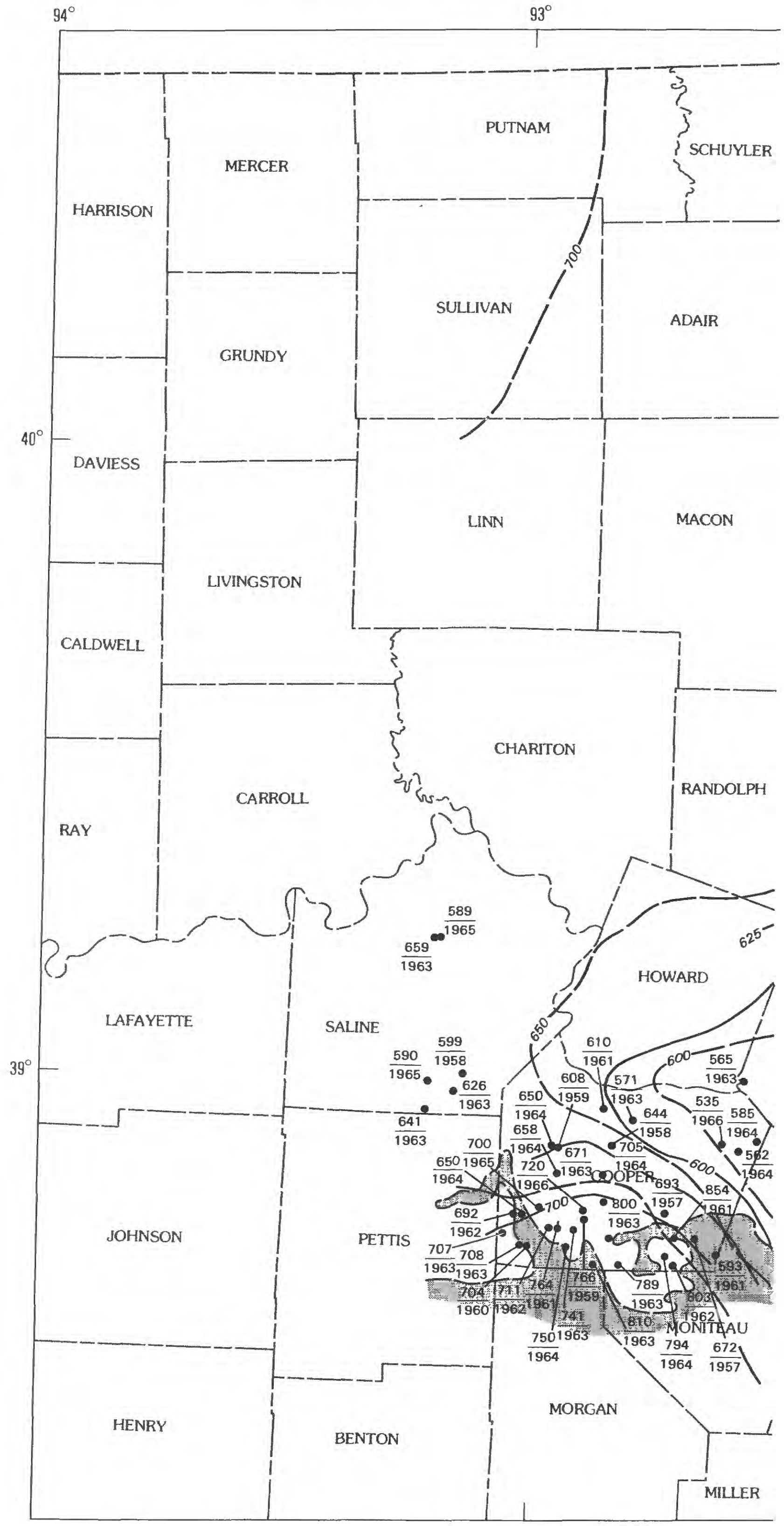
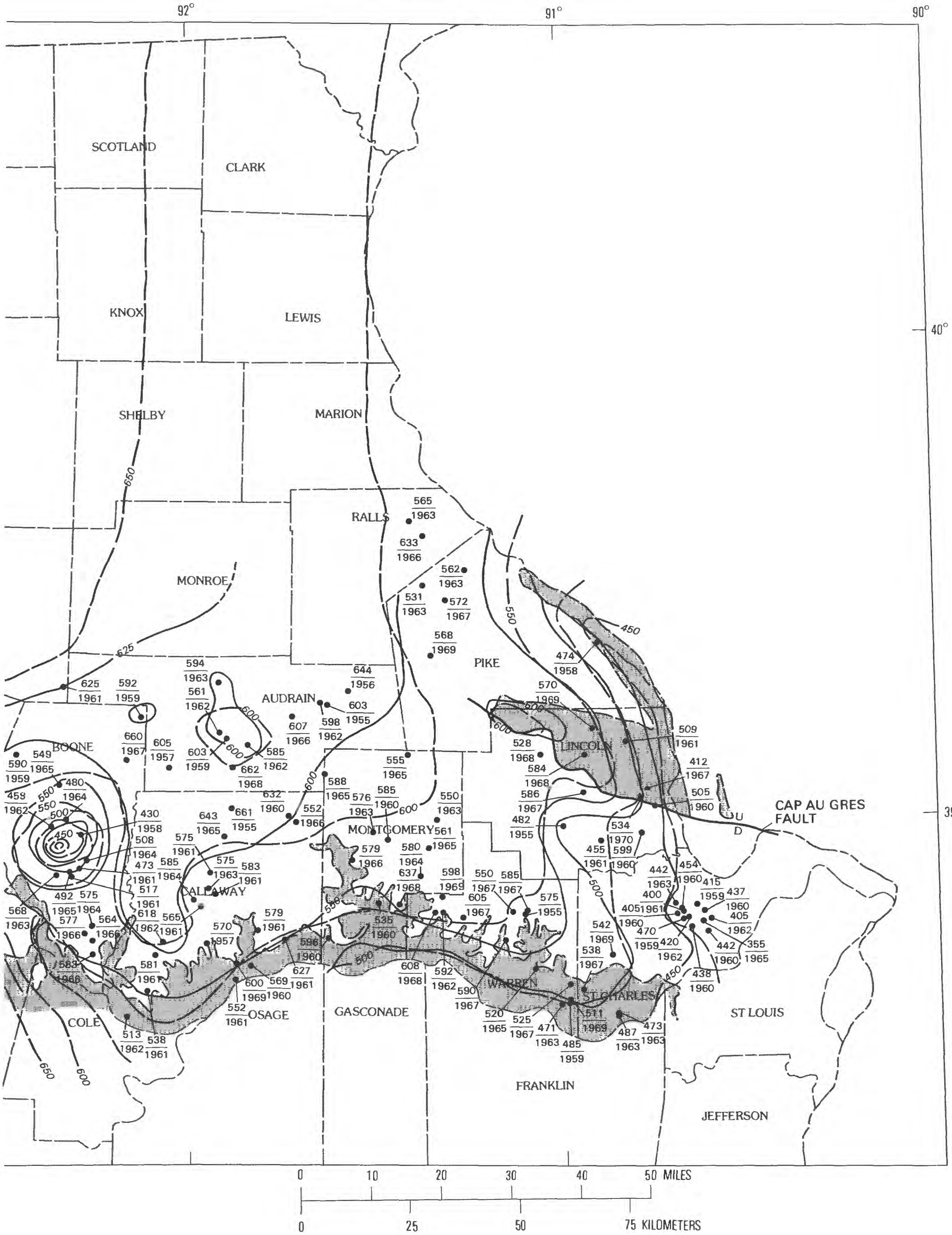


FIGURE 25.—Altitude of the simulated and actual "1965" potentiometric surfaces of the Cambrian-Ordovician aquifer.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91°
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SCOTLAND
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RALLS
MONROE
PIKE
AUDRAIN
BOONE
LINCOLN
MONTGOMERY
CALLAWAY
WARREN
ST CHARLES
COLE
OSAGE
GASCONADE
FRANKLIN
ST LOUIS
JEFFERSON
CAP AU GRES FAULT
U
D
0 10 20 30 40 50 MILES
0 25 50 75 KILOMETERS

EXPLANATION

—575— POTENTIOMETRIC CONTOUR — Shows simulated altitude of potentiometric surface of the Cambrian-Ordovician aquifer. Contour interval, in feet is variable. National Geodetic Vertical Datum of 1929

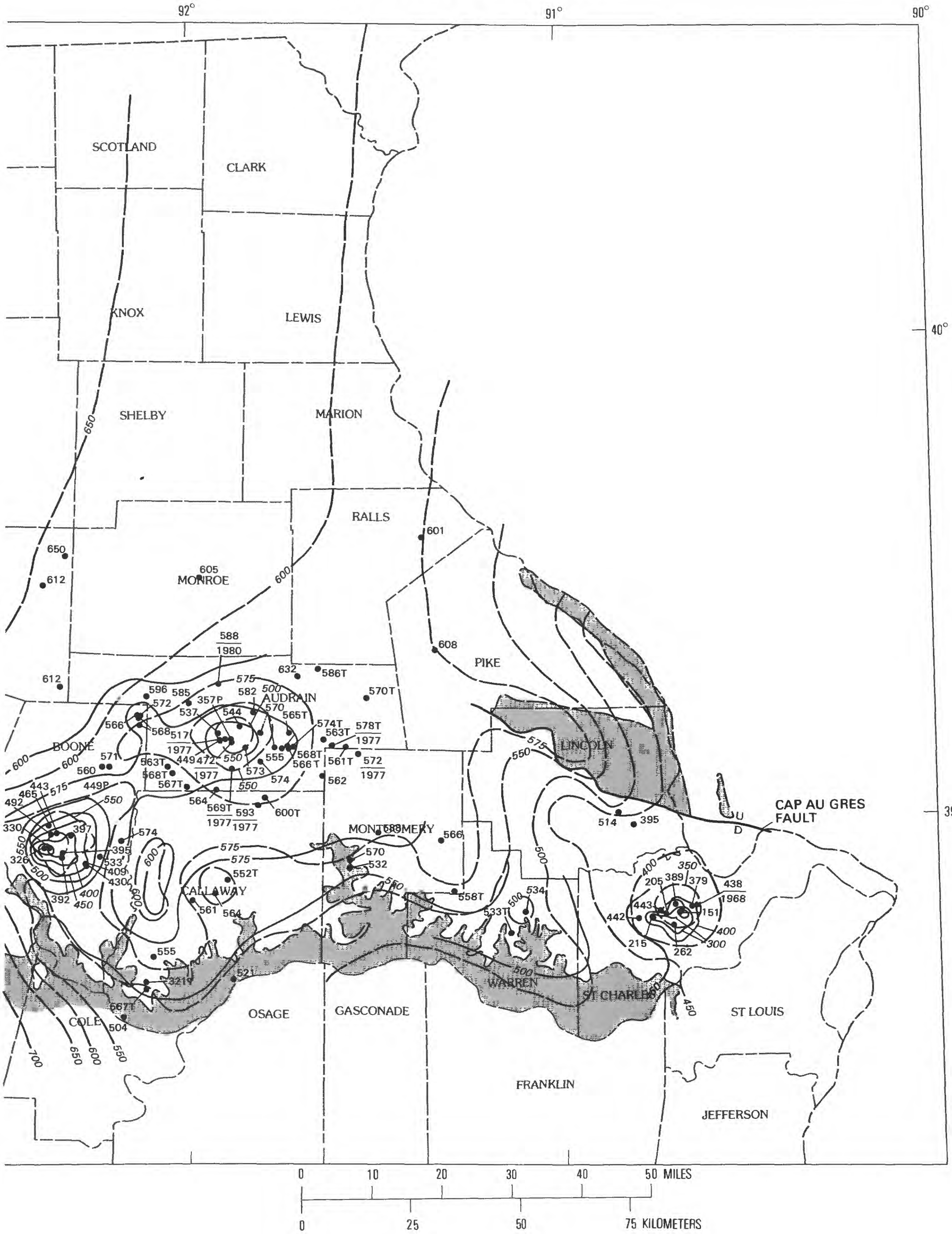
—550— POTENTIOMETRIC CONTOUR — Shows altitude of the actual potentiometric surface of the Cambrian-Ordovician aquifer. Contour interval, in feet, is variable. National Geodetic Vertical Datum of 1929

569T / 1977 WELL — Upper number is altitude of the Cambrian-Ordovician potentiometric surface, in feet above National Geodetic Vertical Datum of 1929. Lower number is year during which the data were collected. If no lower number is present, data were collected during May, 1979. P, measurement made while well was being pumped. T, measurement made while nearby well was being pumped

OUTCROP AREA OF THE CAMBRIAN-ORDOVICIAN AQUIFER

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

FIGURE 26.—Altitude of the simulated and actual May 1979 potentiometric surfaces of the Cambrian-Ordovician aquifer.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ST LOUIS
FRANKLIN
JEFFERSON
0 10 20 30 40 50 MILES
0 25 50 75 KILOMETERS

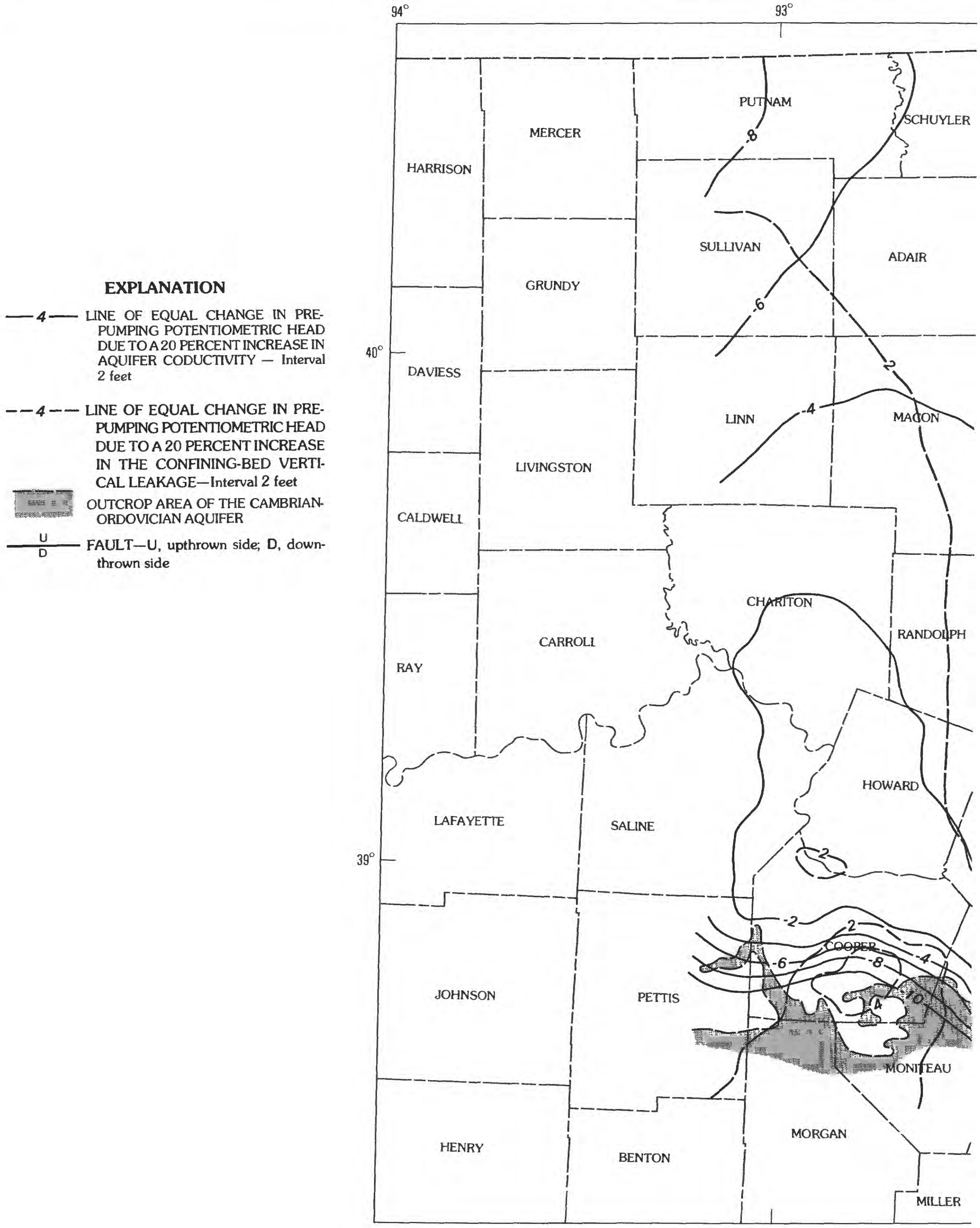
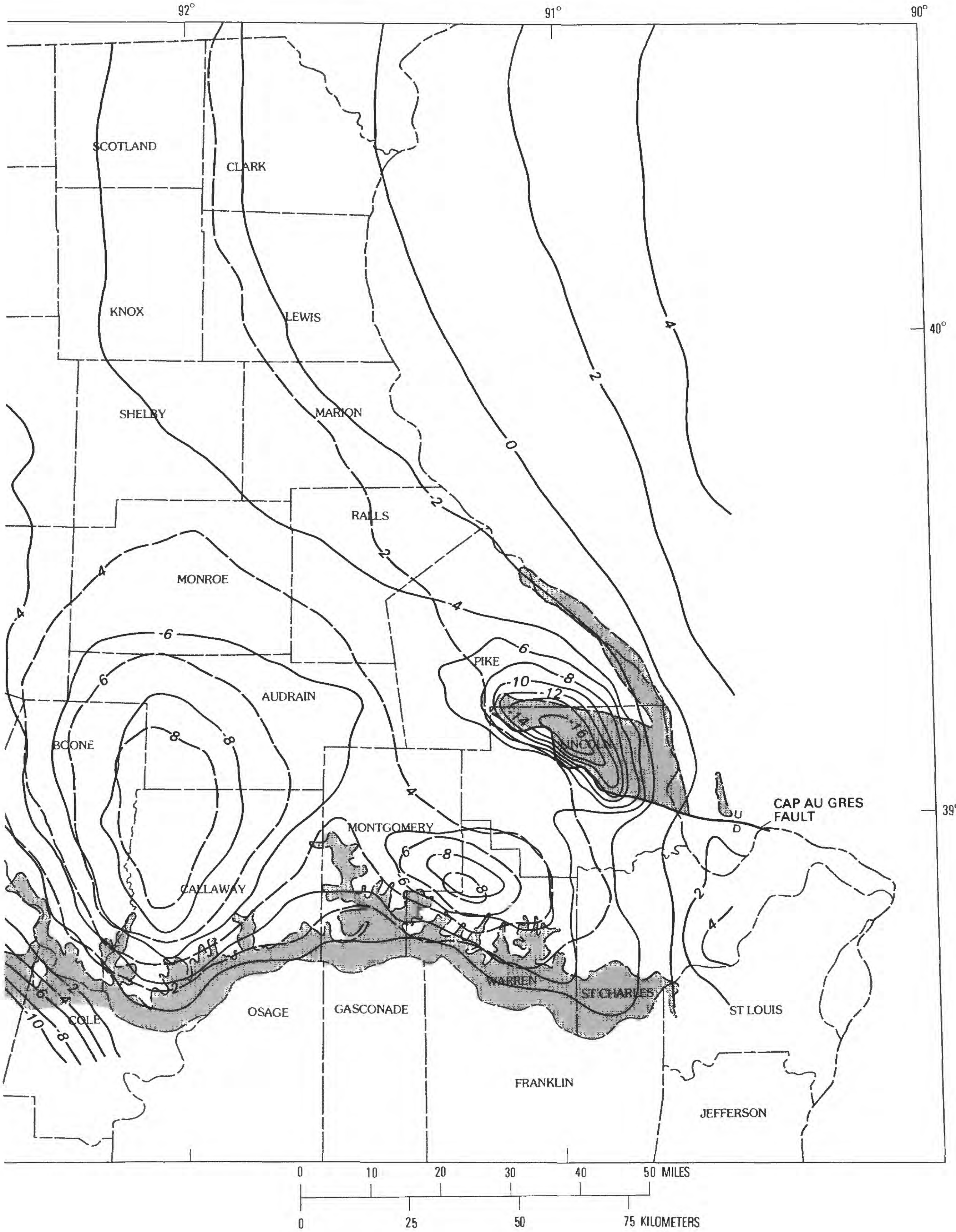


FIGURE 27.—Sensitivity of the simulated potentiometric head to changes in aquifer hydraulic conductivity and confining-bed leakage.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OSAGE
GASCONADE
WARREN
ST CHARLES
ST LOUIS
FRANKLIN
JEFFERSON
CAP AU GRES
FAULT
U
D
0
10
20
30
40
50 MILES
0
25
50
75 KILOMETERS

EXPLANATION

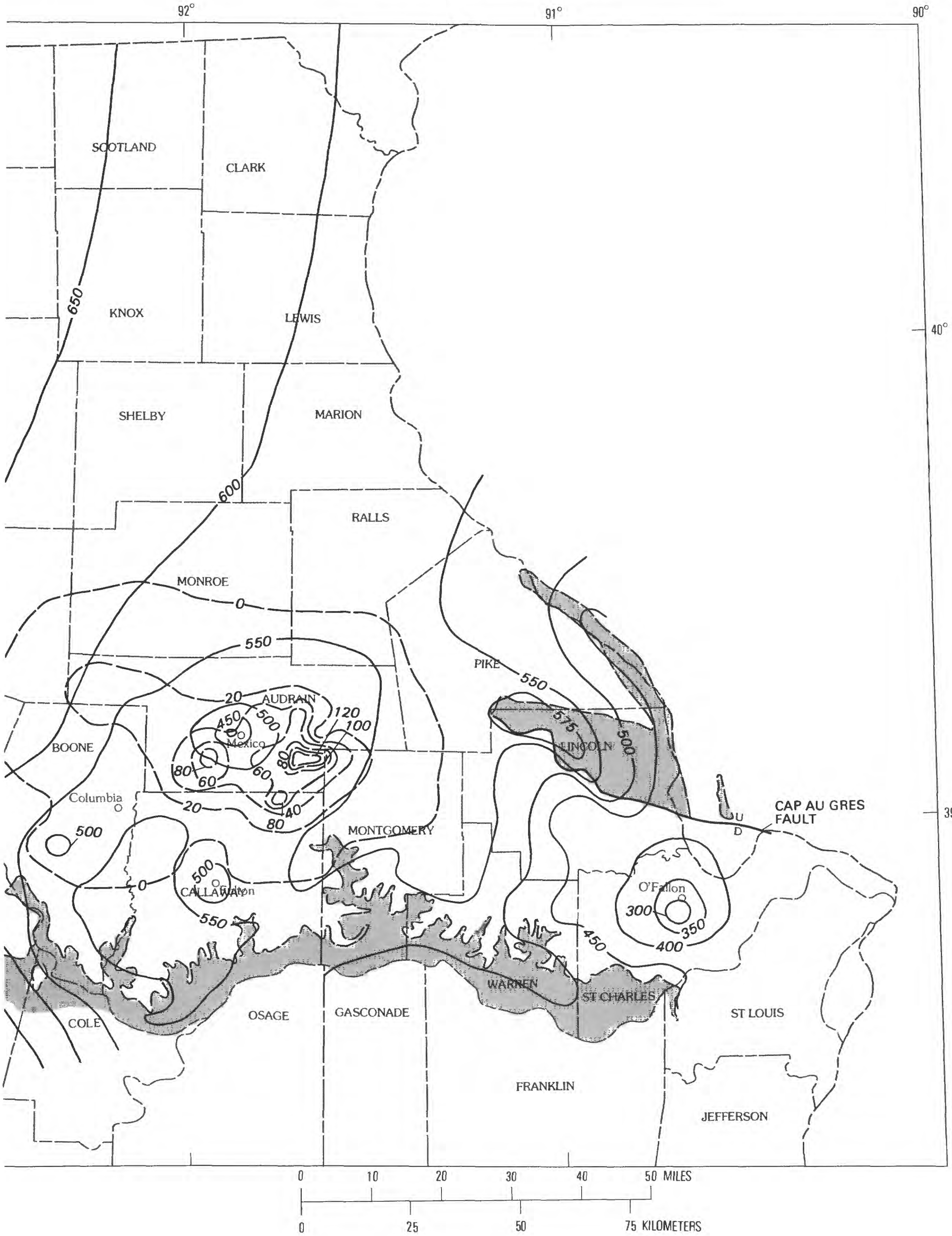
—550— POTENTIOMETRIC CONTOUR — Shows simulated altitude of the potentiometric surface of the Cambrian-Ordovician aquifer. Contour interval 50 feet. National Geodetic Vertical Datum of 1929

- - 80- - LINE OF EQUAL WATER-LEVEL DECLINE FROM SIMULATION OF THE 1990 IRRIGATION SEASON — Interval 20 feet

OUTCROP AREA OF THE CAMBRIAN-ORDOVICIAN AQUIFER

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

FIGURE 28.—Altitude of the simulated May 1990 potentiometric surface of the Cambrian-Ordovician aquifer (assuming continued pumping at 1980 rate) and drawdown during the 1990 irrigation season.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91°
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BOONE
Mexico
Columbia
LINCOLN
CAP AU GRES
FAULT
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D
MONTGOMERY
CALLAWAY
Fulton
O'Fallon
WARREN
ST CHARLES
COLE
OSAGE
GASCONADE
ST LOUIS
FRANKLIN
JEFFERSON
650
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120
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80
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300
350
400
0 10 20 30 40 50 MILES
0 25 50 75 KILOMETERS

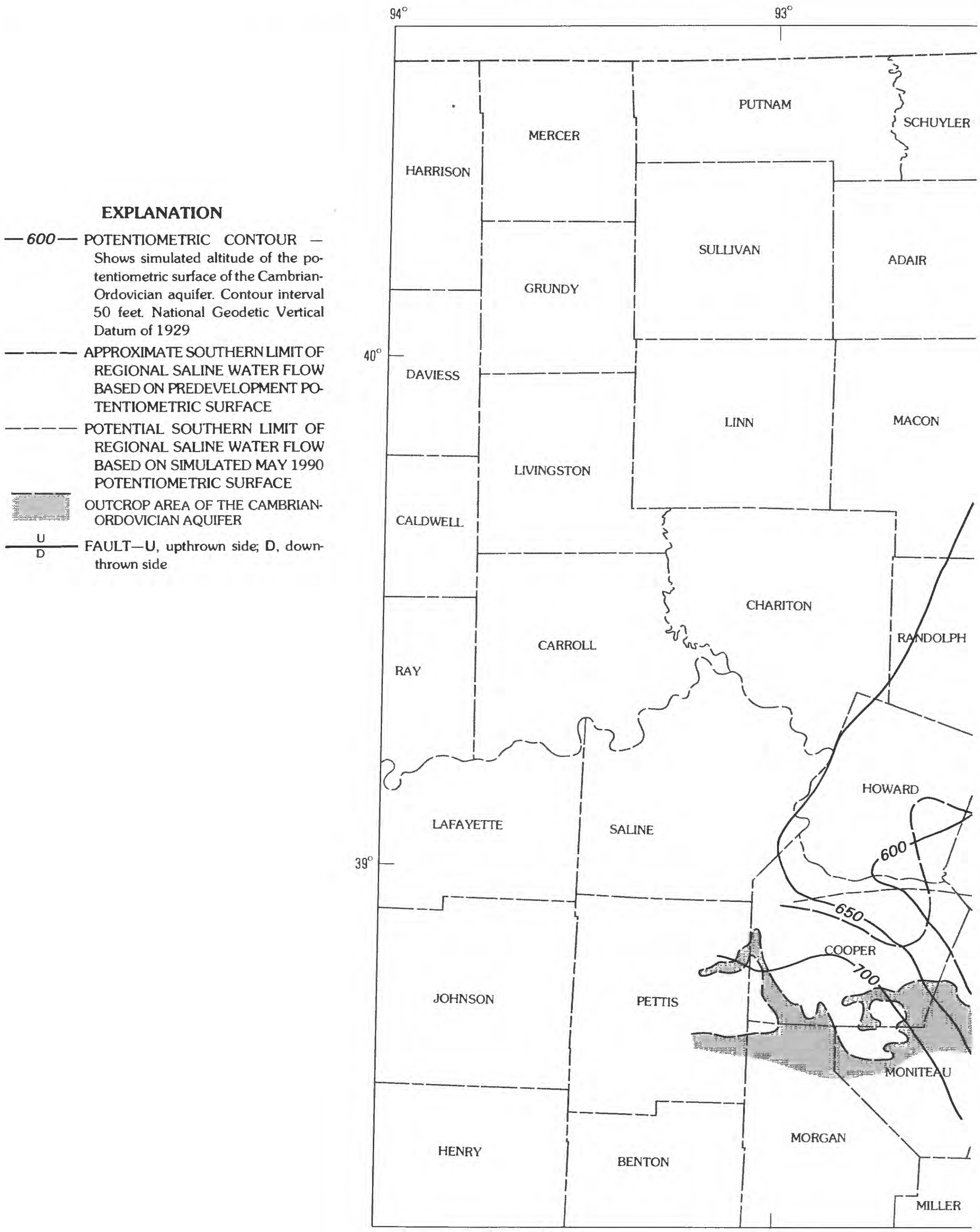
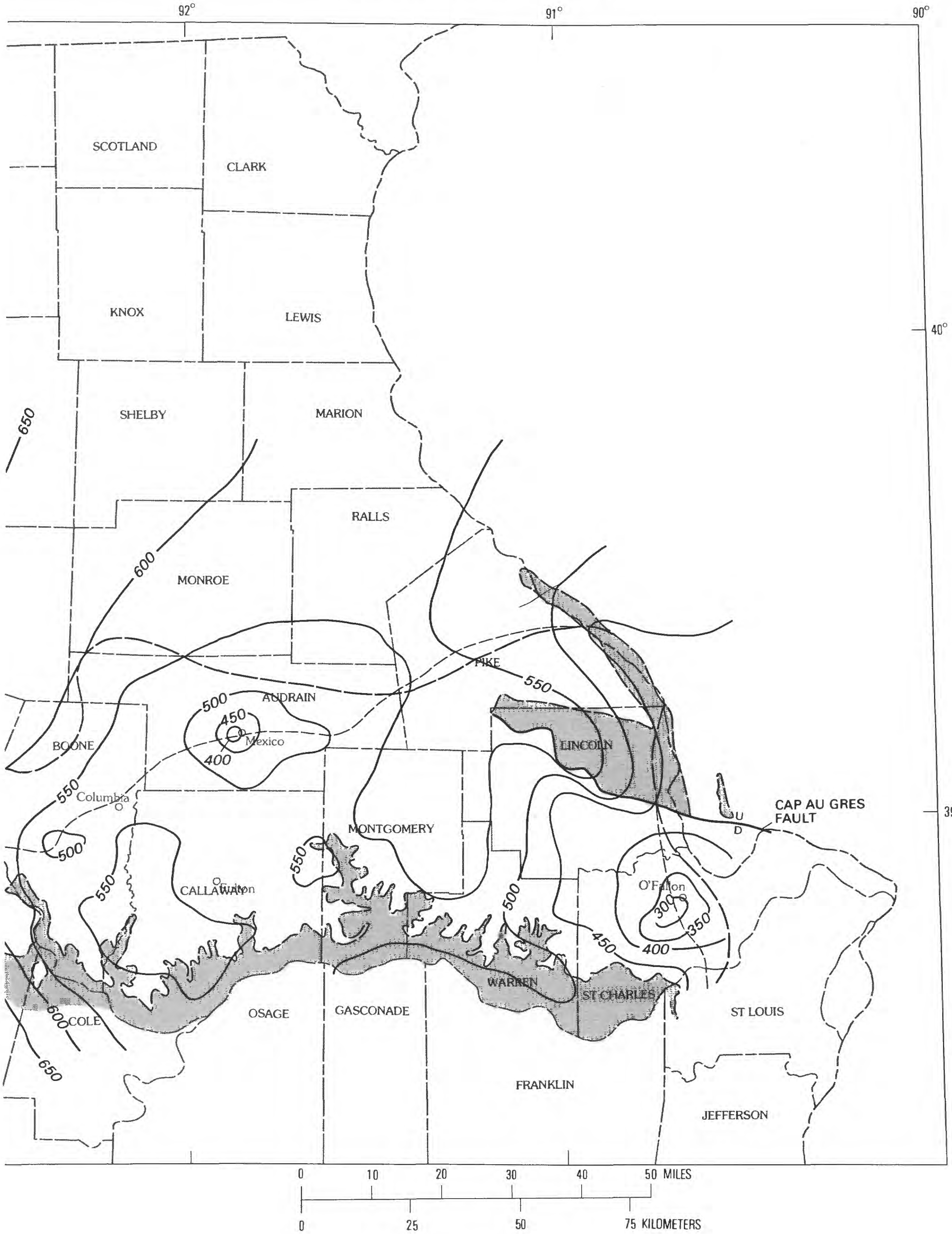


FIGURE 29.—Altitude of the simulated May 1990 potentiometric surface of the Cambrian-Ordovician aquifer (assuming 1 percent per year increase in pumping from the 1980 pumping rate) and potential southern boundary of saline water.


92°
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MONROE
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AUDRAIN
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BOONE
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OSAGE
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50 MILES
25
50
75 KILOMETERS

constructed and calibrated to both prepumping steady-state conditions and to transient potentiometric surfaces during "1965" and May 1979. The steady-state calibration indicates the historical development of a local freshwater flow system, independent from the regional saline-water flow system, in about an eight-county area immediately north of the Missouri River. Freshwater enters the Cambrian-Ordovician aquifer in this area as recharge from precipitation at outcrop locations and leakage from the overlying Mississippian aquifer. The freshwater discharges along the Missouri and Mississippi Rivers. Ground-water movement is predominantly southeastward in the saline-water area, but is deflected around the freshwater area of greater potentiometric head. Part of the saline water flows eastward under the Mississippi River into Illinois, and part flows southward and discharges into the Missouri River in southern Chariton and Howard Counties.

Two potential rates of withdrawal of water from the Cambrian-Ordovician aquifer were used to predict future drawdown in the aquifer: (1) continued pumping at the 1980 pumping rates, and (2) an increase in pumping at one percent per year more than the 1980 rates, based on estimated population and industrial growth. Under both conditions, the potentiometric surface will approach a relatively stable configuration by 1990. The potentiometric surface in the vicinity of Mexico and Fulton will decline by about 50 feet. At Columbia the potentiometric surface, which had recovered about 150 feet by May 1979 because of decreased ground-water withdrawals during the 1970's, will remain relatively stable until 1990. Postdevelopment potentiometric surfaces have altered the prepumping ground-water divide locations. Under present (1983) and projected pumping conditions, saline water has and will penetrate farther southward than was historically possible. The rate of movement of the saline water into the freshwater area is estimated to be 5 to 15 feet per year. However, more rapid movement than predicted here could occur in permeable zones and solution channels within the aquifer, and saline water may eventually be drawn upward from the underlying Lamotte Sandstone.

Further study of this ground-water system is warranted. Any continued investigation of this area needs to include several aquifer tests in the freshwater area and near the freshwater-saltwater transition zone. Presently (1983) there is no reliable multiple-well aquifer-test information for aquifers in northern Missouri. Further study may need potentiometric information for both the basal Cambrian aquifer (Lamotte Sandstone and Bonneterre Dolomite) and the Mississippian aquifer. Much of the hydrologic data essential to the development of a three-dimensional model presently are not available.

Other, more detailed model studies may eventually be valuable to Fulton, Mexico, and Columbia. These three cities are located at the edge of the major shale confining beds underlying northeastern Missouri. The shale confining beds are thin and discontinuous at these locations. As the Cambrian-Ordovician potentiometric surface is lowered, greater volumes of water can be drawn from the overlying Mississippian aquifer into the municipal wells. Thus, if the shallow aquifer is susceptible to pollution it can adversly affect a city's water supply from the deeper Cambrian-Ordovician aquifer. This is much more likely to occur where the confining bed is thin or missing near the surface. Fulton, which also is near the Ordovician outcrop, probably is most susceptible to this potential problem. Only detailed studies can determine the likelihood of such events.

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GLOSSARY OF HYDROLOGIC TERMS

Aquifer. A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Confining bed. A body of relatively impermeable material stratigraphically adjacent to one or more aquifers.

Evapotranspiration. The combined process by which water is vaporized by direct evaporation and by transpiration of vegetation.

Hydraulic conductivity. The property of a medium, such as an aquifer, to transmit a unit volume of water at the prevailing viscosity through a cross section of unit area in unit time.

Hydraulic gradient. The change in static head per unit of distance in a given direction. The direction is that of the maximum rate of decrease in head.

Isotropy. That condition in which all significant properties are independent of direction. Although no aquifers are isotropic in detail, models based on the assumption of isotropy have been shown to be valuable tools for predicting the approximate relationship between discharge and potential in many aquifers.

Potentiometric surface. A surface that represents the static head. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells.

Recharge. The addition of water to the zone of saturation. Infiltration of precipitation is a form of natural recharge.

Specific yield. The ratio of the volume of water that the rock, after being saturated, will yield by gravity to the total volume of the rock.

Steady state. Steady flow of water through permeable material. Under this condition, there is no change in hydraulic head with time or change in volume of water in storage.

Storage coefficient. The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head (dimensionless).

Transmissivity. The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

Water Table. The water table is that surface in a ground-water body at which water pressure is atmospheric. It is defined by the levels at which water stands in wells that only penetrate the aquifer a small distance below the water table.

ADDITIONAL DATA

The modifications to the fortran code of the two-dimensional model (Trescott and others, 1976) are relatively minor. Only the strongly implicit procedure (SIP) code was modified, but other solution subroutines can be changed in a similar manner

1. To eliminate the possibility of unintentionally removing water at the edge of shallow confining beds, insert the following code after SIP 1540 and SIP 2580:

```
If (RIVER (N). LT. TOP(N))
Then
    SL(N) = 0.0
    TL(N) = 0.0
    U = 1.0
    Go to 200
Else
    HED1 = AMAX1 (STRT(N), TOP(N))
ENDIF
```

   and remove SIP 1550 and SIP 2590.

2. To insure the proper storage variable at the edge of a shallow confining bed that thins out before reaching the surface, insert the following code after SIP 1410 and SIP 2450.

```
If (M(N). EQ.0.)
Then
    RHO = SY(N)/DELT
    Go to 180
ENDIF
```

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